

**Numerical Recipes  
in Fortran 90  
Second Edition**

**Volume 2 of  
Fortran Numerical Recipes**

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# Numerical Recipes in Fortran 90

The Art of *Parallel* Scientific Computing  
Second Edition

Volume 2 of  
Fortran Numerical Recipes

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# Contents

<b><i>Preface to Volume 2</i></b>	<b><i>viii</i></b>
<b><i>Foreword by Michael Metcalf</i></b>	<b><i>x</i></b>
<b><i>License Information</i></b>	<b><i>xvii</i></b>
<b>21 <i>Introduction to Fortran 90 Language Features</i></b>	<b>935</b>
21.0 Introduction	935
21.1 Quick Start: Using the Fortran 90 Numerical Recipes Routines	936
21.2 Fortran 90 Language Concepts	937
21.3 More on Arrays and Array Sections	941
21.4 Fortran 90 Intrinsic Procedures	945
21.5 Advanced Fortran 90 Topics	953
21.6 And Coming Soon: Fortran 95	959
<b>22 <i>Introduction to Parallel Programming</i></b>	<b>962</b>
22.0 Why Think Parallel?	962
22.1 Fortran 90 Data Parallelism: Arrays and Intrinsic	964
22.2 Linear Recurrence and Related Calculations	971
22.3 Parallel Synthetic Division and Related Algorithms	977
22.4 Fast Fourier Transforms	981
22.5 Missing Language Features	983
<b>23 <i>Numerical Recipes Utility Functions for Fortran 90</i></b>	<b>987</b>
23.0 Introduction and Summary Listing	987
23.1 Routines That Move Data	990
23.2 Routines Returning a Location	992
23.3 Argument Checking and Error Handling	994
23.4 Routines for Polynomials and Recurrences	996
23.5 Routines for Outer Operations on Vectors	1000
23.6 Routines for Scatter with Combine	1002
23.7 Routines for Skew Operations on Matrices	1004
23.8 Other Routines	1007
<b><i>Fortran 90 Code Chapters</i></b>	<b>1009</b>
<b>B1 <i>Preliminaries</i></b>	<b>1010</b>
<b>B2 <i>Solution of Linear Algebraic Equations</i></b>	<b>1014</b>
<b>B3 <i>Interpolation and Extrapolation</i></b>	<b>1043</b>

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<b>B4</b>	<b><i>Integration of Functions</i></b>	<b>1052</b>
<b>B5</b>	<b><i>Evaluation of Functions</i></b>	<b>1070</b>
<b>B6</b>	<b><i>Special Functions</i></b>	<b>1083</b>
<b>B7</b>	<b><i>Random Numbers</i></b>	<b>1141</b>
<b>B8</b>	<b><i>Sorting</i></b>	<b>1167</b>
<b>B9</b>	<b><i>Root Finding and Nonlinear Sets of Equations</i></b>	<b>1182</b>
<b>B10</b>	<b><i>Minimization or Maximization of Functions</i></b>	<b>1201</b>
<b>B11</b>	<b><i>Eigensystems</i></b>	<b>1225</b>
<b>B12</b>	<b><i>Fast Fourier Transform</i></b>	<b>1235</b>
<b>B13</b>	<b><i>Fourier and Spectral Applications</i></b>	<b>1253</b>
<b>B14</b>	<b><i>Statistical Description of Data</i></b>	<b>1269</b>
<b>B15</b>	<b><i>Modeling of Data</i></b>	<b>1285</b>
<b>B16</b>	<b><i>Integration of Ordinary Differential Equations</i></b>	<b>1297</b>
<b>B17</b>	<b><i>Two Point Boundary Value Problems</i></b>	<b>1314</b>
<b>B18</b>	<b><i>Integral Equations and Inverse Theory</i></b>	<b>1325</b>
<b>B19</b>	<b><i>Partial Differential Equations</i></b>	<b>1332</b>
<b>B20</b>	<b><i>Less-Numerical Algorithms</i></b>	<b>1343</b>
	<b><i>References</i></b>	<b>1359</b>
	<b><i>Appendices</i></b>	
<b>C1</b>	<b><i>Listing of Utility Modules (nrtype and nrutil)</i></b>	<b>1361</b>
<b>C2</b>	<b><i>Alphabetical Listing of Explicit Interfaces</i></b>	<b>1384</b>
<b>C3</b>	<b><i>Index of Programs and Dependencies</i></b>	<b>1434</b>
	<b><i>General Index to Volumes 1 and 2</i></b>	<b>1447</b>

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**Contents of Volume 1: Numerical Recipes in Fortran 77**

	<b><i>Plan of the Two-Volume Edition</i></b>	<b><i>xiii</i></b>
	<b><i>Preface to the Second Edition</i></b>	<b><i>xv</i></b>
	<b><i>Preface to the First Edition</i></b>	<b><i>xviii</i></b>
	<b><i>License Information</i></b>	<b><i>xx</i></b>
	<b><i>Computer Programs by Chapter and Section</i></b>	<b><i>xxiv</i></b>
<b>1</b>	<b><i>Preliminaries</i></b>	<b><i>1</i></b>
<b>2</b>	<b><i>Solution of Linear Algebraic Equations</i></b>	<b><i>22</i></b>
<b>3</b>	<b><i>Interpolation and Extrapolation</i></b>	<b><i>99</i></b>
<b>4</b>	<b><i>Integration of Functions</i></b>	<b><i>123</i></b>
<b>5</b>	<b><i>Evaluation of Functions</i></b>	<b><i>159</i></b>
<b>6</b>	<b><i>Special Functions</i></b>	<b><i>205</i></b>
<b>7</b>	<b><i>Random Numbers</i></b>	<b><i>266</i></b>
<b>8</b>	<b><i>Sorting</i></b>	<b><i>320</i></b>
<b>9</b>	<b><i>Root Finding and Nonlinear Sets of Equations</i></b>	<b><i>340</i></b>
<b>10</b>	<b><i>Minimization or Maximization of Functions</i></b>	<b><i>387</i></b>
<b>11</b>	<b><i>Eigensystems</i></b>	<b><i>449</i></b>
<b>12</b>	<b><i>Fast Fourier Transform</i></b>	<b><i>490</i></b>
<b>13</b>	<b><i>Fourier and Spectral Applications</i></b>	<b><i>530</i></b>
<b>14</b>	<b><i>Statistical Description of Data</i></b>	<b><i>603</i></b>
<b>15</b>	<b><i>Modeling of Data</i></b>	<b><i>650</i></b>
<b>16</b>	<b><i>Integration of Ordinary Differential Equations</i></b>	<b><i>701</i></b>
<b>17</b>	<b><i>Two Point Boundary Value Problems</i></b>	<b><i>745</i></b>
<b>18</b>	<b><i>Integral Equations and Inverse Theory</i></b>	<b><i>779</i></b>
<b>19</b>	<b><i>Partial Differential Equations</i></b>	<b><i>818</i></b>
<b>20</b>	<b><i>Less-Numerical Algorithms</i></b>	<b><i>881</i></b>
	<b><i>References</i></b>	<b><i>916</i></b>
	<b><i>Index of Programs and Dependencies</i></b>	<b><i>921</i></b>

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# Preface to Volume 2

Fortran 90 is not just the long-awaited updating of the Fortran language to modern computing practices. It is also the vanguard of a much larger revolution in computing, that of multiprocessor computers and widespread parallel programming. Parallel computing has been a feature of the largest supercomputers for quite some time. Now, however, it is rapidly moving towards the desktop.

As we watched the gestation and birth of Fortran 90 by its governing “X3J3 Committee” (a process interestingly described by a leading committee member, Michael Metcalf, in the Foreword that follows), it became clear to us that the right moment for moving Numerical Recipes from Fortran 77 to Fortran 90 was sooner, rather than later.

Fortran 90 compilers are now widely available. Microsoft’s Fortran PowerStation for Windows 95 brings that firm’s undeniable marketing force to PC desktop; we have tested this compiler thoroughly on our code and found it excellent in compatibility and performance. In the UNIX world, we have similarly tested, and had generally fine experiences with, DEC’s Fortran 90 for Alpha AXP and IBM’s xlf for RS/6000 and similar machines. NAG’s Fortran 90 compiler also brings excellent Fortran 90 compatibility to a variety of UNIX platforms. There are no doubt other excellent compilers, both available and on the way. Fortran 90 is completely backwards compatible with Fortran 77, by the way, so you don’t have to throw away your legacy code, or keep an old compiler around.

There have been previous special versions of Fortran for parallel supercomputers, but always specific to a particular hardware. Fortran 90, by contrast, is designed to provide a general, architecture-independent framework for parallel computation. Equally importantly, it is an international standard, agreed upon by a large group of computer hardware and software manufacturers and international standards bodies.

With the Fortran 90 language as a tool, we want this volume to be your complete guide for learning how to “think parallel.” The language itself is very general in this regard, and applicable to many present and future computers, or even to other parallel computing languages as they come along. Our treatment emphasizes general principles, but we are also not shy about pointing out parallelization “tricks” that have frequent applicability. These are not only discussed in this volume’s principal text chapters (Chapters 21–23), but are also sprinkled throughout the chapters of Fortran 90 code, called out by a special “parallel hint” logo (left, above). Also scattered throughout the code chapters are specific “Fortran 90 tips,” with their own distinct graphic call-out (left). After you read the text chapters, you might want simply to browse among these hints and tips.

A special note to C programmers: Right now, there is no effort at producing a parallel version of C that is comparable to Fortran 90 in maturity, acceptance, and stability. We think, therefore, that C programmers will be well served by using this volume for an educational excursion into Fortran 90, its parallel programming constructions, and the numerical algorithms that capitalize on them. C and C++ programming have not been far from our minds as we have written this volume, and we think that you will find that time spent in absorbing its principal lessons (in Chapters 21–23) will be amply repaid in the future, as C and C++ eventually develop standard parallel extensions.

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A final word of truth in packaging: **Don't buy this volume unless you also buy (or already have) Volume 1** (now retitled *Numerical Recipes in Fortran 77*). Volume 2 does not repeat any of the discussion of what individual programs actually do, or of the mathematical methods they utilize, or how to use them. While our Fortran 90 code is thoroughly commented, and includes a header comment for each routine that describes its input and output quantities, these comments are *not* supposed to be a complete description of the programs; the complete descriptions are in Volume 1, which we reference frequently. But here's a money-saving hint to our previous readers: If you already own a Second Edition version whose title is *Numerical Recipes in FORTRAN* (which doesn't indicate either "Volume 1" or "Volume 2" on its title page) then take a marking pen and write in the words "Volume 1." There! (Differences between the previous reprintings and the newest reprinting, the one labeled "Volume 1," are minor.)

## Acknowledgments

We continue to be in the debt of many colleagues who give us the benefit of their numerical and computational experience. Many, though not all, of these are listed by name in the preface to the second edition, in Volume 1. To that list we must now certainly add George Marsaglia, whose ideas have greatly influenced our new discussion of random numbers in this volume (Chapter B7).

With this volume, we must acknowledge our additional gratitude and debt to a number of people who generously provided advice, expertise, and time (a great deal of time, in some cases) in the areas of parallel programming and Fortran 90. The original inspiration for this volume came from Mike Metcalf, whose clear lectures on Fortran 90 (in this case, overlooking the beautiful Adriatic at Trieste) convinced us that Fortran 90 could serve as the vehicle for a book with the larger scope of parallel programming generally, and whose continuing advice throughout the project has been indispensable. Gyan Bhanot also played a vital early role in the development of this book; his first translations of our Fortran 77 programs taught us a lot about parallel programming. We are also grateful to Greg Lindhorst, Charles Van Loan, Amos Yahil, Keith Kimball, Malcolm Cohen, Barry Caplin, Loren Meissner, Mitsu Sakamoto, and George Schnurer for helpful correspondence and/or discussion of Fortran 90's subtler aspects.

We once again express in the strongest terms our gratitude to programming consultant Seth Finkelstein, whose contribution to both the coding and the thorough testing of all the routines in this book (against multiple compilers and in sometimes-buggy, and always challenging, early versions) cannot be overstated.

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February 1996

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# Foreword

by Michael Metcalf

Sipping coffee on a sunbaked terrace can be surprisingly productive. One of the *Numerical Recipes* authors and I were each lecturing at the International Center for Theoretical Physics in Trieste, Italy, he on numerical analysis and I on Fortran 90. The numerical analysis community had made important contributions to the development of the new Fortran standard, and so, unsurprisingly, it became quickly apparent that the algorithms for which *Numerical Recipes* had become renowned could, to great advantage, be recast in a new mold. These algorithms had, hitherto, been expressed in serial form, first in Fortran 77 and then in C, Pascal, and Basic. Now, nested iterations could be replaced by array operations and assignments, and the other features of a rich array language could be exploited. Thus was the idea of a "Numerical Recipes in Fortran 90" first conceived and, after three years' gestation, it is a delight to assist at the birth.

But what *is* Fortran 90? How did it begin, what shaped it, and how, after nearly foundering, did its driving forces finally steer it to a successful conclusion?

## ***The Birth of a Standard***

Back in 1966, the version of Fortran now known as Fortran 66 was the first language ever to be standardized, by the predecessor of the present American National Standards Institute (ANSI). It was an all-American affair. Fortran had first been developed by John Backus of IBM in New York, and it was the dominant scientific programming language in North America. Many Europeans preferred Algol (in which Backus had also had a hand). Eventually, however, the mathematicians who favored Algol for its precisely expressible syntax began to defer to the scientists and engineers who appreciated Fortran's pragmatic, even natural, style. In 1978, the upgraded Fortran 77 was standardized by the ANSI technical committee, X3J3, and subsequently endorsed by other national bodies and by ISO in Geneva, Switzerland. Its dominance in all fields of scientific and numerical computing grew as new, highly optimizing compilers came onto the market. Although newer languages, particularly Pascal, Basic, PL/1, and later Ada attracted their own adherents, scientific users throughout the 1980s remained true to Fortran. Only towards the end of that decade did C draw increasing support from scientific programmers who had discovered the power of structures and pointers.

During all this time, X3J3 kept functioning, developing the successor version to Fortran 77. It was to be a decade of strife and contention. The early plans, in the late 1970s, were mainly to add to Fortran 77 features that had had to be left out of that standard. Among these were dynamic storage and an array language, enabling it to map directly onto the architecture of supercomputers, then coming onto the market. The intention was to have this new version ready within five years, in 1982. But two new factors became significant at that time. The first was the decision that the next standard should not just codify existing practice, as had largely been the case in 1966 and 1978, but also extend the functionality of the language through

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innovative additions (even though, for the array language, there was significant borrowing from John Iverson's APL and from DAP Fortran). The second factor was that X3J3 no longer operated under only American auspices. In the course of the 1980s, the standardization of programming languages came increasingly under the authority of the international body, ISO. Initially this was in an advisory role, but now ISO is the body that, through its technical committee WG5 (in full, ISO/IEC JTC1/SC22/WG5), is responsible for determining the course of the language. WG5 also steers the work of the development body, then as now, the highly skilled and competent X3J3. As we shall see, this shift in authority was crucial at the most difficult moment of Fortran 90's development.

The internationalization of the standards effort was reflected in the welcome given by X3J3 to six or seven European members; they, and about one-third of X3J3's U.S. members, provided the overlapping core of membership of X3J3 and WG5 that was vital in the final years in bringing the work to a successful conclusion. X3J3 membership, which peaked at about 45, is restricted to one voting member per organization, and significant decisions require a majority of two-thirds of those voting. Nationality plays no role, except in determining the U.S. position on an international issue. Members, who are drawn mainly from the vendors, large research laboratories, and academia, must be present or represented at two-thirds of all meetings in order to retain voting rights.

In 1980, X3J3 reported on its plans to the forerunner of WG5 in Amsterdam, Holland. Fortran 8x, as it was dubbed, was to have a basic array language, new looping constructs, a bit data type, data structures, a free source form, a mechanism to "group" procedures, and another to manage the global name space. Old features, including COMMON, EQUIVALENCE, and the arithmetic-IF, were to be consigned to a so-called obsolete module, destined to disappear in a subsequent revision. This was part of the "core plus modules" architecture, for adding new features and retiring old ones, an aid to backwards compatibility. Even though Fortran 77 compilers were barely available, the work seemed well advanced and the mood was optimistic. Publication was intended to take place in 1985. It was not to be.

One problem was the sheer number of new features that were proposed as additions to the language, most of them worthwhile in themselves but with the totality being too large. This became a recurrent theme throughout the development of the standard. One example was the suggestion of Lawrie Schonfelder (Liverpool University), at a WG5 meeting in Vienna, Austria, in 1982, that certain features already proposed as additions could be combined to provide a full-blown derived data type facility, thus providing Fortran with abstract data types. This idea was taken up by X3J3 and has since come to be recognized, along with the array language, as one of the two main advances brought about by what became Fortran 90. However, the ramifications go very deep: all the technical details of how to handle arrays of objects of derived types that in turn have array components that have the pointer attribute, and so forth, have to be precisely defined and rigorously specified.

## **Conflict**

The meetings of X3J3 were often full of drama. Most compiler vendors were represented as a matter of course but, for many, their main objective appeared to be to maintain the status quo and to ensure that Fortran 90 never saw the light of

day. One vendor's extended (and much-copied) version of Fortran 77 had virtually become an industry standard, and it saw as its mission the maintenance of this lead. A new standard would cost it its perceived precious advantage. Other large vendors had similar points of view, although those marketing supercomputers were clearly keen on the array language. Most users, on the other hand, were hardly prepared to invest large amounts of their employers' and their own resources in simply settling for a trivial set of improvements to the existing standard. However, as long as X3J3 worked under a simple-majority voting rule, at least some apparent progress could be made, although the underlying differences often surfaced. These were even sometimes between users — those who wanted Fortran to become a truly modern language and those wanting to maintain indefinite backwards compatibility for their billions of lines of existing code.

At a watershed meeting, in Scranton, Pennsylvania, in 1986, held in an atmosphere that sometimes verged on despair, a fragile compromise was reached as a basis for further work. One breakthrough was to weaken the procedures for removing outdated features from the language, particularly by removing no features whatsoever from the next standard and by striking storage association (i.e., COMMON and EQUIVALENCE) from the list of features to be designated as obsolescent (as they are now known). A series of votes definitively removed from the language all plans to add: arrays of arrays, exception handling, nesting of internal procedures, the FORALL statement (now in Fortran 95), and a means to access skew array sections. There were other features on this list that, although removed, were reinstated at later meetings: user-defined operators, operator overloading, array and structure constructors, and vector-valued subscripts. After many more travails, the committee voted, a year later, by 26 votes to 9, to forward the document for what was to become the first of three periods of public comment.

While the document was going through the formal standards bureaucracy and being placed before the public, X3J3 polished it further. X3J3 also prepared procedures for processing the comments it anticipated receiving from the public, and to each of which, under the rules, it would have to reply individually. It was just as well. Roughly 400 replies flooded in, many of them very detailed and, disappointingly for those of us wanting a new standard quickly, unquestionably negative towards our work. For many it was too radical, but many others pleaded for yet more modern features, such as pointers.

Now the committee was deadlocked. Given that a document had already been published, any further change required not a simple but a two-thirds majority. The conservatives and the radicals could each block a move to modify the draft standard, or to accept a revised one for public review — and just that happened, in Champagne-Urbana, Illinois, in 1988. Any change, be it on the one hand to modify the list of obsolescent features, to add the pointers or bit data type wanted by the public, to add multi-byte characters to support Kanji and other non-European languages or, on the other hand, to emasculate the language by removing modules or operator overloading, and hence abstract data types, to name but some suggestions, none of these could be done individually or collectively in a way that would achieve consensus. I wrote:

“In my opinion, no standard can now emerge without either a huge concession by the users to the vendors (MODULE / USE) and/or a major change in the composition of the committee. I do not see how members who have worked for up to a decade

or more, devoting time and intellectual energy far beyond the call of duty, can be expected to make yet more personal sacrifices if no end to the work is in sight, or if that end is nothing but a travesty of what had been designed and intended as a modern scientific programming language. . . . I think the August meeting will be a watershed — if no progress is achieved there will be dramatic resignations, and ISO could even remove the work from ANSI, which is failing conspicuously in its task."

(However, the same notes began with a quotation from *The Taming of the Shrew*: "And do as adversaries do in law, / Strive mightily, but eat and drink / as friend." That we always did, copiously.)

## Resolution

The "August meeting" was, unexpectedly, imbued with a spirit of compromise that had been so sadly lacking at the previous one. Nevertheless, after a week of discussing four separate plans to rescue the standard, no agreement was reached. Now the question seriously arose: Was X3J3 incapable of producing a new Fortran standard for the international community, doomed to eternal deadlock, a victim of ANSI procedures?

Breakthrough was achieved at a traumatic meeting of WG5 in Paris, France, a month later. The committee spent several extraordinary days drawing up a detailed list of what *it* wanted to be in Fortran 8x. Finally, it set X3J3 an ultimatum that was unprecedented in the standards world: The ANSI committee was to produce a new draft document, corresponding to WG5's wishes, within five months! Failing that, WG5 would assume responsibility and produce the new standard itself.

This decision was backed by the senior U.S. committee, X3, which effectively directed X3J3 to carry out WG5's wishes. And it did! The following November, it implemented most of the technical changes, adding pointers, bit manipulation intrinsic procedures, and vector-valued subscripts, and removing user-defined elemental functions (now in Fortran 95). The actual list of changes was much longer. X3J3 and WG5, now collaborating closely, often in gruelling six-day meetings, spent the next 18 months and two more periods of (positive) public comment putting the finishing touches to what was now called Fortran 90, and it was finally adopted, after some cliff-hanging votes, for forwarding as a U.S. and international standard on April 11, 1991, in Minneapolis, Minnesota.

Among the remaining issues that were decided along the way were whether pointers should be a data type or be defined in terms of an attribute of a variable, implying strong typing (the latter was chosen), whether the new standard should coexist alongside the old one rather than definitively replace it (it coexisted for a while in the U.S., but was a replacement elsewhere, under ISO rules), and whether, in the new free source form, blanks should be significant (fortunately, they are).

## Fortran 90

The main new features of Fortran 90 are, first and foremost, the array language and abstract data types. The first is built on whole array operations and assignments, array sections, intrinsic procedures for arrays, and dynamic storage. It was designed with optimization in mind. The second is built on modules and module procedures, derived data types, operator overloading and generic interfaces, together with

pointers. Also important are the new facilities for numerical computation including a set of numeric inquiry functions, the parametrization of the intrinsic types, new control constructs — SELECT CASE and new forms of DO, internal and recursive procedures and optional and keyword arguments, improved I/O facilities, and many new intrinsic procedures. Last but not least are the new free source form, an improved style of attribute-oriented specifications, the IMPLICIT NONE statement, and a mechanism for identifying redundant features for subsequent removal from the language. The requirement on compilers to be able to identify, for example, syntax extensions, and to report why a program has been rejected, are also significant. The resulting language is not only a far more powerful tool than its successor, but a safer and more reliable one too. Storage association, with its attendant dangers, is not abolished, but rendered unnecessary. Indeed, experience shows that compilers detect errors far more frequently than before, resulting in a faster development cycle. The array syntax and recursion also allow quite compact code to be written, a further aid to safe programming.

No programming language can succeed if it consists simply of a definition (witness Algol 68). Also required are robust compilers from a wide variety of vendors, documentation at various levels, and a body of experience. The first Fortran 90 compiler appeared surprisingly quickly, in 1991, especially in view of the widely touted opinion that it would be very difficult to write one. Even more remarkable was that it was written by one person, Malcolm Cohen of NAG, in Oxford, U.K. There was a gap before other compilers appeared, but now they exist as native implementations for almost all leading computers, from the largest to PCs. For the most part, they produce very efficient object code; where, for certain new features, this is not the case, work is in progress to improve them.

The first book, *Fortran 90 Explained*, was published by John Reid and me shortly before the standard itself was published. Others followed in quick succession, including excellent texts aimed at the college market. At the time of writing there are at least 19 books in English and 22 in various other languages: Chinese, Dutch, French, Japanese, Russian, and Swedish. Thus, the documentation condition is fulfilled.

The body of experience, on the other hand, has yet to be built up to a critical size. Teaching of the language at college level has only just begun. However, I am certain that this present volume will contribute decisively to a significant breakthrough, as it provides models not only of the numerical algorithms for which previous editions are already famed, but also of an excellent Fortran 90 style, something that can develop only with time. Redundant features are abjured. It shows that, if we abandon these features and use new ones in their place, the appearance of code can initially seem unfamiliar, but, in fact, the advantages become rapidly apparent. This new edition of *Numerical Recipes* stands as a landmark in this regard.

## **Fortran Evolution**

The formal procedures under which languages are standardized require them either to evolve or to die. A standard that has not been revised for some years must either be revised and approved anew, or be withdrawn. This matches the technical pressure on the language developers to accommodate the increasing complexity both of the problems to be tackled in scientific computation and of the underlying hardware

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on which programs run. Increasing problem complexity requires more powerful features and syntax; new hardware needs language features that map onto it well.

Thus it was that X3J3 and WG5, having finished Fortran 90, began a new round of improvement. They decided very quickly on new procedures that would avoid the disputes that bedevilled the previous work: WG5 would decide on a plan for future standards, and X3J3 would act as the so-called development body that would actually produce them. This would be done to a strict timetable, such that any feature that could not be completed on time would have to wait for the next round. It was further decided that the next major revision should appear a decade after Fortran 90 but, given the somewhat discomfiting number of requests for interpretation that had arrived, about 200, that a minor revision should be prepared for mid-term, in 1995. This should contain only “corrections, clarifications and interpretations” and a very limited number (some thought none) of minor improvements.

At the same time, scientific programmers were becoming increasingly concerned at the variety of methods that were necessary to gain efficient performance from the ever-more widely used parallel architectures. Each vendor provided a different set of parallel extensions for Fortran, and some academic researchers had developed yet others. On the initiative of Ken Kennedy of Rice University, a High-Performance Fortran Forum was established. A coalition of vendors and users, its aim was to produce an ad hoc set of extensions to Fortran that would become an informal but widely accepted standard for portable code. It set itself the daunting task of achieving that in just one year, and succeeded. Melding existing dialects like Fortran D, CM Fortran, and Vienna Fortran, and adopting the new Fortran 90 as a base, because of its array syntax, High-Performance Fortran (HPF) was published in 1993 and has since become widely implemented. However, although HPF was designed for data parallel codes and mainly implemented in the form of directives that appear to non-HPF processors as comment lines, an adequate functionality could not be achieved without extending the Fortran syntax. This was done in the form of the PURE attribute for functions — an assertion that they contain no side effects — and the FORALL construct — a form of array assignment expressed with the help of indices.

The dangers of having diverging or competing forms of Fortran 90 were immediately apparent, and the standards committees wisely decided to incorporate these two syntactic changes also into Fortran 95. But they didn’t stop there. Two further extensions, useful not only for their expressive power but also to access parallel hardware, were added: elemental functions, ones written in terms of scalars but that accept array arguments of any permitted shape or size, and an extension to allow nesting of WHERE constructs, Fortran’s form of masked assignment. To readers of *Numerical Recipes*, perhaps the most relevant of the minor improvements that Fortran 95 brings are the ability to distinguish between a negative and a positive real zero, automatic deallocation of allocatable arrays, and a means to initialize the values of components of objects of derived data types and to initialize pointers to null.

The medium-term objective of a relatively minor upgrade has been achieved on schedule. But what does the future hold? Developments in the underlying principles of procedural programming languages have not ceased. Early Fortran introduced the concepts of expression abstraction ( $X=Y+Z$ ) and later control expression (e.g., the DO loop). Fortran 77 continued this with the `if-then-else`, and Fortran 90 with the DO and SELECT CASE constructs. Fortran 90 has a still higher level of expression abstraction (array assignments and expressions) as well as data structures and even

full-blown abstract data types. However, during the 1980s the concept of objects came to the fore, with methods bound to the objects on which they operate. Here, one particular language, C++, has come to dominate the field. Fortran 90 lacks a means to point to functions, but otherwise has most of the necessary features in place, and the standards committees are now faced with the dilemma of deciding whether to make the planned Fortran 2000 a fully object-oriented language. This could possibly jeopardize its powerful, and efficient, numerical capabilities by too great an increase in language complexity, so should they simply batten down the hatches and not defer to what might be only a passing storm? At the time of writing, this is an open issue. One issue that is not open is Fortran's lack of in-built exception handling. It is virtually certain that such a facility, much requested by the numerical community, and guided by John Reid, will be part of the next major revision. The list of other requirements is long but speculative, but some at the top of the list are conditional compilation, command line argument handling, I/O for objects of derived type, and asynchronous I/O (which is also planned for the next release of HPF). In the meantime, some particularly pressing needs have been identified, for the handling of floating-point exceptions, interoperability with C, and allowing allocatable arrays as structure components, dummy arguments, and function results. These have led WG5 to begin processing these three items using a special form of fast track, so that they might become optional but standard extensions well before Fortran 2000 itself is published in the year 2001.

## Conclusion

Writing a book is always something of a gamble. Unlike a novel that stands or falls on its own, a book devoted to a programming language is dependent on the success of others, and so the risk is greater still. However, this new *Numerical Recipes in Fortran 90* volume is no ordinary book, since it comes as the continuation of a highly successful series, and so great is its significance that it can, in fact, influence the outcome in its own favor. I am entirely confident that its publication will be seen as an important event in the story of Fortran 90, and congratulate its authors on having performed a great service to the field of numerical computing.

Geneva, Switzerland  
January 1996

Michael Metcalf



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# Chapter 21. Introduction to Fortran 90 Language Features

## 21.0 Introduction

Fortran 90 is in many respects a backwards-compatible modernization of the long-used (and much abused) Fortran 77 language, but it is also, in other respects, a new language for parallel programming on present and future multiprocessor machines. These twin design goals of the language sometimes add confusion to the process of becoming fluent in Fortran 90 programming.

In a certain trivial sense, Fortran 90 is strictly backwards-compatible with Fortran 77. That is, any Fortran 90 compiler is supposed to be able to compile any legacy Fortran 77 code without error. The reason for terming this compatibility trivial, however, is that you have to tell the compiler (usually via a source file name ending in “.f” or “.for”) that it is dealing with a Fortran 77 file. If you instead try to pass off Fortran 77 code as native Fortran 90 (e.g., by naming the source file something ending in “.f90”) it will not always work correctly!

It is best, therefore, to approach Fortran 90 as a new computer language, albeit one with a lot in common with Fortran 77. Indeed, in such terms, Fortran 90 is a fairly *big* language, with a large number of new constructions and intrinsic functions. Here, in one short chapter, we do not pretend to provide a complete description of the language. Luckily, there are good books that do exactly that. Our favorite one is by Metcalf and Reid [1], cited throughout this chapter as “M&R.” Other good starting points include [2] and [3].

Our goal, in the remainder of this chapter, is to give a good, working description of those Fortran 90 language features that are not immediately self-explanatory to Fortran 77 programmers, with particular emphasis on those that occur most frequently in the Fortran 90 versions of the Numerical Recipes routines. This chapter, by itself, will not teach you to write Fortran 90 code. But it ought to help you acquire a reading knowledge of the language, and perhaps provide enough of a head start that you can rapidly pick up the rest of what you need to know from M&R or another Fortran 90 reference book.

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## 21.1 Quick Start: Using the Fortran 90 Numerical Recipes Routines

This section is for people who want to jump right in. We'll compute a Bessel function  $J_0(x)$ , where  $x$  is equal to the fourth root of the Julian Day number of the 200th full moon since January 1900. (Now *there's* a useful quantity!)

First, locate the important files `nrtype.f90`, `nrutil.f90`, and `nr.f90`, as listed in Appendices C1, C1, and C2, respectively. These contain *modules* that either are (i) used by our routines, or else (ii) describe the calling conventions of our routines to (your) user programs. Compile each of these files, producing (with most compilers) a `.mod` file and a `.o` (or similarly named) file for each one.

Second, create this main program file:

```
PROGRAM hello_bessel
USE nrtype
USE nr, ONLY: flmoon, bessj0
IMPLICIT NONE
INTEGER(I4B) :: n=200,nph=2,jd
REAL(SP) :: x,frac,ans
call flmoon(n,nph,jd,frac)
x=jd**0.25_sp
ans=bessj0(x)
write (*,*) 'Hello, Bessel: ', ans
END PROGRAM
```

Here is a quick explanation of some elements of the above program:

The first `USE` statement includes a module of ours named `nrtype`, whose purpose is to give symbolic names to some kinds of data types, among them single-precision reals (“`sp`”) and four-byte integers (“`i4b`”). The second `USE` statement includes a module of ours that defines the calling sequences, and variable types, expected by (in this case) the Numerical Recipes routines `flmoon` and `bessj0`.

The `IMPLICIT NONE` statement signals that we want the compiler to require us explicitly to declare all variable types. *We strongly urge that you always take this option.*

The next two lines declare integer and real variables of the desired kinds. The variable `n` is initialized to the value 200, `nph` to 2 (a value expected by `flmoon`).

We call `flmoon`, and take the fourth root of the answer it returns as `jd`. Note that the constant 0.25 is typed to be single-precision by the appended `_sp`.

We call the `bessj0` routine, and print the answer.

Third, compile the main program file, and also the files `flmoon.f90`, `bessj0.f90`. Then, link the resulting object files with also `nrutil.o` (or similar system-dependent name, as produced in step 1). Some compilers will also require you to link with `nr.o` and `nrtype.o`.

Fourth, run the resulting executable file. Typical output is:

```
Hello, Bessel: 7.3096365E-02
```

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## 21.2 Fortran 90 Language Concepts

The Fortran 90 language standard defines and uses a number of standard terms for concepts that occur in the language. Here we summarize briefly some of the most important concepts. Standard Fortran 90 terms are shown in *italics*. While by no means complete, the information in this section should help you get a quick start with your favorite Fortran 90 reference book or language manual.

A note on capitalization: Outside a character context, Fortran 90 is not case-sensitive, so you can use upper and lower case any way you want, to improve readability. A variable like SP (see below) is the same variable as the variable sp. We like to capitalize keywords whose use is primarily at compile-time (statements that delimit program and subprogram boundaries, declaration statements of variables, fixed parameter values), and use lower case for the bulk of run-time code. You can adopt any convention that you find helpful to your own programming style; but we strongly urge you to adopt and follow *some* convention.

### Data Types and Kinds

*Data types* (also called simply *types*) can be either *intrinsic data types* (the familiar INTEGER, REAL, LOGICAL, and so forth) or else *derived data types* that are built up in the manner of what are called “structures” or “records” in other computer languages. (We’ll use derived data types very sparingly in this book.) Intrinsic data types are further specified by their *kind parameter* (or simply *kind*), which is simply an integer. Thus, on many machines, REAL(4) (with kind = 4) is a single-precision real, while REAL(8) (with kind = 8) is a double-precision real. *Literal constants* (or simply *literals*) are specified as to kind by appending an underscore, as 1.5\_4 for single precision, or 1.5\_8 for double precision. [M&R, §2.5–§2.6]

Unfortunately, the specific integer values that define the different kind types are not specified by the language, but can vary from machine to machine. For that reason, one almost never uses literal kind parameters like 4 or 8, but rather defines in some central file, and imports into all one’s programs, symbolic names for the kinds. For this book, that central file is the *module* named *nrtype*, and the chosen symbolic names include SP, DP (for reals); I2B, I4B (for two- and four-byte integers); and LGT for the default logical type. You will therefore see us consistently writing REAL(SP), or 1.5\_sp, and so forth.

Here is an example of declaring some variables, including a one-dimensional array of length 500, and a two-dimensional array with 100 rows and 200 columns:

```
USE nrtype
REAL(SP) :: x,y,z
INTEGER(I4B) :: i,j,k
REAL(SP), DIMENSION(500) :: arr
REAL(SP), DIMENSION(100,200) :: barr
REAL(SP) :: carr(500)
```

The last line shows an alternative form for array syntax. And yes, there *are* default kind parameters for each intrinsic type, but these vary from machine to machine and can get you into trouble when you try to move code. We therefore specify all kind parameters explicitly in almost all situations.

## Array Shapes and Sizes

The *shape* of an *array* refers to both its dimensionality (called its *rank*), and also the lengths along each dimension (called the *extents*). The shape of an array is specified by a rank-one array whose elements are the extents along each dimension, and can be queried with the shape intrinsic (see p. 949). Thus, in the above example, `shape(barr)` returns an array of length 2 containing the values (100, 200).

The *size* of an array is its total number of elements, so the intrinsic `size(barr)` would return 20000 in the above example. More often one wants to know the extents along each dimension, separately: `size(barr,1)` returns the value 100, while `size(barr,2)` returns the value 200. [M&R, §2.10]

Section §21.3, below, discusses additional aspects of arrays in Fortran 90.

## Memory Management

Fortran 90 is greatly superior to Fortran 77 in its memory-management capabilities, seen by the user as the ability to create, expand, or contract workspace for programs. Within *subprograms* (that is, *subroutines* and *functions*), one can have *automatic arrays* (or other *automatic data objects*) that come into existence each time the subprogram is entered, and disappear (returning their memory to the pool) when the subprogram is exited. The size of automatic objects can be specified by arbitrary expressions involving values passed as *actual arguments* in the calling program, and thus received by the subprogram through its corresponding *dummy arguments*. [M&R, §6.4]

Here is an example that creates some automatic workspace named `carr`:

```
SUBROUTINE dosomething(j,k)
  USE nrtype
  REAL(SP), DIMENSION(2*j,k**2) :: carr
```

Finer control on when workspace is created or destroyed can be achieved by declaring *allocatable arrays*, which exist as names only, without associated memory, until they are *allocated* within the program or subprogram. When no longer needed, they can be *deallocated*. The *allocation status* of an allocatable array can be tested by the program via the `allocated` intrinsic function (p. 952). [M&R, §6.5]

Here is an example in outline:

```
REAL(SP), DIMENSION(:,,:), ALLOCATABLE :: darr
...
allocate(darr(10,20))
...
deallocate(darr)
...
allocate(darr(100,200))
...
deallocate(darr)
```

Notice that `darr` is originally declared with only “slots” (colons) for its dimensions, and is then allocated/deallocated twice, with different sizes.

Yet finer control is achieved by the use of *pointers*. Like an allocatable array, a pointer can be allocated, at will, its own associated memory. However, it has the additional flexibility of alternatively being *pointer associated* with a *target* that



already exists under another name. Thus, pointers can be used as redefinable aliases for other variables, arrays, or (see §21.3) *array sections*. [M&R, §6.12]

Here is an example that first associates the pointer `parr` with the array `earr`, then later cancels that association and allocates it its own storage of size 50:

```
REAL(SP), DIMENSION(:), POINTER :: parr
REAL(SP), DIMENSION(100), TARGET :: earr
...
parr => earr
...
nullify(parr)
allocate(parr(50))
...
deallocate(parr)
```

## Procedure Interfaces

When a procedure is *referenced* (e.g., called) from within a program or subprogram (examples of *scoping units*), the scoping unit must be told, or must deduce, the procedure's *interface*, that is, its calling sequence, including the types and kinds of all dummy arguments, returned values, etc. The recommended procedure is to specify this interface via an *explicit interface*, usually an *interface block* (essentially a declaration statement for subprograms) in the calling subprogram or in some *module* that the calling program includes via a USE statement. In this book all interfaces are explicit, and the module named `nr` contains interface blocks for all of the Numerical Recipes routines. [M&R, §5.11]

Here is a typical example of an interface block:

```
INTERFACE
  SUBROUTINE caldat(julian,mm,id,iyyy)
  USE nrtype
  INTEGER(I4B), INTENT(IN) :: julian
  INTEGER(I4B), INTENT(OUT) :: mm,id,iyyy
  END SUBROUTINE caldat
END INTERFACE
```

Once this interface is made known to a program that you are writing (by either explicit inclusion or a USE statement), then the compiler is able to flag for you a variety of otherwise difficult-to-find bugs. Although interface blocks can sometimes seem overly wordy, they give a big payoff in ultimately minimizing programmer time and frustration.

For compatibility with Fortran 77, the language also allows for *implicit interfaces*, where the calling program tries to figure out the interface by the old rules of Fortran 77. These rules are quite limited, and prone to producing devilishly obscure program bugs. We strongly recommend that implicit interfaces never be used.

## Elemental Procedures and Generic Interfaces

Many *intrinsic procedures* (those defined by the language standard and thus usable without any further definition or specification) are also *generic*. This means that a single procedure name, such as `log(x)`, can be used with a variety of types and kind parameters for the argument `x`, and the result returned will have the same type and kind parameter as the argument. In this example, `log(x)` allows any real or complex argument type.

Better yet, most generic functions are also *elemental*. The argument of an elemental function can be an array of arbitrary shape! Then, the returned result is an array of the same shape, with each element containing the result of applying the function to the corresponding element of the argument. (Hence the name *elemental*, meaning “applied element by element.”) [M&R, §8.1] For example:

```
REAL(SP), DIMENSION(100,100) :: a,b
b=sin(a)
```

Fortran 90 has no facility for creating new, user-defined elemental functions. It does have, however, the related facility of *overloading* by the use of *generic interfaces*. This is invoked by the use of an interface block that attaches a single *generic name* to a number of distinct subprograms whose dummy arguments have different types or kinds. Then, when the generic name is referenced (e.g., called), the compiler chooses the specific subprogram that matches the types and kinds of the actual arguments used. [M&R, §5.18] Here is an example of a generic interface block:

```
INTERFACE myfunc
  FUNCTION myfunc_single(x)
    USE nrtype
    REAL(SP) :: x,myfunc_single
  END FUNCTION myfunc_single

  FUNCTION myfunc_double(x)
    USE nrtype
    REAL(DP) :: x,myfunc_double
  END FUNCTION myfunc_double
END INTERFACE
```

A program with knowledge of this interface could then freely use the function reference `myfunc(x)` for `x`'s of both type SP and type DP.

We use overloading quite extensively in this book. A typical use is to provide, under the same name, both scalar and vector versions of a function such as a Bessel function, or to provide both single-precision and double-precision versions of procedures (as in the above example). Then, to the extent that we have provided all the versions that you need, you can pretend that our routine is elemental. In such a situation, if you ever call our function with a type or kind that we have *not* provided, the compiler will instantly flag the problem, because it is unable to resolve the generic interface.

## Modules

*Modules*, already referred to several times above, are Fortran 90's generalization of Fortran 77's common blocks, INCLUDED files of parameter statements, and (to some extent) statement functions. Modules are *program units*, like main programs or subprograms (subroutines and functions), that can be separately compiled. A module is a convenient place to stash global data, *named constants* (what in Fortran 77 are called “symbolic constants” or “PARAMETERS”), interface blocks to subprograms and/or actual subprograms themselves (*module subprograms*). The convenience is that a module's information can be incorporated into another program unit via a simple, one-line USE statement. [M&R, §5.5]

Here is an example of a simple module that defines a few parameters, creates some global storage for an array named `arr` (as might be done with a Fortran 77 common block), and defines the interface to a function `yourfunc`:

```

MODULE mymodule
  USE nrtype
  REAL(SP), PARAMETER :: con1=7.0_sp/3.0_sp, con2=10.0_sp
  INTEGER(I4B), PARAMETER :: ndim=10, mdim=9
  REAL(SP), DIMENSION(ndim,mdim) :: arr
  INTERFACE
    FUNCTION yourfunc(x)
      USE nrtype
      REAL(SP) :: x, yourfunc
    END FUNCTION yourfunc
  END INTERFACE
END MODULE mymodule

```

As mentioned earlier, the module `nr` contains `INTERFACE` declarations for all the Numerical Recipes. When we include a statement of the form

```
USE nr, ONLY: recipe1
```

it means that the program uses the additional routine `recipe1`. The compiler is able to use the explicit interface declaration in the module to check that `recipe1` is invoked with arguments of the correct type, shape, and number. However, a weakness of Fortran 90 is that there is no fail-safe way to be sure that the interface module (here `nr`) stays synchronized with the underlying routine (here `recipe1`). You might think that you could accomplish this by putting `USE nr, ONLY: recipe1` into the `recipe1` program itself. Unfortunately, the compiler interprets this as an erroneous double definition of `recipe1`'s interface, rather than (as would be desirable) as an opportunity for a consistency check. (To achieve this kind of consistency check, you can put the procedures themselves, not just their interfaces, into the module.)

#### CITED REFERENCES AND FURTHER READING:

Metcalf, M., and Reid, J. 1996, *Fortran 90/95 Explained* (Oxford: Oxford University Press).

## 21.3 More on Arrays and Array Sections

Arrays are the central conceptual core of Fortran 90 as a *parallel* programming language, and thus worthy of some further discussion. We have already seen that arrays can “come into existence” in Fortran 90 in several ways, either directly declared, as

```
REAL(SP), DIMENSION(100,200) :: arr
```

or else allocated by an *allocatable* variable or a *pointer* variable,

```

REAL(SP), DIMENSION(:, :), ALLOCATABLE :: arr
REAL(SP), DIMENSION(:, :), POINTER :: barr
...
allocate(arr(100,200), barr(100,200))

```

or else (not previously mentioned) passed into a subprogram through a dummy argument:

```

SUBROUTINE myroutine(carr)
  USE nrtype
  REAL(SP), DIMENSION(:, :), DIMENSION :: carr
  ...
  i=size(carr,1)

```

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```
j=size(carr,2)
```

In the above example we also show how the subprogram can find out the size of the actual array that is passed, using the `size` intrinsic. This routine is an example of the use of an *assumed-shape array*, new to Fortran 90. The actual extents along each dimension are inherited from the calling routine at run time. A subroutine with assumed-shape array arguments *must* have an explicit interface in the calling routine, otherwise the compiler doesn't know about the extra information that must be passed. A typical setup for calling `myroutine` would be:

```
PROGRAM use_myroutine
USE nrtype
REAL(SP), DIMENSION(10,10) :: arr
INTERFACE
  SUBROUTINE myroutine(carr)
  USE nrtype
  REAL(SP), DIMENSION(:, :) :: carr
  END SUBROUTINE myroutine
END INTERFACE
...
call myroutine(a)
```

Of course, for the recipes we have provided all the interface blocks in the file `nr.f90`, and you need only a `USE nr` statement in your calling program.

## Conformable Arrays

Two arrays are said to be *conformable* if their shapes are the same. Fortran 90 allows practically all operations among conformable arrays and elemental functions that are allowed for scalar variables. Thus, if `arr`, `barr`, and `carr` are mutually conformable, we can write,

```
arr=barr+cos(carr)+2.0_sp
```

and have the indicated operations performed, element by corresponding element, on the entire arrays. The above line also illustrates that a scalar (here the constant `2.0_sp`, but a scalar variable would also be fine) is deemed conformable with *any* array — it gets “expanded” to the shape of the rest of the expression that it is in. [M&R, §3.11]

In Fortran 90, as in Fortran 77, the default lower bound for an array subscript is 1; however, it can be made some other value at the time that the array is declared:

```
REAL(SP), DIMENSION(100,200) :: farr
REAL(SP), DIMENSION(0:99,0:199) :: garr
...
farr = 3.0_sp*garr + 1.0_sp
```

Notice that `farr` and `garr` are conformable, since they have the same shape, in this case (100,200). Also note that when they are used in an array expression, the operations are taken between the corresponding elements *of their shapes*, not necessarily the corresponding elements *of their indices*. [M&R, §3.10] In other words, one of the components evaluated is,

```
farr(1,1) = 3.0_sp*garr(0,0) + 1.0_sp
```

This illustrates a fundamental aspect of array (or data) parallelism in Fortran 90. Array constructions should *not* be thought of as merely abbreviations for do-loops

over indices, but rather as genuinely parallel operations on same-shaped objects, abstracted of their indices. This is why the standard makes no statement about the order in which the individual operations in an array expression are executed; they might in fact be carried out simultaneously, on parallel hardware.

By default, array expressions and assignments are performed for all elements of the same-shaped arrays referenced. This can be modified, however, by use of a *where* construction like this:

```
where (harr > 0.0_sp)
  farr = 3.0_sp*garr + 1.0_sp
end where
```

Here *harr* must also be conformable to *farr* and *garr*. Analogously with the Fortran *if*-statement, there is also a one-line form of the *where*-statement. There is also a *where ... elsewhere ... end where* form of the statement, analogous to *if ... else if ... end if*. A significant language limitation in Fortran 90 is that nested *where*-statements are not allowed. [M&R, §6.8]

## Array Sections

Much of the versatility of Fortran 90's array facilities stems from the availability of *array sections*. An array section acts like an array, but its memory location, and thus the values of its elements, is actually a subset of the memory location of an already-declared array. Array sections are thus "windows into arrays," and they can appear on either the left side, or the right side, or both, of a replacement statement. Some examples will clarify these ideas.

Let us presume the declarations

```
REAL(SP), DIMENSION(100) :: arr
INTEGER(I4B), DIMENSION(6) :: iarr=(/11,22,33,44,55,66/)
```

Note that *iarr* is not only declared, it is also initialized by an *initialization expression* (a replacement for Fortran 77's *DATA* statement). [M&R, §7.5] Here are some array sections constructed from these arrays:

<i>Array Section</i>	<i>What It Means</i>
<code>arr(:)</code>	same as <code>arr</code>
<code>arr(1:100)</code>	same as <code>arr</code>
<code>arr(1:10)</code>	one-dimensional array containing first 10 elements of <code>arr</code>
<code>arr(51:100)</code>	one-dimensional array containing second half of <code>arr</code>
<code>arr(51:)</code>	same as <code>arr(51:100)</code>
<code>arr(10:1:-1)</code>	one-dimensional array containing first 10 elements of <code>arr</code> , but in <i>reverse order</i>
<code>arr( (/10,99,1,6/ ) )</code>	one-dimensional array containing elements 10, 99, 1, and 6 of <code>arr</code> , in that order
<code>arr(iarr)</code>	one-dimensional array containing elements 11, 22, 33, 44, 55, 66 of <code>arr</code> , in that order

Now let's try some array sections of the two-dimensional array

```
REAL(SP), DIMENSION(100,100) :: barr
```

<i>Array Section</i>	<i>What It Means</i>
<code>barr(:, :)</code>	same as <code>barr</code>
<code>barr(1:100, 1:100)</code>	same as <code>barr</code>
<code>barr(7, :)</code>	one-dimensional array containing the 7th row of <code>barr</code>
<code>barr(7, 1:100)</code>	same as <code>barr(7, :)</code>
<code>barr(:, 7)</code>	one-dimensional array containing the 7th column of <code>barr</code>
<code>barr(21:30, 71:90)</code>	two-dimensional array containing the sub-block of <code>barr</code> with the indicated ranges of indices; the shape of this array section is (10, 20)
<code>barr(100:1:-1, 100:1:-1)</code>	two-dimensional array formed by flipping <code>barr</code> upside down and backwards
<code>barr(2:100:2, 2:100:2)</code>	two-dimensional array of shape (50, 50) containing the elements of <code>barr</code> whose row and column indices are both even

Some terminology: A construction like `2:100:2`, above, is called a *subscript triplet*. Its integer pieces (which may be integer constants, or more general integer expressions) are called *lower*, *upper*, and *stride*. Any of the three may be omitted. An omitted stride defaults to the value 1. Notice that, if (*upper* – *lower*) has a different sign from *stride*, then a subscript triplet defines an empty or *zero-length* array, e.g., `1:5:-1` or `10:1:1` (or its equivalent form, simply `10:1`). Zero-length arrays are not treated as errors in Fortran 90, but rather as “no-ops.” That is, no operation is performed in an expression or replacement statement among zero-length arrays. (This is essentially the same convention as in Fortran 77 for do-loop indices, which array expressions often replace.) [M&R, §6.10]

It is important to understand that array sections, when used in array expressions, match elements with other parts of the expression *according to shape*, not according to indices. (This is exactly the same principle that we applied, above, to arrays with subscript lower bounds different from the default value of 1.) One frequently exploits this feature in using array sections to carry out operations on arrays that access neighboring elements. For example,

```
carr(1:n-1, 1:n-1) = barr(1:n-1, 1:n-1) + barr(2:n, 2:n)
```

constructs in the  $(n-1) \times (n-1)$  matrix `carr` the sum of each of the corresponding elements in  $n \times n$  `barr` added to its diagonally lower-right neighbor.

Pointers are often used as aliases for array sections, especially if the same array sections are used repeatedly. [M&R, §6.12] For example, with the setup

```
REAL(SP), DIMENSION(:, :), POINTER :: leftb, rightb
```

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```
leftb=>barr(1:n-1,1:n-1)
rightb=>barr(2:n,2:n)
```

the statement above can be coded as

```
carr(1:n-1,1:n-1)=leftb+rightb
```

We should also mention that array sections, while powerful and concise, are sometimes not quite powerful enough. While any row or column of a matrix is easily accessible as an array section, there is no good way, in Fortran 90, to access (e.g.) the diagonal of a matrix, even though its elements are related by a linear progression in the Fortran storage order (by columns). These so-called *skew-sections* were much discussed by the Fortran 90 standards committee, but they were not implemented. We will see examples later in this volume of work-around programming tricks (none totally satisfactory) for this omission. (Fortran 95 corrects the omission; see §21.6.)

#### CITED REFERENCES AND FURTHER READING:

Metcalfe, M., and Reid, J. 1996, *Fortran 90/95 Explained* (Oxford: Oxford University Press).

## 21.4 Fortran 90 Intrinsic Procedures

Much of Fortran 90's power, both for parallel programming and for its concise expression of algorithmic ideas, comes from its rich set of intrinsic procedures. These have the effect of making the language “large,” hence harder to learn. However, effort spent on learning to use the intrinsics — particularly some of their more obscure, and more powerful, optional arguments — is often handsomely repaid.

This section summarizes the intrinsics that we find useful in numerical work. We omit, here, discussion of intrinsics whose exclusive use is for character and string manipulation. We intend only a summary, not a complete specification, which can be found in M&R's Chapter 8, or other reference books.

If you find the sheer number of new intrinsic procedures daunting, you might want to start with our list of the “top 10” (with the number of different Numerical Recipes routines that use each shown in parentheses): `size` (254), `sum` (44), `dot_product` (31), `merge` (27), `all` (25), `maxval` (23), `matmul` (19), `pack` (18), `any` (17), and `spread` (15). (Later, in Chapter 23, you can compare these numbers with our frequency of using the short utility functions that we define in a module named `nrtutil` — several of which we think ought to have been included as Fortran 90 intrinsic procedures.)

The type, kind, and shape of the value returned by intrinsic functions will usually be clear from the short description that we give. As an additional hint (though not necessarily a precise description), we adopt the following codes:

<i>Hint</i>	<i>What It Means</i>
[Int]	an INTEGER kind type
[Real]	a REAL kind type
[Cmplx]	a COMPLEX kind type
[Num]	a numerical type and kind
[Lgcl]	a LOGICAL kind type
[Iarr]	a one-dimensional INTEGER array
[argTS]	same type and shape as the first argument
[argT]	same type as the first argument, but not necessarily the same shape

### Numerical Elemental Functions

Little needs to be said about the numerical functions with identical counterparts in Fortran 77: `abs`, `acos`, `aimag`, `asin`, `atan`, `atan2`, `conjg`, `cos`, `cosh`, `dim`, `exp`, `log`, `log10`, `max`, `min`, `mod`, `sign`, `sin`, `sinh`, `sqrt`, `tan`, and `tanh`. In Fortran 90 these are all *elemental* functions, so that any plausible type, kind, and shape of argument may be used. Except for `aimag`, which returns a real type from a complex argument, these all return [argTS] (see table above).

Although Fortran 90 recognizes, for compatibility, Fortran 77's so-called *specific names* for these functions (e.g., `iabs`, `dabs`, and `cabs` for the generic `abs`), these are entirely superfluous and should be avoided.

Fortran 90 corrects some ambiguity (or at least inconvenience) in Fortran 77's `mod(a,p)` function, by introducing a new function `modulo(a,p)`. The functions are essentially identical for positive arguments, but for negative `a` and positive `p`, `modulo` gives results more compatible with one's mathematical expectation that the answer should always be in the positive range 0 to `p`. E.g., `modulo(11,5)=1`, and `modulo(-11,5)=4`. [M&R, §8.3.2]

### Conversion and Truncation Elemental Functions

Fortran 90's conversion (or, in the language of C, casting) and truncation functions are generally modeled on their Fortran 77 antecedents, but with the addition of an optional second integer argument, `kind`, that determines the kind of the result. Note that, if `kind` is omitted, you get a default kind — not necessarily related to the kind of your argument. The kind of the argument is of course known to the compiler by its previous declaration. Functions in this category (see below for explanation of arguments in slanted type) are:

[Real] `aint(a,kind)`  
Truncate to integer value, return as a real kind.

[Real] `anint(a,kind)`  
Nearest whole number, return as a real kind.

[Cmplx] `cmplx(x,y,kind)`



Convert to complex kind. If *y* is omitted, it is taken to be 0.

- [Int] `int(a,kind)`  
Convert to integer kind, truncating towards zero.
- [Int] `nint(a,kind)`  
Convert to integer kind, choosing the nearest whole number.
- [Real] `real(a,kind)`  
Convert to real kind.
- [Lgcl] `logical(a,kind)`  
Convert one logical kind to another.

We must digress here to explain the use of *optional arguments* and *keywords* as Fortran 90 language features. [M&R, §5.13] When a routine (either intrinsic or user-defined) has arguments that are declared to be optional, then the dummy names given to them also become keywords that distinguish — independent of their position in a calling list — which argument is intended to be passed. (There are some additional rules about this that we will not try to summarize here.) In this section's tabular listings, we indicate optional arguments in intrinsic routines by printing them in smaller slanted type. For example, the intrinsic function

```
eoshift(array,shift,boundary,dim)
```

has two required arguments, `array` and `shift`, and two optional arguments, `boundary` and `dim`. Suppose we want to call this routine with the actual arguments `myarray`, `myshift`, and `mydim`, but omitting the argument in the boundary slot. We do this by the expression

```
eoshift(myarray,myshift,dim=mydim)
```

Conversely, if we wanted a boundary argument, but no `dim`, we might write

```
eoshift(myarray,myshift,boundary=myboundary)
```

It is always a good idea to use this kind of keyword construction when invoking optional arguments, even though the rules allow keywords to be omitted in some unambiguous cases. Now back to the lists of intrinsic routines.

A peculiarity of the `real` function derives from its use both as a type conversion and for extracting the real part of complex numbers (related, but not identical, usages): If the argument of `real` is complex, and `kind` is omitted, then the result *isn't* a default real kind, but rather *is* (as one generally would want) the `real` kind type corresponding to the kind type of the complex argument, that is, single-precision real for single-precision complex, double-precision for double-precision, and so on. [M&R, §8.3.1] We recommend *never* using `kind` when you intend to extract the real part of a complex, and *always* using `kind` when you intend conversion of a real or integer value to a particular kind of REAL. (Use of the deprecated function `dble` is not recommended.)

The last two conversion functions are the exception in that they *don't* allow a `kind` argument, but rather return default integer kinds. (The X3J3 standards committee has fixed this in Fortran 95.)

- [Int] `ceiling(a)`  
Convert to integer, truncating towards more positive.

[Int] `floor(a)`  
Convert to integer, truncating towards more negative.

### Reduction and Inquiry Functions on Arrays

These are mostly the so-called *transformational functions* that accept array arguments and return either scalar values or else arrays of lesser rank. [M&R, §8.11] With no optional arguments, such functions act on all the elements of their single array argument, regardless of its shape, and produce a scalar result. When the optional argument `dim` is specified, they instead act on all one-dimensional sections that span the dimension `dim`, producing an answer one rank lower than the first argument (that is, omitting the `dim` dimension from its shape). When the optional argument `mask` is specified, only the elements with a corresponding true value in `mask` are scanned.

[Lgcl] `all(mask, dim)`  
Returns true if all elements of `mask` are true, false otherwise.

[Lgcl] `any(mask, dim)`  
Returns true if any of the elements of `mask` are true, false otherwise.

[Int] `count(mask, dim)`  
Counts the true elements in `mask`.

[Num] `maxval(array, dim, mask)`  
Maximum value of the array elements.

[Num] `minval(array, dim, mask)`  
Minimum value of the array elements.

[Num] `product(array, dim, mask)`  
Product of the array elements.

[Int] `size(array, dim)`  
Size (total number of elements) of `array`, or its extent along dimension `dim`.

[Num] `sum(array, dim, mask)`  
Sum of the array elements.

The use of the `dim` argument can be confusing, so an example may be helpful. Suppose we have

$$\text{myarray} = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \end{bmatrix}$$

where, as always, the `i` index in `array(i, j)` numbers the rows while the `j` index numbers the columns. Then

$$\text{sum(myarray, dim=1)} = (15, 18, 21, 24)$$

that is, the `i` indices are “summed away” leaving only a `j` index on the result; while

$$\text{sum(myarray, dim=2)} = (10, 26, 42)$$

that is, the *j* indices are “summed away” leaving only an *i* index on the result. Of course we also have

$$\text{sum}(\text{myarray}) = 78$$

Two related functions return the location of particular elements in an array. The returned value is a one-dimensional integer array containing the respective subscript of the element along each dimension. Note that when the argument object is a *one*-dimensional array, the returned object is an integer *array of length 1*, not simply an integer. (Fortran 90 distinguishes between these.)

[Iarr] `maxloc(array, mask)`  
Location of the maximum value in an array.

[Iarr] `minloc(array, mask)`  
Location of the minimum value in an array.

Similarly returning a one-dimensional integer array are

[Iarr] `shape(array)`  
Returns the shape of array as a one-dimensional integer array.

[Iarr] `lbound(array, dim)`  
When *dim* is absent, returns an array of lower bounds for each dimension of subscripts of *array*. When *dim* is present, returns the value only for dimension *dim*, as a scalar.

[Iarr] `ubound(array, dim)`  
When *dim* is absent, returns an array of upper bounds for each dimension of subscripts of *array*. When *dim* is present, returns the value only for dimension *dim*, as a scalar.

## Array Unary and Binary Functions

The most powerful array operations are simply built into the language as operators. All the usual arithmetic and logical operators (+, -, \*, /, \*\*, .not., .and., .or., .eqv., .neqv.) can be applied to arrays of arbitrary shape or (for the binary operators) between two arrays of the same shape, or between arrays and scalars. The types of the arrays must, of course, be appropriate to the operator used. The result in all cases is to perform the operation element by element on the arrays.

We also have the intrinsic functions,

[Num] `dot_product(veca, vecb)`  
Scalar dot product of two one-dimensional vectors *veca* and *vecb*.

[Num] `matmul(mata, matb)`  
Result of matrix-multiplying the two two-dimensional matrices *mata* and *matb*. The shapes have to be such as to allow matrix multiplication. Vectors (one-dimensional arrays) are additionally allowed as either the first or second argument, but not both; they are treated as row vectors in the first argument, and as column vectors in the second.

You might wonder how to form the *outer* product of two vectors, since `matmul` specifically excludes this case. (See §22.1 and §23.5 for answer.)

## Array Manipulation Functions

These include many powerful features that a good Fortran 90 programmer should master.

[argTS] `cshift(array, shift, dim)`

If `dim` is omitted, it is taken to be 1. Returns the result of circularly left-shifting every one-dimensional section of `array` (in dimension `dim`) by `shift` (which may be negative). That is, for positive `shift`, values are moved to smaller subscript positions. Consult a Fortran 90 reference (e.g., [M&R, §8.13.5]) for the case where `shift` is an array.

[argTS] `merge(tsource, fsource, mask)`

Returns same shape object as `tsource` and `fsource` containing the former's components where `mask` is true, the latter's where it is false.

[argTS] `eoshift(array, shift, boundary, dim)`

If `dim` is omitted, it is taken to be 1. Returns the result of end-off left-shifting every one-dimensional section of `array` (in dimension `dim`) by `shift` (which may be negative). That is, for positive `shift`, values are moved to smaller subscript positions. If `boundary` is present as a scalar, it supplies elements to fill in the blanks; if it is not present, zero values are used. Consult a Fortran 90 reference (e.g., [M&R, §8.13.5]) for the case where `boundary` and/or `shift` is an array.

[argT] `pack(array, mask, vector)`

Returns a one-dimensional array containing the elements of `array` that pass the mask. Components of optional `vector` are used to pad out the result to the size of `vector` with specified values.

[argT] `reshape(source, shape, pad, order)`

Takes the elements of `source`, in normal Fortran order, and returns them (as many as will fit) as an array whose shape is specified by the one-dimensional integer array `shape`. If there is space remaining, then `pad` must be specified, and is used (as many sequential copies as necessary) to fill out the rest. For description of `order`, consult a Fortran 90 reference, e.g., [M&R, 8.13.3].

[argT] `spread(source, dim, ncopies)`

Returns an array whose rank is one greater than `source`, and whose `dim` dimension is of length `ncopies`. Each of the result's `ncopies` array sections having a fixed subscript in dimension `dim` is a copy of `source`. (That is, it spreads `source` into the `dim`th dimension.)

[argT] `transpose(matrix)`

Returns the transpose of `matrix`, which must be two-dimensional.

[argT] `unpack(vector, mask, field)`

Returns an array whose type is that of `vector`, but whose shape is that of `mask`. The components of `vector` are put, in order, into the positions where `mask` is true. Where `mask` is false, components of `field` (which may be a scalar or an array with the same shape as `mask`) are used instead.

## Bitwise Functions

Most of the bitwise functions should be familiar to Fortran 77 programmers as longstanding standard extensions of that language. Note that the bit *positions* number from zero to one less than the value returned by the `bit_size` function. Also note that bit positions number *from right to left*. Except for `bit_size`, the following functions are all elemental.

- [Int] `bit_size(i)`  
Number of bits in the integer type of *i*.
- [Lgcl] `btest(i,pos)`  
True if bit position *pos* is 1, false otherwise.
- [Int] `iand(i,j)`  
Bitwise logical and.
- [Int] `ibclr(i,pos)`  
Returns *i* but with bit position *pos* set to zero.
- [Int] `ibits(i,pos,len)`  
Extracts *len* consecutive bits starting at position *pos* and puts them in the low bit positions of the returned value. (The high positions are zero.)
- [Int] `ibset(i,pos)`  
Returns *i* but with bit position *pos* set to 1.
- [Int] `ieor(i,j)`  
Bitwise exclusive or.
- [Int] `ior(i,j)`  
Bitwise logical or.
- [Int] `ishft(i,shift)`  
Bitwise left shift by *shift* (which may be negative) with zeros shifted in from the other end.
- [Int] `ishftc(i,shift)`  
Bitwise circularly left shift by *shift* (which may be negative).
- [Int] `not(i)`  
Bitwise logical complement.

## Some Functions Relating to Numerical Representations

- [Real] `epsilon(x)`  
Smallest nonnegligible quantity relative to 1 in the numerical model of *x*.
- [Num] `huge(x)`  
Largest representable number in the numerical model of *x*.
- [Int] `kind(x)`

Returns the kind value for the numerical model of  $x$ .

- [Real] `nearest(x, s)`  
Real number nearest to  $x$  in the direction specified by the sign of  $s$ .
- [Real] `tiny(x)`  
Smallest positive number in the numerical model of  $x$ .

### Other Intrinsic Procedures

- [Lgcl] `present(a)`  
True, within a subprogram, if an optional argument is actually present, otherwise false.
- [Lgcl] `associated(pointer, target)`  
True if `pointer` is associated with `target` or (if `target` is absent) with any target, otherwise false.
- [Lgcl] `allocated(array)`  
True if the allocatable array is allocated, otherwise false.

There are some pitfalls in using `associated` and `allocated`, having to do with arrays and pointers that can find themselves in *undefined* status [see §21.5, and also M&R, §3.3 and §6.5.1]. For example, pointers are always “born” in an undefined status, where the `associated` function returns unpredictable values.

For completeness, here is a list of Fortran 90’s intrinsic procedures not already mentioned:

**Other Numerical Representation Functions:** `digits`, `exponent`, `fraction`, `rrspacing`, `scale`, `set_exponent`, `spacing`, `maxexponent`, `minexponent`, `precision`, `radix`, `range`, `selected_int_kind`, `selected_real_kind`.

**Lexical comparison:** `lge`, `lgt`, `lle`, `llt`.

**Character functions:** `ichar`, `char`, `achar`, `iachar`, `index`, `adjustl`, `adjustr`, `len_trim`, `repeat`, `scan`, `trim`, `verify`.

**Other:** `mvbits`, `transfer`, `date_and_time`, `system_clock`, `random_seed`, `random_number`. (We will discuss random numbers in some detail in Chapter B7.)

#### CITED REFERENCES AND FURTHER READING:

Metcalfe, M., and Reid, J. 1996, *Fortran 90/95 Explained* (Oxford: Oxford University Press).

## 21.5 Advanced Fortran 90 Topics

### Pointers, Arrays, and Memory Management

One of the biggest improvements in Fortran 90 over Fortran 77 is in the handling of arrays, which are the cornerstone of many numerical algorithms. In this subsection we will take a closer look at how to use some of these new array features effectively. We will look at how to code certain commonly occurring elements of program design, and we will pay particular attention to avoiding “memory leaks,” where — usually inadvertently — we keep cumulatively allocating new storage for an array, every time some piece of code is invoked.

Let’s first review some of the rules for using allocatable arrays and pointers to arrays. Recall that a pointer is born with an undefined status. Its status changes to “associated” when you make it refer to a target, and to “disassociated” when you nullify the pointer. [M&R, §3.3] You can also use nullify on a newly born pointer to change its status from undefined to disassociated; this allows you to test the status with the `associated` inquiry function. [M&R, §6.5.4] (While many compilers will not produce a run-time error if you test an undefined pointer with `associated`, you can’t rely on this *laissez-faire* in your programming.)

The initial status of an allocatable array is “not currently allocated.” Its status changes to “allocated” when you give it storage with `allocate`, and back to “not currently allocated” when you use `deallocate`. [M&R, §6.5.1] You can test the status with the `allocated` inquiry function. Note that while you can also give a pointer fresh storage with `allocate`, you can’t test this with `allocated` — only `associated` is allowed with pointers. Note also that nullifying an allocated pointer leaves its associated storage in limbo. You must instead `deallocate`, which gives the pointer a testable “disassociated” status.

While allocating an array that is already allocated gives an error, you are allowed to allocate a pointer that already has a target. This breaks the old association, and could leave the old target inaccessible if there is no other pointer associated with it. [M&R, §6.5.2] Deallocating an array or pointer that has not been allocated is always an error.

Allocated arrays that are local to a subprogram acquire the “undefined” status on exit from the subprogram unless they have the `SAVE` attribute. (Again, not all compilers enforce this, but be warned!) Such undefined arrays cannot be referenced in any way, so you should explicitly deallocate all allocated arrays that are not saved before returning from a subprogram. [M&R, §6.5.1] The same rule applies to arrays declared in modules that are currently accessed only by the subprogram. While you can reference undefined pointers (e.g., by first nullifying them), it is good programming practice to deallocate explicitly any allocated pointers declared locally before leaving a subprogram or module.

Now let’s turn to using these features in programs. The simplest example is when we want to implement global storage of an array that needs to be accessed by two or more different routines, and we want the size of the array to be determined at run time. As mentioned earlier, we implement global storage with a `MODULE` rather than a `COMMON` block. (We ignore here the additional possibility of passing

global variables by having one routine CONTAINED within the other.) There are two good ways of handling the dynamical allocation in a MODULE. Method 1 uses an allocatable array:

```

MODULE a
  REAL(SP), DIMENSION(:), ALLOCATABLE :: x
END MODULE a

SUBROUTINE b(y)
  USE a
  REAL(SP), DIMENSION(:) :: y
  ...
  allocate(x(size(y)))
  ... [other routines using x called here] ...
END SUBROUTINE b

```

Here the global variable `x` gets assigned storage in subroutine `b` (in this case, the same as the length of `y`). The length of `y` is of course defined in the procedure that calls `b`. The array `x` is made available to any other subroutine called by `b` by including a `USE a` statement. The status of `x` can be checked with an `allocated` inquiry function on entry into either `b` or the other subroutine if necessary. As discussed above, you must be sure to deallocate `x` before returning from subroutine `b`. If you want `x` to retain its values between calls to `b`, you add the `SAVE` attribute to its declaration in `a`, and *don't* deallocate it on returning from `b`. (Alternatively, you could put a `USE a` in your main program, but we consider that bug-prone, since forgetting to do so can create all manner of difficult-to-diagnose havoc.) To avoid allocating `x` more than once, you test it on entry into `b`:

```

if (.not. allocated(x)) allocate(x(size(y)))

```

The second way to implement this type of global storage (Method 2) uses a pointer:

```

MODULE a
  REAL(SP), DIMENSION(:), POINTER :: x
END MODULE a

SUBROUTINE b(y)
  USE a
  REAL(SP), DIMENSION(:) :: y
  REAL(SP), DIMENSION(size(y)), TARGET :: xx
  ...
  x=>xx
  ... [other routines using x called here] ...
END SUBROUTINE b

```

Here the *automatic array* `xx` gets its temporary storage automatically on entry into `b`, and automatically gets deallocated on exit from `b`. [M&R, §6.4] The global pointer `x` can access this storage in any routine with a `USE a` that is called by `b`. You can check that things are in order in such a called routine by testing `x` with `associated`. If you are going to use `x` for some other purpose as well, you should nullify it on leaving `b` so that it doesn't have undefined status. Note that this implementation does not allow values to be saved between calls: You can't `SAVE` automatic arrays — that's not what they're for. You would have to `SAVE x` in the module, and `allocate` it in the subroutine instead of pointing it to a suitable automatic array. But this is essentially Method 1 with the added complication of using a pointer, so Method 1 is simpler when you want to save values. When you don't



need to save values between calls, we lean towards Method 2 over Method 1 because we like the automatic allocation and deallocation, but either method works fine.

An example of Method 1 (allocatable array) is in routine `rkdumb` on page 1297. An example of Method 1 with `SAVE` is in routine `pwtset` on p. 1265. Method 2 (pointer) shows up in routines `newt` (p. 1196), `broydn` (p. 1199), and `fitexy` (p. 1286). A variation is shown in routines `linmin` (p. 1211) and `dlinmin` (p. 1212): When the array that needs to be shared is an argument of one of the routines, Method 2 is better.

An extension of these ideas occurs if we allocate some storage for an array initially, but then might need to increase the size of the array later without losing the already-stored values. The function `reallocate` in our utility module `nrutil` will handle this for you, but it expects a pointer argument as in Method 2. Since no automatic arrays are used, you are free to `SAVE` the pointer if necessary. Here is a simple example of how to use `reallocate` to create a workspace array that is local to a subroutine:

```

SUBROUTINE a
USE nrutil, ONLY : reallocate
REAL(SP), DIMENSION(:), POINTER, SAVE :: wksp
LOGICAL(LGT), SAVE :: init=.true.
if (init) then
  init=.false.
  nullify(wksp)
  wksp=>reallocate(wksp,100)
end if
...
if (nterm > size(wksp)) wksp=>reallocate(wksp,2*size(wksp))
...
END SUBROUTINE a

```

Here the workspace is initially allocated a size of 100. If the number of elements used (`nterm`) ever exceeds the size of the workspace, the workspace is doubled. (In a realistic example, one would of course check that the doubled size is in fact big enough.) Fortran 90 experts can note that the `SAVE` on `init` is not strictly necessary: Any local variable that is initialized is automatically saved. [M&R, §7.5]

You can find similar examples of `reallocate` (with some further discussion) in `eulsum` (p. 1070), `hufenc` (p. 1348), and `arcode` (p. 1350). Examples of `reallocate` used with global variables in modules are in `odeint` (p. 1300) and `ran_state` (p. 1144).

Another situation where we have to use pointers and not allocatable arrays is when the storage is required for components of a derived type, which are not allowed to have the allocatable attribute. Examples are in `hufmak` (p. 1346) and `arcmak` (p. 1349).

Turning away from issues relating to global variables, we now consider several other important programming situations that are nicely handled with pointers. The first case is when we want a subroutine to return an array whose size is not known in advance. Since dummy arguments are not allocatable, we must use a pointer. Here is the basic construction:

```

SUBROUTINE a(x,nx)
REAL(SP), DIMENSION(:), POINTER :: x
INTEGER(I4B), INTENT(OUT) :: nx
LOGICAL(LGT), SAVE :: init=.true.
if (init) then

```

```

    init=.false.
    nullify(x)
  else
    if (associated(x)) deallocate(x)
  end if
  ...
  nx=...
  allocate(x(nx))
  x(1:nx)=...
END SUBROUTINE a

```

Since the length of `x` can be found from `size(x)`, it is not absolutely necessary to pass `nx` as an argument. Note the use of the initial logic to avoid memory leaks. If a higher-level subroutine wants to recover the memory associated with `x` from the last call to SUBROUTINE `a`, it can do so by first deallocating it, and then nullifying the pointer. Examples of this structure are in `zbrak` (p. 1184), `period` (p. 1258), and `fasper` (p. 1259). A related situation is where we want a function to return an array whose size is not predetermined, such as in `voltra` on (p. 1326). The discussion of `voltra` also explains the potential pitfalls of functions returning pointers to dynamically allocated arrays.

A final useful pointer construction enables us to set up a data structure that is essentially an array of arrays, independently allocatable on each part. We are not allowed to declare an array of pointers in Fortran 90, but we can do this indirectly by defining a derived type that consists of a pointer to the appropriate kind of array. [M&R, §6.11] We can then define a variable that is an allocatable array of the new type. For example,

```

TYPE ptr_to_arr
  REAL(SP), DIMENSION(:), POINTER :: arr
END TYPE
TYPE(ptr_to_arr), DIMENSION(:), ALLOCATABLE :: x
...
allocate(x(n))
...
do i=1,n
  allocate(x(i)%arr(m))
end do

```

sets up a set `x` of `n` arrays of length `m`. See also the example in `mglin` (p. 1334).

There is a potential problem with dynamical memory allocation that we should mention. The Fortran 90 standard does not require that the compiler perform “garbage collection,” that is, it is not required to recover deallocated memory into nice contiguous pieces for reuse. If you enter and exit a subroutine many times, and each time a large chunk of memory gets allocated and deallocated, you could run out of memory with a “dumb” compiler. You can often alleviate the problem by deallocating variables in the reverse order that you allocated them. This tends to keep a large contiguous piece of memory free at the top of the heap.

## Scope, Visibility, and Data Hiding

An important principle of good programming practice is *modularization*, the idea that different parts of a program should be insulated from each other as much as possible. An important subcase of modularization is *data hiding*, the principle that actions carried out on variables in one part of the code should not be able to

affect the values of variables in other parts of the code. When it is necessary for one “island” of code to communicate with another, the communication should be through a well-defined interface that makes it obvious exactly what communication is taking place, and prevents any other interchange from occurring. Otherwise, different sections of code should not have access to variables that they don’t need.

The concept of data hiding extends not only to variables, but also to the names of procedures that manipulate the variables: A program for screen graphics might give the user access to a routine for drawing a circle, but it might “hide” the names (and methods of operation) of the primitive routines used for calculating the coordinates of the points on the circumference. Besides producing code that is easier to understand and to modify, data hiding prevents unintended side effects from producing hard-to-find errors.

In Fortran, the principal language construction that effects data hiding is the use of subroutines. If all subprograms were restricted to have no more than ten executable statements per routine, and to communicate between routines only by an explicit list of arguments, the number of programming errors might be greatly reduced! Unfortunately few tasks can be easily coded in this style. For this and other reasons, we think that too much procedurization is a bad thing; one wants to find the *right* amount. Fortunately Fortran 90 provides several additional tools to help with data hiding.

Global variables and routine names are important, but potentially dangerous, things. In Fortran 90, global variables are typically encapsulated in modules. Access is granted only to routines with an appropriate USE statement, and can be restricted to specific identifiers by the ONLY option. [M&R, §7.10] In addition, variable and routine names within the module can be designated as PUBLIC or PRIVATE (see, e.g., quad3d on p. 1065). [M&R, §7.6]

The other way global variables get communicated is by having one routine CONTAINED within another. [M&R, §5.6] This usage is potentially lethal, however, because *all* the outer routine’s variables are visible to the inner routine. You can try to control the problem somewhat by passing some variables back and forth as arguments of the inner routine, but that still doesn’t prevent inadvertent side effects. (The most common, and most stupid, is inadvertent reuse of variables named *i* or *j* in the CONTAINED routine.) Also, a long list of arguments reduces the convenience of using an internal routine in the first place. We advise that internal subprograms be used with caution, and only to carry out simple tasks.

There are some good ways to use CONTAINS, however. Several of our recipes have the following structure: A principal routine is invoked with several arguments. It calls a subsidiary routine, which needs to know some of the principal routine’s arguments, some global variables, and some values communicated directly as arguments to the subsidiary routine. In Fortran 77, we have usually coded this by passing the global variables in a COMMON block and all other variables as arguments to the subsidiary routine. If necessary, we copied the arguments of the primary routine before passing them to the subsidiary routine. In Fortran 90, there is a more elegant way of accomplishing this, as follows:

```
SUBROUTINE recipe(arg)
  REAL(SP) :: arg
  REAL(SP) :: global_var
  call recipe_private
CONTAINS
```

```

SUBROUTINE recipe_private
...
call subsidiary(local_arg)
...
END SUBROUTINE recipe_private

SUBROUTINE subsidiary(local_arg)
...
END SUBROUTINE subsidiary
END SUBROUTINE recipe

```

Notice that the principal routine (`recipe`) has practically nothing in it — only declarations of variables intended to be visible to the subsidiary routine (`subsidiary`). All the real work of `recipe` is done in `recipe_private`. This latter routine has visibility on all of `recipe`'s variables, while any additional variables that `recipe_private` defines are *not* visible to `subsidiary` — which is the whole purpose of this way of organizing things. Obviously `arg` and `global_var` can be much more general data types than the example shown here, including function names. For examples of this construction, see `amoeba` (p. 1208), `amebsa` (p. 1222), `mrqmin` (p. 1292), and `medfit` (p. 1294).

## Recursion

A subprogram is recursive if it calls itself. While forbidden in Fortran 77, recursion is allowed in Fortran 90. [M&R, §5.16–§5.17] You must supply the keyword `RECURSIVE` in front of the `FUNCTION` or `SUBROUTINE` keyword. In addition, if a `FUNCTION` calls itself directly, as opposed to calling another subprogram that in turn calls it, you must supply a variable to hold the result with the `RESULT` keyword. Typical syntax for this case is:

```

RECURSIVE FUNCTION f(x) RESULT(g)
REAL(SP) :: x,g
if ...
    g=...
else
    g=f(...)
end if
END FUNCTION f

```

When a function calls itself directly, as in this example, there always has to be a “base case” that does not call the function; otherwise the recursion never terminates. We have indicated this schematically with the `if...else...end if` structure.

On serial machines we tend to avoid recursive implementations because of the additional overhead they incur at execution time. Occasionally there are algorithms for which the recursion overhead is relatively small, and the recursive implementation is simpler than an iterative version. Examples in this book are `quad_3d` (p. 1065), `miser` (p. 1164), and `mglin` (p. 1334). Recursion is much more important when parallelization is the goal. We will encounter in Chapter 22 numerous examples of algorithms that can be parallelized with recursion.

## SAVE Usage Style

A quirk of Fortran 90 is that any variable with initial values acquires the `SAVE` attribute automatically. [M&R, §7.5 and §7.9] As a help to understanding

an algorithm, we have elected to put an explicit `SAVE` on all variables that really do need to retain their values between calls to a routine. We do this even if it is redundant because the variables are initialized. Note that we generally prefer to assign initial values with initialization expressions rather than with `DATA` statements. We reserve `DATA` statements for cases where it is convenient to use the repeat count feature to set multiple occurrences of a value, or when binary, octal, or hexadecimal constants are used. [M&R, §2.6.1]

## Named Control Structures

Fortran 90 allows control structures such as `do` loops and `if` blocks to be named. [M&R, §4.3–§4.5] Typical syntax is

```
name:do i=1,n
    ...
end do name
```

One use of naming control structures is to improve readability of the code, especially when there are many levels of nested loops and `if` blocks. A more important use is to allow `exit` and `cycle` statements, which normally refer to the innermost `do` loop in which they are contained, to transfer execution to the end of some outer loop. This is effected by adding the name of the outer loop to the statement: `exit name` or `cycle name`.

There is great potential for misuse with named control structures, since they share some features of the much-maligned `goto`. We recommend that you use them sparingly. For a good example of their use, contrast the Fortran 77 version of `simplx` with the Fortran 90 version on p. 1216.

### CITED REFERENCES AND FURTHER READING:

Metcalf, M., and Reid, J. 1996, *Fortran 90/95 Explained* (Oxford: Oxford University Press).

## 21.6 And Coming Soon: Fortran 95

One of the more positive effects of Fortran 90's long gestation period has been the general recognition, both by the X3J3 committee and by the community at large, that Fortran needs to evolve over time. Indeed, as we write, the process of bringing forth a minor, but by no means insignificant, updating of Fortran 90 — named Fortran 95 — is well under way.

Fortran 95 will differ from Fortran 90 in about a dozen features, only a handful of which are of any importance to this book. Generally these are extensions that will make programming, especially parallel programming, easier. In this section we give a summary of the anticipated language changes. In §22.1 and §22.5 we will comment further on the implications of Fortran 95 to some parallel programming tasks; in §23.7 we comment on what differences Fortran 95 will make to our `nrutil` utility functions.

No programs in Chapters B1 through B20 of this book edition use any Fortran 95 extensions.

## FORALL Statements and Blocks

Fortran 95 introduces a new `forall` control structure, somewhat akin to the `where` construct, but allowing for greater flexibility. It is something like a `do-loop`, but with the proviso that the indices looped over are allowed to be done in any order (ideally, in parallel). The `forall` construction comes in both single-statement and block variants. Instead of using the `do-loop`'s comma-separated triplets of lower-value, upper-value, and increment, it borrows its syntax from the colon-separated form of array sections. Some examples will give you the idea.

Here is a simple example that could alternatively be done with Fortran 90's array sections and `transpose` intrinsic:

```
forall (i=1:20, j=1:10:2) x(i,j)=y(j,i)
```

The block form allows more than one executable statement:

```
forall (i=1:20, j=1:10:2)
  x(i,j)=y(j,i)
  z(i,j)=y(i,j)**2
end forall
```

Here is an example that cannot be done with Fortran 90 array sections:

```
forall (i=1:20, j=1:20) a(i,j)=3*i+j**2
```

`forall` statements can also take optional masks that restrict their action to a subset of the loop index combinations:

```
forall (i=1:100, j=1:100, (i>=j .and. x(i,j)/=0.0) ) x(i,j)=1.0/x(i,j)
```

`forall` constructions can be nested, or nested inside `where` blocks, or have `where` constructions inside them. An additional new feature in Fortran 95 is that `where` blocks can themselves be nested.

## PURE Procedures

Because the inside iteration of a `forall` block can be done in any order, or in parallel, there is a logical difficulty in allowing functions or subroutines inside such blocks: If the function or subroutine has *side effects* (that is, if it changes any data elsewhere in the machine, or in its own saved variables) then the result of a `forall` calculation could depend on the order in which the iterations happen to be done. This can't be tolerated, of course; hence a new `PURE` attribute for subprograms.

While the exact stipulations are somewhat technical, the basic idea is that if you declare a function or subroutine as `PURE`, with a syntax like,

```
PURE FUNCTION myfunc(x,y,z)
```

or

```
PURE SUBROUTINE mysub(x,y,z)
```

then you are guaranteeing to the compiler (and it will enforce) that the only values changed by `mysub` or `myfunc` are returned function values, subroutine arguments with the `INTENT(OUT)` attribute, and automatic (scratch) variables within the procedure.

You can then use your pure procedures within `forall` constructions. Pure functions are also allowed in some specification statements.

## ELEMENTAL Procedures

Fortran 95 removes Fortran 90's nagging restriction that only intrinsic functions are elemental. The way this works is that you write a pure procedure that operates on scalar values, but include the attribute `ELEMENTAL` (which automatically implies `PURE`). Then, as long as the function has an explicit interface in the referencing program, you can call it with any shape of argument, and it will act elementally. Here's an example:

```
ELEMENTAL FUNCTION myfunc(x,y,z)
REAL :: x,y,z,myfunc
...
myfunc = ...
END
```

In a program with an explicit interface for `myfunc` you could now have

```
REAL, DIMENSION(10,20) :: x,y,z,w
...
w=myfunc(x,y,z)
```

## Pointer and Allocatable Improvements

Fortran 95, unlike Fortran 90, requires that any allocatable variables (except those with `SAVE` attributes) that are allocated within a subprogram be automatically deallocated by the compiler when the subprogram is exited. This will remove Fortran 90's "undefined allocation status" bugaboo.

Fortran 95 also provides a method for pointer variables to be born with disassociated association status, instead of the default (and often inconvenient) "undefined" status. The syntax is to add an initializing `=> NULL()` to the declaration, as:

```
REAL, DIMENSION(:,:), POINTER :: mypoint => NULL()
```

This does not, however, eliminate the possibility of undefined association status, because you have to remember to use the null initializer if want your pointer to be disassociated.

## Some Other Fortran 95 Features

In Fortran 95, `maxloc` and `minloc` have the additional optional argument `DIM`, which causes them to act on all one-dimensional sections that span through the named dimension. This provides a means for getting the locations of the values returned by the corresponding functions `maxval` and `minval` in the case that their `DIM` argument is present.

The `sign` intrinsic can now distinguish a negative from a positive real zero value: `sign(2.0,-0.0)` is `-2.0`.

There is a new intrinsic subroutine `cpu_time(time)` that returns as a real value time a process's elapsed CPU time.

There are some minor changes in the namelist facility, in defining minimum field widths for the `I`, `B`, `O`, `Z`, and `F` edit descriptors, and in resolving minor conflicts with some other standards.

# Chapter 22. Introduction to Parallel Programming

## 22.0 Why Think Parallel?

In recent years we Numerical Recipes authors have increasingly become convinced that a certain revolution, cryptically denoted by the words “parallel programming,” is about to burst forth from its gestation and adolescence in the community of supercomputer users, and become the mainstream methodology for all computing.

Let’s review the past: Take a screwdriver and open up the computer (workstation or PC) that sits on your desk. (Don’t blame us if this voids your warranty; and be sure to unplug it first!) Count the integrated circuits — just the bigger ones, with more than a million gates (transistors). As we write, in 1995, even lowly memory chips have one or four million gates, and this number will increase rapidly in coming years. You’ll probably count at least dozens, and often hundreds, of such chips in your computer.

Next ask, how many of these chips are CPUs? That is, how many implement von Neumann processors capable of executing arbitrary, stored program code? For most computers, in 1995, the answer is: about one. A significant number of computers do have secondary processors that offload input-output and/or video functions. So, two or three is often a more accurate answer, but only one is usually under the user’s direct control.

Why do our desktop computers have dozens or hundreds of memory chips, but most often only one (user-accessible) CPU? Do CPU chips intrinsically cost more to manufacture? No. Are CPU chips more expensive than memory chips? Yes, primarily because fixed development and design costs must be distributed over a smaller number of units sold. We have been in a kind of economic equilibrium: CPU’s are relatively expensive because there is only one per computer; and there is only one per computer, because they are relatively expensive.

Stabilizing this equilibrium has been the fact that there has been no standard, or widely taught, methodology for parallel programming. Except for the special case of scientific computing on supercomputers (where large problems often have a regular or geometric character), it is not too much of an exaggeration to say that nobody *really knows how* to program multiprocessor machines. Symmetric multiprocessor

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operating systems, for example, have been very slow in developing; and efficient, parallel methodologies for query-serving on large databases are even now a subject of continuing research.

However, things are now changing. We consider it an easy prognostication that, by the first years of the new century, the typical desktop computer will have 4 to 8 user-accessible CPUs; ten years after that, the typical number will be between 16 and 512. It is not coincidence that these numbers are characteristic of supercomputers (including some quite different architectures) in 1995. The rough rule of ten years' lag from supercomputer to desktop has held firm for quite some time now.

Scientists and engineers have the advantage that techniques for parallel computation in their disciplines *have* already been developed. With multiprocessor workstations right around the corner, we think that now is the right time for scientists and engineers who use computers to start *thinking parallel*. We don't mean that you should put an axe through the screen of your fast serial (single-CPU) workstation. We do mean, however, that you should start programming somewhat differently on that workstation, indeed, start thinking a bit differently about the way that you approach numerical problems in general.

In this volume of *Numerical Recipes in Fortran*, our pedagogical goal is to show you that there are conceptual and practical benefits in parallel thinking, even if you are using a serial machine today. These benefits include conciseness and clarity of code, reusability of code in wider contexts, and (not insignificantly) increased portability of code to today's parallel supercomputers. Of course, on parallel machines, either supercomputers today or desktop machines tomorrow, the benefits of thinking parallel are much more tangible: They translate into significant improvements in efficiency and computational capability.

### **Thinking Parallel with Fortran 90**

Until very recently, a strong inhibition to thinking parallel was the lack of any standard, architecture-independent, computer language in which to think. That has changed with the finalization of the Fortran 90 language standard, and with the availability of good, optimizing Fortran 90 compilers on a variety of platforms.

There is a significant body of opinion (with which we, however, disagree) that there is no such thing as architecture-independent parallel programming. Proponents of this view, who are generally committed wizards at programming on one or another particular architecture, point to the fact that algorithms that are optimized to one architecture can run hundreds of times more slowly on other architectures. And, they are correct!

Our opposing point of view is one of pragmatism. We think that it is not hard to learn, in a general way, what kinds of architectures are in general use, and what kinds of parallel constructions work well (or poorly) on each kind. With this knowledge (much of which we hope to develop in this book) the user can, we think, write good, general-purpose parallel code that works on a variety of architectures — including, importantly, on purely serial machines. Equally important, the user will be aware of when certain parts of a code can be significantly improved on some, but not other, architectures.

Fortran 90 is a good test-bench for this point of view. It is not the perfect language for parallel programming. But it is *a* language, and it is the only

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cross-platform *standard* language now available. The committee that developed the language between 1978 and 1991 (known technically as X3J3) had strong representation from both a traditional “vectorization” viewpoint (e.g., from the Cray XMP and YMP series of computers), and also from the “data parallel” or “SIMD” viewpoints of parallel machines like the CM-2 and CM-5 from Thinking Machines, Inc. Language compromises were made, and a few (in our view) almost essential features were left out (see §22.5). But, by and large, the necessary tools are there: If you learn to think parallel in Fortran 90, you will easily be able to transfer the skill to future parallel standards, whether they are Fortran-based, C-based, or other.

#### CITED REFERENCES AND FURTHER READING:

Metcalfe, M., and Reid, J. 1996, *Fortran 90/95 Explained* (Oxford: Oxford University Press).

## 22.1 Fortran 90 Data Parallelism: Arrays and Ininsics

The underlying model for parallel computation in Fortran 90 is *data parallelism*, implemented by the use of arrays of data, and by the provision of operations and intrinsic functions that act on those arrays in parallel, in a manner optimized by the compiler for each particular hardware architecture. We will not try to draw a fine definitional distinction between “data parallelism” and so-called SIMD (single instruction multiple data) programming. For our purposes the two terms mean about the same thing: The programmer writes a single operation, “+” say, and the compiler causes it to be carried out on multiple pieces of data in as parallel a manner as the underlying hardware allows.

Any kind of parallel computing that is not SIMD is generally called MIMD (multiple instruction multiple data). A parallel programming language with MIMD features might allow, for example, several different subroutines — acting on different parts of the data — to be called into execution simultaneously. Fortran 90 has few, if any, MIMD constructions. A Fortran 90 compiler might, on some machines, execute MIMD code in implementing some Fortran 90 intrinsic functions (pack or unpack, e.g.), but this will be hidden from the Fortran 90 user. Some extensions of Fortran 90, like HPF, do implement MIMD features explicitly; but we will not consider these in this book. Fortran 95’s `forall` and `PURE` extensions (see §21.6) will allow some significantly greater access to MIMD features (see §22.5).

### Array Parallel Operations

We have already met the most basic, and most important, parallel facility of Fortran 90, namely, the ability to use whole arrays in expressions and assignments, with the indicated operations being effected in parallel across the array. Suppose, for example, we have the two-dimensional matrices `a`, `b`, and `c`,

```
REAL, DIMENSION(30,30) :: a,b,c
```

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Then, instead of the serial construction,

```
do j=1,30
  do k=1,30
    c(j,k)=a(j,k)+b(j,k)
  end do
end do
```

which is of course perfectly valid Fortran 90 code, we can simply write

```
c=a+b
```

The compiler deduces from the declaration statement that *a*, *b*, and *c* are matrices, and what their bounding dimensions are.

Let us dwell for a moment on the conceptual differences between the serial code and parallel code for the above matrix addition. Although one is perhaps used to seeing the nested do-loops as simply an idiom for “do-the-enclosed-on-all-components,” it in fact, according to the rules of Fortran, specifies a very particular time-ordering for the desired operations. The matrix elements are added by rows, in order (*j*=1, 30), and within each row, by columns, in order (*k*=1, 30).

In fact, the serial code above *overspecifies* the desired task, since it is guaranteed by the laws of mathematics that the order in which the element operations are done is of no possible relevance. Over the 50 year lifetime of serial von Neuman computers, we programmers have been brainwashed to break up all problems into single executable streams *in the time dimension only*. Indeed, the major design problem for supercomputer compilers for the last 20 years has been to *undo* such serial constructions and recover the underlying “parallel thoughts,” for execution in vector or parallel processors. Now, rather than taking this expensive detour into and out of serial-land, we are asked simply to say what we mean in the first place, *c=a+b*.

**The essence of parallel programming is *not* to force “into the time dimension” (i.e., to serialize) operations that naturally extend across a span of data, that is, “in the space dimension.”** If it were not for 50-year-old collective habits, and the languages designed to support them, parallel programming would probably strike us as more natural than its serial counterpart.

### **Broadcasts and Dimensional Expansion: SSP vs. MMP**

We have previously mentioned the Fortran 90 rule that a scalar variable is conformable with any shape array. Thus, we can implement a calculation such as

$$y_i = x_i + s, \quad i = 1, \dots, n \quad (22.1.1)$$

with code like

```
y=x+s
```

where we of course assume previous declarations like

```
REAL(SP) :: s
REAL(SP), DIMENSION(n) :: x,y
```

with *n* a compile-time constant or dummy argument. (Hereafter, we will omit the declarations in examples that are this simple.)

This seemingly simple construction actually hides an important underlying parallel capability, namely, that of *broadcast*. The sums in *y=x+s* are done in parallel

on different CPUs, each CPU accessing different components of  $x$  and  $y$ . Yet, they all must access the same scalar value  $s$ . If the hardware has local memory for each CPU, the value of  $s$  must be replicated and transferred to each CPU's local memory. On the other hand, if the hardware implements a single, global memory space, it is vital to do something that mitigates the traffic jam potentially caused by all the CPUs trying to access the same memory location at the same time. (We will use the term "broadcast" to refer equally to both cases.) Although hidden from the user, Fortran 90's ability to do broadcasts is an essential feature of it as a parallel language.

Broadcasts can be more complicated than the above simple example. Consider, for example, the calculation

$$w_i = \sum_{j=1}^n |x_i + x_j|, \quad i = 1, \dots, n \quad (22.1.2)$$

Here, we are doing  $n^2$  operations: For each of  $n$  values of  $i$  there is a sum over  $n$  values of  $j$ .

Serial code for this calculation might be

```
do i=1,n
  w(i)=0.
  do j=1,n
    w(i)=w(i)+abs(x(i)+x(j))
  end do
end do
```

The obvious immediate parallelization in Fortran 90 uses the `sum` intrinsic function to eliminate the inner `do`-loop. This would be a suitable amount of parallelization for a small-scale parallel machine, with a few processors:

```
do i=1,n
  w(i)=sum(abs(x(i)+x))
end do
```

Notice that the conformability rule implies that a new value of  $x(i)$ , a scalar, is being broadcast to all the processors involved in the `abs` and `sum`, with each iteration of the loop over  $i$ .

What about the outer `do`-loop? Do we need, or want, to eliminate it, too? That depends on the architecture of your computer, and on the tradeoff between time and memory in your problem (a common feature of all computing, no less so parallel computing). Here is an implementation that is free of all `do`-loops, in principle capable of being executed in a small number (independent of  $n$ ) of parallel operations:

```
REAL(SP), DIMENSION(n,n) :: a
...
a = spread(x,dim=2,ncopies=n)+spread(x,dim=1,ncopies=n)
w = sum(abs(a),dim=1)
```

This is an example of what we call *dimensional expansion*, as implemented by the `spread` intrinsic. Although the above may strike you initially as quite a cryptic construction, it is easy to learn to read it. In the first assignment line, a matrix is constructed with all possible values of  $x(i)+x(j)$ . In the second assignment line, this matrix is collapsed back to a vector by applying the `sum` operation to the absolute value of its elements, across one of its dimensions.

More explicitly, the first line creates a matrix `a` by adding two matrices each constructed via `spread`. In `spread`, the `dim` argument specifies which argument is *duplicated*, so that the first term *varies* across its first (row) dimension, and vice versa for the second term:

$$a_{ij} = x_i + x_j$$

$$= \begin{pmatrix} x_1 & x_1 & x_1 & \dots \\ x_2 & x_2 & x_2 & \dots \\ x_3 & x_3 & x_3 & \dots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} + \begin{pmatrix} x_1 & x_2 & x_3 & \dots \\ x_1 & x_2 & x_3 & \dots \\ x_1 & x_2 & x_3 & \dots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \quad (22.1.3)$$

Since equation (22.1.2) above is symmetric in  $i$  and  $j$ , it doesn't really matter what value of `dim` we put in the `sum` construction, but the value `dim=1` corresponds to summing across the rows, that is, down each column of equation (22.1.3).

Be sure that you understand that the `spread` construction changed an  $O(n)$  memory requirement into an  $O(n^2)$  one! If your values of  $n$  are large, this is an impossible burden, and the previous implementation with a single `do-loop` remains the only practical one. On the other hand, if you are working on a massively parallel machine, whose number of processors is comparable to  $n^2$  (or at least much larger than  $n$ ), then the `spread` construction, and the underlying broadcast capability that it invokes, leads to a big win: All  $n^2$  operations can be done in parallel. This distinction between small-scale parallel machines — which we will hereafter refer to as *SSP machines* — and massively multiprocessor machines — which we will refer to as *MMP machines* — is an important one. A main goal of parallelism is to saturate the available number of processors, and algorithms for doing so are often different in the SSP and MMP opposite limits. Dimensional expansion is one method for saturating processors in the MMP case.

### Masks and “Index Loss”

An instructive extension of the above example is the following case of a product that omits one term (the diagonal one):

$$w_i = \prod_{\substack{j=1 \\ j \neq i}}^n (x_j - x_i), \quad i = 1, \dots, n \quad (22.1.4)$$

Formulas like equation (22.1.4) frequently occur in the context of interpolation, where all the  $x_i$ 's are known to be distinct, so let us for the moment assume that this is the case.

Serial code for equation (22.1.4) could be

```
do i=1,n
  w(i)=1.0_sp
  do j=1,n
    if (j /= i) w(i)=w(i)*(x(j)-x(i))
  end do
end do
```

Parallel code for SSP machines, or for large enough  $n$  on MMP machines, could be

```

do i=1,n
  w(i)=product( x-x(i), mask=(x/=x(i)) )
end do

```

Here, the `mask` argument in the `product` intrinsic function causes the diagonal term to be omitted from the product, as we desire. There are some features of this code, however, that bear commenting on.

First, notice that, according to the rules of conformability, the expression `x/=x(i)` broadcasts the scalar `x(i)` and generates a logical array of length  $n$ , suitable for use as a mask in the `product` intrinsic. It is quite common in Fortran 90 to generate masks “on the fly” in this way, particularly if the mask is to be used only once.

Second, notice that the `j` index has disappeared completely. It is now implicit in the two occurrences of `x` (equivalent to `x(1:n)`) on the right-hand side. With the disappearance of the `j` index, we also lose the ability to do the test on `i` and `j`, but must use, in essence, `x(i)` and `x(j)` instead! That is a very general feature in Fortran 90: when an operation is done in parallel across an array, there is *no associated index* available within the operation. This “index loss,” as we will see in later discussion, can sometimes be quite an annoyance.

A language construction present in CM [Connection Machine] Fortran, the so-called `forall`, which would have allowed access to an associated index in many cases, was eliminated from Fortran 90 by the X3J3 committee, in a controversial decision. Such a construction will come into the language in Fortran 95.

What about code for an MMP machine, where we are willing to use dimensional expansion to achieve greater parallelism? Here, we can write,

```

a = spread(x,dim=2,ncopies=n)-spread(x,dim=1,ncopies=n)
w = product(a,dim=1,mask=(a/=0.))

```

This time it does matter that the value of `dim` in the `product` intrinsic is 1 rather than 2. If you write out the analog of equation (22.1.3) for the present example, you’ll see that the above fragment is the right way around. The problem of index loss is still with us: we have to construct a mask from the array `a`, not from its indices, *both* of which are now lost to us!

In most cases, there are workarounds (more, or less, awkward as they may be) for the problem of index loss. In the worst cases, which are quite rare, you have to create objects to hold, and thus bring back into play, the lost indices. For example,

```

INTEGER(I4B), DIMENSION(n) :: jj
...
jj = (/ (i,i=1,n) /)
do i=1,n
  w(i)=product( x-x(i), mask=(jj/=i) )
end do

```

Now the array `jj` is filled with the “lost” `j` index, so that it is available for use in the mask. A similar technique, involving spreads of `jj`, can be used in the above MMP code fragment, which used dimensional expansion. (Fortran 95’s `forall` construction will make index loss much less of a problem. See §21.6.)

Incidentally, the above Fortran 90 construction, `(/ (i,i=1,n) /)`, is called an *array constructor with implied do list*. For reasons to be explained in §22.2, we almost never use this construction, in most cases substituting a Numerical Recipes utility function for generating arithmetical progressions, which we call `arth`.

## Interprocessor Communication Costs

It is both a blessing and a curse that Fortran 90 completely hides from the user the underlying machinery of interprocessor communication, that is, the way that data values computed by (or stored locally near) one CPU make their way to a different CPU that might need them next. The blessing is that, by and large, the Fortran 90 programmer need not be concerned with how this machinery works. If you write

```
a(1:10,1:10) = b(1:10,1:10) + c(10:1:-1,10:1:-1)
```

the required upside-down-and-backwards values of the array *c* are just *there*, no matter that a great deal of routing and switching may have taken place. An ancillary blessing is that this book, unlike so many other (more highly technical) books on parallel programming (see references below) need not be filled with complex and subtle discussions of CPU connectivity, topology, routing algorithms, and so on.

The curse is, just as you might expect, that the Fortran 90 programmer can't control the interprocessor communication, even when it is desirable to do so. A few regular communication patterns are "known" to the compiler through Fortran 90 intrinsic functions, for example `b=transpose(a)`. These, presumably, are done in an optimal way. However, many other regular patterns of communication, which might also allow highly optimized implementations, don't have corresponding intrinsic functions. (An obvious example is the "butterfly" pattern of communication that occurs in fast Fourier transforms.) These, if coded in Fortran 90 by using general vector subscripts (e.g., `barr=arr(iarr)` or `barr(jarr)=arr`, where `iarr` and `jarr` are integer arrays), lose all possibility of being optimized. The compiler can't distinguish a communication step with regular structure from one with general structure, so it must assume the worst case, potentially resulting in very slow execution.

About the only thing a Fortran 90 programmer can do is to start with a general awareness of the kind of apparently parallel constructions that *might* be quite slow on his/her parallel machine, and then to refine that awareness by actual experience and experiment. Here is our list of constructions most likely to cause interprocessor communication bottlenecks:

- vector subscripts, like `barr=arr(iarr)` or `barr(jarr)=arr` (that is, general gather/scatter operations)
- the `pack` and `unpack` intrinsic functions
- mixing positive strides and negative strides in a single expression (as in the above `b(1:10,1:10)+c(10:1:-1,10:1:-1)`)
- the `reshape` intrinsic when used with the `order` argument
- possibly, the `cshift` and `eoshift` extrinsics, especially for non-small values of the shift.

On the other hand, the fact is that these constructions *are* parallel, and *are* there for you to use. If the alternative to using them is strictly serial code, you should almost always give them a try.

## Linear Algebra

You should be alert for opportunities to use combinations of the `matmul`, `spread`, and `dot_product` intrinsics to perform complicated linear algebra calculations. One useful intrinsic that is not provided in Fortran 90 is the *outer product*

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of two vectors,

$$c_{ij} = a_i b_j \quad (22.1.5)$$

We already know how to implement this (cf. equation 22.1.3):

```
c = spread(a,dim=2,ncopies=size(b))*spread(b,dim=1,ncopies=size(a))
```

In fact, this operation occurs frequently enough to justify making it a utility function, `outerprod`, which we will do in Chapter 23. There we also define other “outer” operations between vectors, where the multiplication in the outer product is replaced by another binary operation, such as addition or division.

Here is an example of using these various functions: Many linear algebra routines require that a submatrix be updated according to a formula like

$$a_{jk} = a_{jk} + b_i a_{ji} \sum_{p=i}^m a_{pi} a_{pk}, \quad j = i, \dots, m, \quad k = l, \dots, n \quad (22.1.6)$$

where  $i, m, l$ , and  $n$  are fixed values. Using an array slice like `a(:,i)` to turn  $a_{pi}$  into a vector indexed by  $p$ , we can code the sum with a `matmul`, yielding a vector indexed by  $k$ :

```
temp(1:n)=b(i)*matmul(a(i:m,i),a(i:m,1:n))
```

Here we have also included the multiplication by  $b_i$ , a scalar for fixed  $i$ . The vector `temp`, along with the vector  $a_{ji} = a(:,i)$ , is then turned into a matrix by the `outerprod` utility and used to increment  $a_{jk}$ :

```
a(i:m,1:n)=a(i:m,1:n)+outerprod(a(i:m,i),temp(1:n))
```

Sometimes the update formula is similar to (22.1.6), but with a slight permutation of the indices. Such cases can be coded as above if you are careful about the order of the quantities in the `matmul` and the `outerprod`.

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## 22.2 Linear Recurrence and Related Calculations

We have already seen that Fortran 90's *array constructor with implied do list* can be used to generate simple series of integers, like `(/ (i, i=1, n) /)`. Slightly more generally, one might want to generate an arithmetic progression, by the formula

$$v_j = b + (j - 1)a, \quad j = 1, \dots, n \quad (22.2.1)$$

This is readily coded as

```
v(1:n) = (/ (b+(j-1)*a, j=1,n) /)
```

Although it is concise, and valid, *we don't like this coding*. The reason is that it violates the fundamental rule of "thinking parallel": it turns a parallel operation across a data vector into a serial do-loop over the components of that vector. Yes, we know that the compiler might be smart enough to generate parallel code for implied do lists; but it also might *not* be smart enough, here or in more complicated examples.

Equation (22.2.1) is also the simplest example of a *linear recurrence relation*. It can be rewritten as

$$v_1 = b, \quad v_j = v_{j-1} + a, \quad j = 2, \dots, n \quad (22.2.2)$$

In this form (assuming that, in more complicated cases, one doesn't know an explicit solution like equation 22.2.1) one can't write an explicit array constructor. Code like

```
v(1) = b
v(2:n) = (/ (v(j-1)+a, j=2,n) /) ! wrong
```

is legal Fortran 90 syntax, but illegal semantics; it does *not* do the desired recurrence! (The rules of Fortran 90 require that all the components of  $v$  on the right-hand side be evaluated before any of the components on the left-hand side are set.) Yet, as we shall see, techniques for accomplishing the evaluation in parallel are available.

With this as our starting point, we now survey some particular tricks of the (parallel) trade.

## Subvector Scaling: Arithmetic and Geometric Progressions

For explicit arithmetic progressions like equation (22.2.1), the simplest parallel technique is *subvector scaling* [1]. The idea is to work your way through the desired vector in larger and larger parallel chunks:

$$\begin{aligned}v_1 &= b \\v_2 &= b + a \\v_{3\dots 4} &= v_{1\dots 2} + 2a \\v_{5\dots 8} &= v_{1\dots 4} + 4a \\v_{9\dots 16} &= v_{1\dots 8} + 8a\end{aligned}\tag{22.2.3}$$

And so on, until you reach the length of your vector. (The last step will not necessarily go all the way to the next power of 2, therefore.) The powers of 2, times  $a$ , can of course be obtained by successive doublings, rather than the explicit multiplications shown above.

You can see that subvector scaling requires about  $\log_2 n$  parallel steps to process a vector of length  $n$ . Equally important for serial machines, or SSP machines, the scalar operation count for subvector scaling is no worse than entirely serial code: each new component  $v_i$  is produced by a single addition.

If addition is replaced by multiplication, the identical algorithm will produce geometric progressions, instead of arithmetic progressions. In Chapter 23, we will use subvector scaling to implement our utility functions `arth` and `geop` for these two progressions. (You can then call one of these functions instead of recoding equation 22.2.3 every time you need it.)

## Vector Reduction: Evaluation of Polynomials

Logically related to subvector scaling is the case where a calculation can be parallelized across a vector that *shrinks* by a factor of 2 in each iteration, until a desired *scalar* result is reached. A good example of this is the parallel evaluation of a polynomial [2]

$$P(x) = \sum_{j=0}^N c_j x^j\tag{22.2.4}$$

For clarity we take the special case of  $N = 5$ . Start with the vector of coefficients (imagining appended zeros, as shown):

$$c_0, \quad c_1, \quad c_2, \quad c_3, \quad c_4, \quad c_5, \quad 0, \quad \dots$$

Now, add the elements by pairs, multiplying the second of each pair by  $x$ :

$$c_0 + c_1x, \quad c_2 + c_3x, \quad c_4 + c_5x, \quad 0, \quad \dots$$

Now, the same operation, but with the multiplier  $x^2$ :

$$(c_0 + c_1x) + (c_2 + c_3x)x^2, \quad (c_4 + c_5x) + (0)x^2, \quad 0, \quad \dots$$

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And a final time, with multiplier  $x^4$ :

$$[(c_0 + c_1x) + (c_2 + c_3x)x^2] + [(c_4 + c_5x) + (0)x^2]x^4, \quad 0, \quad \dots$$

We are left with a vector of (active) length 1, whose value is the desired polynomial evaluation. (You can see that the zeros are just a bookkeeping device for taking account of the case where the active subvector has odd length.) The key point is that the combining by pairs is a parallel operation at each stage.

As in subvector scaling, there are about  $\log_2 n$  parallel stages. Also as in subvector scaling, our total operations count is only negligibly different from purely scalar code: We do one add and one multiply for each original coefficient  $c_j$ . The only extra operations are  $\log_2 n$  successive squarings of  $x$ ; but this comes with the extra benefit of better roundoff properties than the standard scalar coding. In Chapter 23 we use vector reduction to implement our utility function `poly` for polynomial evaluation.

### Recursive Doubling: Linear Recurrence Relations

Please don't confuse our use of the word "recurrence" (as in "recurrence relation," "linear recurrence," or equation 22.2.2) with the words "recursion" and "recursive," which both refer to the idea of a subroutine calling itself to obtain an efficient or concise algorithm. There are ample grounds for confusion, because recursive algorithms are in fact a good way of obtaining parallel solutions to linear recurrence relations, as we shall now see!

Consider the general first order linear recurrence relation

$$u_j = a_j + b_{j-1}u_{j-1}, \quad j = 2, 3, \dots, n \quad (22.2.5)$$

with initial value  $u_1 = a_1$ . On a serial machine, we evaluate such a recurrence with a simple do-loop. To parallelize the recurrence, we can employ the powerful general strategy of *recursive doubling*. Write down equation (22.2.5) for  $2j$  and for  $2j - 1$ :

$$u_{2j} = a_{2j} + b_{2j-1}u_{2j-1} \quad (22.2.6)$$

$$u_{2j-1} = a_{2j-1} + b_{2j-2}u_{2j-2} \quad (22.2.7)$$

Substitute equation (22.2.7) in equation (22.2.6) to eliminate  $u_{2j-1}$  and get

$$u_{2j} = (a_{2j} + a_{2j-1}b_{2j-1}) + (b_{2j-2}b_{2j-1})u_{2j-2} \quad (22.2.8)$$

This is a new recurrence of the same form as (22.2.5) but over only the even  $u_j$ , and hence involving only  $n/2$  terms. Clearly we can continue this process recursively, halving the number of terms in the recurrence at each stage, until we are left with a recurrence of length 1 or 2 that we can do explicitly. Each time we finish a subpart of the recursion, we fill in the odd terms in the recurrence, using equation (22.2.7). In practice, it's even easier than it sounds. Turn to Chapter B5 to see a straightforward implementation of this algorithm as the recipe `recur1`.

On a machine with more processors than  $n$ , all the arithmetic at each stage of the recursion can be done simultaneously. Since there are of order  $\log n$  stages in the

recursion, the execution time is  $O(\log n)$ . The total number of operations carried out is of order  $n + n/2 + n/4 + \dots = O(n)$ , the same as for the obvious serial do-loop.

In the utility routines of Chapter 23, we will use recursive doubling to implement the routines `poly_term`, `cumsum`, and `cumprod`. We *could* use recursive doubling to implement parallel versions of `arth` and `geop` (arithmetic and geometric progressions), and `zroots_unity` (complex  $n$ th roots of unity), but these can be done slightly more efficiently by subvector scaling, as discussed above.

### Cyclic Reduction: Linear Recurrence Relations

There is a variant of recursive doubling, called *cyclic reduction*, that can be implemented with a straightforward iteration loop, instead of a recursive procedure call. [3] Here we start by writing down the recurrence (22.2.5) for *all* adjacent terms  $u_j$  and  $u_{j-1}$  (not just the even ones, as before). Eliminating  $u_{j-1}$ , just as in equation (22.2.8), gives

$$u_j = (a_j + a_{j-1}b_{j-1}) + (b_{j-2}b_{j-1})u_{j-2} \quad (22.2.9)$$

which is a first order recurrence with new coefficients  $a'_j$  and  $b'_j$ . Repeating this process gives successive formulas for  $u_j$  in terms of  $u_{j-2}$ ,  $u_{j-4}$ ,  $u_{j-8}$ , ... The procedure terminates when we reach  $u_{j-n}$  (for  $n$  a power of 2), which is zero for all  $j$ . Thus the last step gives  $u_j$  equal to the last set of  $a'_j$ 's.

Here is a code fragment that implements cyclic reduction by direct iteration. The quantities  $a'_j$  are stored in the variable `recur1`.

```
recur1=a
bb=b
j=1
do
  if (j >= n) exit
  recur1(j+1:n)=recur1(j+1:n)+bb(j:n-1)*recur1(1:n-j)
  bb(2*j:n-1)=bb(2*j:n-1)*bb(j:n-j-1)
  j=2*j
enddo
```

In cyclic reduction the length of the vector  $u_j$  that is updated at each stage does *not* decrease by a factor of 2 at each stage, but rather only decreases from  $\sim n$  to  $\sim n/2$  during all  $\log_2 n$  stages. Thus the total number of operations carried out is  $O(n \log n)$ , as opposed to  $O(n)$  for recursive doubling. For a serial machine or SSP machine, therefore, cyclic reduction is rarely superior to recursive doubling when the latter can be used. For an MMP machine, however, the issue is less clear cut, because the pattern of communication in cyclic reduction is quite different (and, for some parallel architectures, possibly more favorable) than that of recursive doubling.

### Second Order Recurrence Relations

Consider the second order recurrence relation

$$y_j = a_j + b_{j-2}y_{j-1} + c_{j-2}y_{j-2}, \quad j = 3, 4, \dots, n \quad (22.2.10)$$

with initial values

$$y_1 = a_1, \quad y_2 = a_2 \quad (22.2.11)$$

Our labeling of subscripts is designed to make it easy to enter the coefficients in a computer program: You need to supply  $a_1, \dots, a_n, b_1, \dots, b_{n-2}$ , and  $c_1, \dots, c_{n-2}$ . Rewrite the recurrence relation in the form ([3])

$$\begin{pmatrix} y_j \\ y_{j+1} \end{pmatrix} = \begin{pmatrix} 0 \\ a_{j+1} \end{pmatrix} + \begin{pmatrix} 0 & 1 \\ c_{j-1} & b_{j-1} \end{pmatrix} \begin{pmatrix} y_{j-1} \\ y_j \end{pmatrix}, \quad j = 2, \dots, n-1 \quad (22.2.12)$$

that is,

$$\mathbf{u}_j = \mathbf{a}_j + \mathbf{b}_{j-1} \cdot \mathbf{u}_{j-1}, \quad j = 2, \dots, n-1 \quad (22.2.13)$$

where

$$\mathbf{u}_j = \begin{pmatrix} y_j \\ y_{j+1} \end{pmatrix}, \quad \mathbf{a}_j = \begin{pmatrix} 0 \\ a_{j+1} \end{pmatrix}, \quad \mathbf{b}_{j-1} = \begin{pmatrix} 0 & 1 \\ c_{j-1} & b_{j-1} \end{pmatrix}, \quad j = 2, \dots, n-1 \quad (22.2.14)$$

and

$$\mathbf{u}_1 = \mathbf{a}_1 = \begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad (22.2.15)$$

This is a first order recurrence relation for the vectors  $\mathbf{u}_j$ , and can be solved by the algorithm described above (and implemented in the recipe `recur1`). The only difference is that the multiplications are matrix multiplications with the  $2 \times 2$  matrices  $\mathbf{b}_j$ . After the first recursive call, the zeros in  $\mathbf{a}$  and  $\mathbf{b}$  are lost, so we have to write the routine for general two-dimensional vectors and matrices.

Note that this algorithm does not avoid the potential instability problems associated with second order recurrences that are discussed in §5.5 of Volume 1. Also note that the algorithm generalizes in the obvious way to higher-order recurrences: An  $n$ th order recurrence can be written as a first order recurrence involving  $n$ -dimensional vectors and matrices.

### Parallel Solution of Tridiagonal Systems

Closely related to recurrence relations, recursive doubling, and cyclic reduction is the parallel solution of tridiagonal systems. Since Fortran 90 vectors “know their own size,” it is most logical to number the components of both the sub- and super-diagonals of the tridiagonal matrix from 1 to  $N - 1$ . Thus equation (2.4.1), here written in the special case of  $N = 7$ , becomes (blank elements denoting zero),

$$\begin{bmatrix} b_1 & c_1 & & & & & \\ a_1 & b_2 & c_2 & & & & \\ & a_2 & b_3 & c_3 & & & \\ & & a_3 & b_4 & c_4 & & \\ & & & a_4 & b_5 & c_5 & \\ & & & & a_5 & b_6 & c_6 \\ & & & & & a_6 & b_7 \end{bmatrix} \cdot \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ u_6 \\ u_7 \end{bmatrix} = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \\ r_5 \\ r_6 \\ r_7 \end{bmatrix} \quad (22.2.16)$$

The basic idea for solving equation (22.2.16) on a parallel computer is to partition the problem into even and odd elements, recurse to solve the former, and

then solve the latter in parallel. Specifically, we first rewrite (22.2.16), by permuting its rows and columns, as

$$\begin{bmatrix} b_1 & & & & c_1 & & & & \\ & b_3 & & & a_2 & c_3 & & & \\ & & b_5 & & a_4 & c_5 & & & \\ & & & b_7 & & a_6 & & & \\ a_1 & c_2 & & & b_2 & & & & \\ & a_3 & c_4 & & & b_4 & & & \\ & & a_5 & c_6 & & & b_6 & & \end{bmatrix} \cdot \begin{bmatrix} u_1 \\ u_3 \\ u_5 \\ u_7 \\ u_2 \\ u_4 \\ u_6 \end{bmatrix} = \begin{bmatrix} r_1 \\ r_3 \\ r_5 \\ r_7 \\ r_2 \\ r_4 \\ r_6 \end{bmatrix} \quad (22.2.17)$$

Now observe that, by row operations that subtract multiples of the first four rows from each of the last three rows, we can eliminate all nonzero elements in the lower-left quadrant. The price we pay is bringing some new elements into the lower-right quadrant, whose nonzero elements we now call  $x$ 's,  $y$ 's, and  $z$ 's. We call the modified right-hand sides  $q$ . The transformed problem is now

$$\begin{bmatrix} b_1 & & & & c_1 & & & & \\ & b_3 & & & a_2 & c_3 & & & \\ & & b_5 & & a_4 & c_5 & & & \\ & & & b_7 & & a_6 & & & \\ & & & & y_1 & z_1 & & & \\ & & & & x_1 & y_2 & z_2 & & \\ & & & & & x_2 & y_3 & & \end{bmatrix} \cdot \begin{bmatrix} u_1 \\ u_3 \\ u_5 \\ u_7 \\ u_2 \\ u_4 \\ u_6 \end{bmatrix} = \begin{bmatrix} r_1 \\ r_3 \\ r_5 \\ r_7 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \quad (22.2.18)$$

Notice that the last three rows form a new, smaller, tridiagonal problem, which we can solve simply by recursing! Once its solution is known, the first four rows can be solved by a simple, parallelizable, substitution. This algorithm is implemented in `tridag` in Chapter B2.

The above method is essentially cyclic reduction, but in the case of the tridiagonal problem, it does not “unwind” into a simple iteration; on the contrary, a recursive subroutine is required. For discussion of this and related methods for parallelizing tridiagonal systems, and references to the literature, see Hockney and Jesshope [3].

Recursive doubling can also be used to solve tridiagonal systems, the method requiring the parallel solution (as above) of both a first order recurrence and a second order recurrence [3,4]. For tridiagonal systems, however, cyclic reduction is usually more efficient than recursive doubling.

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## 22.3 Parallel Synthetic Division and Related Algorithms

There are several techniques for parallelization that relate to synthetic division but that can also find application in wider contexts, as we shall see.

### Cumulants of a Polynomial

Suppose we have a polynomial

$$P(x) = \sum_{j=0}^N c_j x^{N-j} \quad (22.3.1)$$

(Note that, here, the  $c_j$ 's are indexed from highest degree to lowest, the reverse of the usual convention.) Then we can define the *cumulants* of the polynomial to be partial sums that occur in the polynomial's usual, serial evaluation,

$$\begin{aligned} P_0 &= c_0 \\ P_1 &= c_0 x + c_1 \\ &\dots \\ P_N &= c_0 x^N + \dots + c_N = P(x) \end{aligned} \quad (22.3.2)$$

Evidently, the cumulants satisfy a simple, linear first order recurrence relation,

$$P_0 = c_0, \quad P_j = c_j + xP_{j-1}, \quad j = 2, \dots, N \quad (22.3.3)$$

This is slightly simpler than the general first order recurrence, because the value of  $x$  does not depend on  $j$ . We already know, from §22.2's discussion of recursive doubling, how to parallelize equation (22.3.3) via a recursive subroutine. In Chapter 23, the utility routine `poly_term` will implement just such a procedure. An example of a routine that calls `poly_term` to evaluate a recurrence equivalent to equation (22.3.3) is `eulsum` in Chapter B5.

Notice that while we could use equation (22.3.3), parallelized by recursive doubling, simply to evaluate the polynomial  $P(x) = P_N$ , this is likely somewhat slower than the alternative technique of vector reduction, also discussed in §22.2, and implemented in the utility function `poly`. Equation (22.3.3) should be saved for cases where the rest of the  $P_j$ 's (not just  $P_N$ ) can be put to good use.

### Synthetic Division by a Monomial

We now show that evaluation of the cumulants of a polynomial is equivalent to synthetic division of the polynomial by a monomial, also called *deflation* (see §9.5 in Volume 1). To review briefly, and by example, here is a standard tableau from high school algebra for the (long) division of a polynomial  $2x^3 - 7x^2 + x + 3$  by the monomial factor  $x - 3$ .

$$\begin{array}{r}
 2x^2 - x - 2 \\
 x - 3 \overline{) 2x^3 - 7x^2 + x + 3} \\
 \underline{2x^3 - 6x^2} \phantom{+ x + 3} \\
 -x^2 + x \phantom{+ 3} \\
 \underline{-x^2 + 3x} \phantom{+ 3} \\
 -2x + 3 \\
 \underline{-2x + 6} \\
 -3 \text{ (remainder)}
 \end{array} \tag{22.3.4}$$

Now, here is the same calculation written as a *synthetic division*, really the same procedure as tableau (22.3.4), but with unnecessary notational baggage omitted (and also a changed sign for the monomial's constant, so that subtractions become additions):

$$\begin{array}{r}
 6 \quad -3 \quad -6 \\
 3 \overline{) 2 \quad -7 \quad +1 \quad +3} \\
 \underline{2 \quad -1 \quad -2 \quad -3}
 \end{array} \tag{22.3.5}$$

If we substitute symbols for the above quantities with the correspondence

$$\begin{array}{r}
 x \overline{) \begin{array}{cccc} c_0 & c_1 & c_2 & c_3 \\ P_0 & P_1 & P_2 & P_3 \end{array}}
 \end{array} \tag{22.3.6}$$

then it is immediately clear that the  $P_j$ 's in equation (22.3.6) are simply the  $P_j$ 's of equation (22.3.3); the calculation is thus parallelizable by recursive doubling. In this context, the utility routine `poly_term` is used by the routine `zroots` in Chapter B9.

## Repeated Synthetic Division

It is well known from high-school algebra that repeated synthetic division of a polynomial yields, as the remainders that occur, first the value of the polynomial, next the value of its first derivative, and then (up to multiplication by the factorial of an integer) the values of higher derivatives.

If you want to parallelize the calculation of the value of a polynomial and one or two of its derivatives, it is not unreasonable to evaluate equation (22.3.3), parallelized by recursive doubling, two or three times. Our routine `ddpoly` in Chapter B5 is meant for such use, and it does just this, as does the routine `laguer` in Chapter B9.

There are other cases, however, for which you want to perform repeated synthetic division and “go all the way,” until only a constant remains. For example, this is the preferred way of “shifting a polynomial,” that is, evaluating the coefficients of a polynomial in a variable  $y$  that differs from the original variable  $x$  by an additive constant. (The recipe `pcshft` has this as its assigned task.) By way of example, consider the polynomial  $3x^3 + x^2 + 4x + 7$ , and let us perform repeated synthetic division by a general monomial  $x - a$ . The conventional calculation then proceeds according to the following tableau, reading it in conventional lexical order (left-to-right and top-to-bottom):



$$\begin{array}{cccc}
 3 & & 1 & & 4 & & 7 \\
 \downarrow & & \downarrow & & \downarrow & & \downarrow \\
 3 & \xrightarrow{a} & 3a + 1 & \xrightarrow{a} & 3a^2 + a + 4 & \xrightarrow{a} & 3a^3 + a^2 + 4a + 7 \\
 \downarrow & & \downarrow & & \downarrow & & \\
 3 & \xrightarrow{a} & 6a + 1 & \xrightarrow{a} & 9a^2 + 2a + 4 & & \\
 \downarrow & & \downarrow & & & & \\
 3 & \xrightarrow{a} & 9a + 1 & & & & \\
 \downarrow & & & & & & \\
 3 & & & & & & 
 \end{array} \tag{22.3.7}$$

Here, each row (after the first) shows a synthetic division or, equivalently, evaluation of the cumulants of the polynomial whose coefficients are the preceding row. The results at the right edge of the rows are the values of the polynomial and (up to integer factorials) its three nonzero derivatives, or (equivalently, without factorials) coefficients of the shifted polynomial.

We could parallelize the calculation of each row of tableau (22.3.7) by recursive doubling. That is a lot of recursion, which incurs a nonnegligible overhead. A much better way of doing the calculation is to deform tableau (22.3.7) into the following equivalent tableau,

$$\begin{array}{cccccc}
 3 \longrightarrow & & 3 & & & & \\
 & & a \downarrow & \searrow & & & \\
 1 \longrightarrow & & 3a + 1 & & 3 & & \\
 & & a \downarrow & \searrow & a \downarrow & \searrow & \\
 4 \longrightarrow & & 3a^2 + a + 4 & & 6a + 1 & & 3 \\
 & & a \downarrow & \searrow & a \downarrow & \searrow & a \downarrow & \searrow \\
 7 \longrightarrow & & 3a^3 + a^2 + 4a + 7 & & 9a^2 + 2a + 4 & & 9a + 1 & & 3
 \end{array} \tag{22.3.8}$$

Now each row explicitly depends on only the previous row (and the given first column), so the rows can be calculated in turn by an explicit parallel expression, with no recursive calls needed. An example of coding (22.3.8) in Fortran 90 can be found in the routine `pcshft` in Chapter B5. (It is also possible to eliminate most of the multiplications in (22.3.8), at the expense of a much smaller number of divisions. We have not done this because of the necessity for then treating all possible divisions by zero as special cases. See [1] for details and references.)

Actually, the deformation of (22.3.7) into (22.3.8) is the same trick as was used in Volume 1, p. 167, for evaluating a polynomial and its derivative simultaneously, also generalized in the Fortran 77 implementation of the routine `ddpoly` (Chapter 5). In the Fortran 90 implementation of `ddpoly` (Chapter B5) we *don't* use this trick, but instead use `poly_term`, because, there, we want to parallelize over the length of the polynomial, not over the number of desired derivatives.

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Don't confuse the cases of *iterated* synthetic division, discussed here, with the simpler case of doing many simultaneous synthetic divisions. In the latter case, you can simply implement equation (22.3.3) serially, exactly as written, but with each operation being data-parallel across your problem set. (This case occurs in our routine `polcoe` in Chapter B3.)

### Polynomial Coefficients from Roots

A parallel calculation algorithmically very similar to (22.3.7) or (22.3.8) occurs when we want to find the coefficients of a polynomial  $P(x)$  from its roots  $r_1, \dots, r_N$ . For this, the tableau is

$$\begin{array}{rcc}
 & r_1 & \\
 r_2 : & \downarrow & \searrow \\
 & r_1 + r_2 & r_1 r_2 \\
 r_3 : & \downarrow & \searrow & \downarrow & \searrow \\
 & r_1 + r_2 + r_3 & r_1 r_2 + r_3(r_1 + r_2) & r_1 r_2 r_3
 \end{array} \quad (22.3.9)$$

As before, the rows are computed consecutively, from top to bottom. Each row is computed via a single parallel expression. Note that values moving on vertical arrows are simply added in, while values moving on diagonal arrows are multiplied by a new root before adding. Examples of coding (22.3.9) in Fortran 90 can be found in the routines `vander` (Chapter B2) and `polcoe` (Chapter B3).

An equivalent deformation of (22.3.9) is

$$\begin{array}{rcc}
 & r_1 & \\
 r_2 : & \downarrow & \searrow \\
 & r_1 r_2 & r_1 + r_2 \\
 r_3 : & \downarrow & \searrow & \downarrow & \searrow \\
 & r_1 r_2 r_3 & r_1 r_2 + r_3(r_1 + r_2) & r_1 + r_2 + r_3
 \end{array} \quad (22.3.10)$$

Here the diagonal arrows are simple additions, while the vertical arrows represent multiplication by a root value. Note that the coefficient answers in (22.3.10) come out in the opposite order from (22.3.9). An example of coding (22.3.10) in Fortran 90 can be found in the routine `fixrts` in Chapter B13.

#### CITED REFERENCES AND FURTHER READING:

Knuth, D.E. 1981, *Seminumerical Algorithms*, 2nd ed., vol. 2 of *The Art of Computer Programming* (Reading, MA: Addison-Wesley), §4.6.4, p. 470. [1]

## 22.4 Fast Fourier Transforms

Fast Fourier transforms are beloved by computer scientists, especially those who are interested in parallel algorithms, because the FFT's hierarchical structure generates a complicated, but analyzable, set of requirements for interprocessor communication on MMPs. Thus, almost all books on parallel algorithms (e.g., [1–3]) have a chapter on FFTs.

Unfortunately, the resulting algorithms are highly specific to particular parallel architectures, and therefore of little use to us in writing general purpose code in an architecture-independent parallel language like Fortran 90.

Luckily there is a good alternative that covers almost all cases of both serial and parallel machines. If, for a one-dimensional FFT of size  $N$ , one is satisfied with parallelism of order  $\sqrt{N}$ , then there is a good, general way of achieving a parallel FFT with *quite minimal* interprocessor communication; and the communication required is simply the matrix transpose operation, which Fortran 90 implements as an intrinsic. That is the approach that we discuss in this section, and implement in Chapter B12.

For a machine with  $M$  processors, this approach will saturate the processors (the desirable condition where none are idle) when the size of a one-dimensional Fourier transform,  $N$ , is large enough:  $N > M^2$ . Smaller  $N$ 's will not achieve maximum parallelism. But such  $N$ 's are in fact so small for one-dimensional problems that they are unlikely to be the rate-determining step in scientific calculations. If they are, it is usually because you are doing many such transforms independently, and you should recover “outer parallelism” by doing them all at once.

For two or more dimensions, the adopted approach will saturate  $M$  processors when *each* dimension of the problem is larger than  $M$ .

### Column- and Row-Parallel FFTs

The basic building block that we assume (and implement in Chapter B12) is a routine for simultaneously taking the FFT of each *row* of a two-dimensional matrix. The method is exactly that of Volume 1's `four1` routine, but with array sections like `data(:,j)` replacing scalars like `data(j)`. Chapter B12's implementation of this is a routine called `fourrow`. If all the data for one column (that is, all the values `data(i,:)`, for some  $i$ ) are local to a single processor, then the parallelism involves no interprocessor communication at all: The independent FFTs simply proceed, data parallel and in lockstep. This is architecture-independent parallelism with a vengeance.

We will also need to take the FFT of each *column* of a two-dimensional matrix. One way to do this is to take the transpose (a Fortran 90 intrinsic that hides a lot of interprocessor communication), then take the FFT of the rows using `fourrow`, then take the transpose again. An alternative method is to recode the `four1` routine with array sections in the other dimension (`data(j,:)`) replacing `four1`'s scalars (`data(j)`). This scheme, in Chapter B12, is a routine called `fourcol`. In this case, good parallelism will be achieved only if the values `data(:,i)`, for some  $i$ , are local to a single processor. Of course, Fortran 90 does not give the user direct control over how data are distributed over the machine; but extensions such as HPF are designed to give just such control.

On a serial machine, you might think that `fourrow` and `fourcol` should have identical timings (acting on a square matrix, say). The two routines do exactly the same operations, after all. Not so! On modern serial computers, `fourrow` and `fourcol` can have timings that differ by a factor of 2 or more, even when their detailed arithmetic is made identical (by giving to one a data array that is the transpose of the data array given to the other). This effect is due to the multilevel cache architecture of most computer memories, and the fact that serial Fortran always stores matrices by columns (first index changing most rapidly). On our workstations, `fourrow` is significantly faster than `fourcol`, and this is likely the generic behavior. However, we do not exclude the possibility that some machines, and some sizes of matrices, are the other way around.

### One-Dimensional FFTs

Turn now to the problem of how to do a single, one-dimensional, FFT. We are given a complex array  $f$  of length  $N$ , an integer power of 2. The basic idea is to address the input array as if it were a two-dimensional array of size  $m \times M$ , where  $m$  and  $M$  are each integer powers of 2. Then the components of  $f$  can be addressed as

$$f(Jm + j), \quad 0 \leq j < m, \quad 0 \leq J < M \quad (22.4.1)$$

where the  $j$  index changes more rapidly, the  $J$  index more slowly, and parentheses denote Fortran-style subscripts.

Now, suppose we had some magical (parallel) method to compute the discrete Fourier transform

$$F(kM + K) \equiv \sum_{j,J} e^{2\pi i(kM+K)(Jm+j)/(Mm)} f(Jm + j), \quad 0 \leq k < m, \quad 0 \leq K < M \quad (22.4.2)$$

Then, you can see that the indices  $k$  and  $K$  would address the desired result (FFT of the original array), with  $K$  varying more rapidly.

Starting with equation (22.4.2) it is easy to verify the following identity,

$$F(kM + K) = \sum_j \left[ e^{2\pi ijk/m} \left( e^{2\pi ijk/(Mm)} \left[ \sum_J e^{2\pi iJK/M} f(Jm + j) \right] \right) \right] \quad (22.4.3)$$

But this, reading it from the innermost operation outward, is just the magical method that we need:

- Reshape the original array to  $m \times M$  in Fortran normal order (storage by columns).
- FFT on the second (column) index for all values of the first (row) index, using the routine `fourrow`.
- Multiply each component by a phase factor  $\exp[2\pi ijk/(Mm)]$ .
- Transpose.

- Again FFT on the second (column) index for all values of the first (row) index, using the routine `fourrow`.
- Reshape the two-dimensional array back into one-dimensional output.

The above scheme uses `fourrow` exclusively, on the assumption that it is faster than its sibling `fourcol`. When that is the case (as we typically find), it is likely that the above method, implemented as `four1` in Chapter B12, is faster, even on scalar machines, than Volume 1's scalar version of `four1` (Chapter 12). The reason, as already mentioned, is that `fourrow`'s parallelism is taking better advantage of cache memory locality.

If `fourrow` is *not* faster than `fourcol` on your machine, then you should instead try the following alternative scheme, using `fourcol` only:

- Reshape the original array to  $m \times M$  in Fortran normal order (storage by columns).
- Transpose.
- FFT on the first (row) index for all values of the second (column) index, using the routine `fourcol`.
- Multiply each component by a phase factor  $\exp[2\pi i j K / (Mm)]$ .
- Transpose.
- Again FFT on the first (row) index for all values of the second (column) index, using the routine `fourcol`.
- Transpose.
- Reshape the two-dimensional array back into one-dimensional output.

In Chapter B12, this scheme is implemented as `four1_alt`. You might wonder why `four1_alt` has three transpose operations, while `four1` had only one. Shouldn't there be a symmetry here? No. Fortran makes the arbitrary, but consistent, choice of storing two-dimensional arrays by columns, and this choice favors `four1` in terms of transposes. Luckily, at least on our serial workstations, `fourrow` (used by `four1`) is faster than `fourcol` (used by `four1_alt`), so it is a double win.

For further discussion and references on the ideas behind `four1` and `four1_alt` see [4], where these algorithms are called the four-step and six-step frameworks, respectively.

#### CITED REFERENCES AND FURTHER READING:

- Fox, G.C., et al. 1988, *Solving Problems on Concurrent Processors*, Volume I (Englewood Cliffs, NJ: Prentice Hall), Chapter 11. [1]
- Akl, S.G. 1989, *The Design and Analysis of Parallel Algorithms* (Englewood Cliffs, NJ: Prentice Hall), Chapter 9. [2]
- Hockney, R.W., and Jesshope, C.R. 1988, *Parallel Computers 2* (Bristol and Philadelphia: Adam Hilger), §5.5. [3]
- Van Loan, C. 1992, *Computational Frameworks for the Fast Fourier Transform* (Philadelphia: S.I.A.M.), §3.3. [4]

## 22.5 Missing Language Features

A few facilities that are fairly important to parallel programming are missing from the Fortran 90 language standard. On scalar machines this lack is not a

problem, since one can readily program the missing features by using do-loops. On parallel machines, both SSP machines and MMP machines, one must hope that hardware manufacturers provide library routines, callable from Fortran 90, that provide access to the necessary facilities, or use extensions of Fortran 90, such as High Performance Fortran (HPF).

### Scatter-with-Combine Functions

Fortran 90 allows the use of *vector subscripts* for so-called *gather* and *scatter* operations. For example, with the setup

```
REAL(SP), DIMENSION(6) :: arr,barr,carr
INTEGER(I4B), DIMENSION(6) :: iarr,jarr
...
iarr = (/ 1,3,5,2,4,6 /)
jarr = (/ 3,2,3,2,1,1 /)
```

Fortran 90 allows both the *one-to-one* gather and the *one-to-many* gather,

```
barr=arr(iarr)
carr=arr(jarr)
```

It also allows the one-to-one scatter,

```
barr(iarr)=carr
```

where the elements of *carr* are “scattered” into *barr* under the direction of the vector subscript *iarr*.

Fortran 90 does *not* allow the *many-to-one* scatter

```
barr(jarr)=carr      ! illegal for this jarr
```

because the repeated values in *jarr* try to assign different components of *carr* to the same location in *barr*. The result would not be deterministic.

Sometimes, however, one would in fact like a many-to-one construction, where the colliding elements get combined by a (commutative and associative) operation, like + or \*, or *max()*. These so-called *scatter-with-combine* functions are readily implemented on serial machines by a do-loop, for example,

```
barr=0.
do j=1,size(carr)
  barr(jarr(j))=barr(jarr(j))+carr(j)
end do
```

Fortran 90 unfortunately provides no means for effecting scatter-with-combine functions in parallel. Luckily, almost all parallel machines do provide such a facility as a library program, as does HPF, where the above facility is called *SUM\_SCATTER*. In Chapter 23 we will define utility routines *scatter\_add* and *scatter\_max* for scatter-with-combine functionalities, but the implementation given in Fortran 90 will be strictly serial, with a do-loop.

## Skew Sections

Fortran 90 provides no good, parallel way to access the diagonal elements of a matrix, either to read them or to set them. Do-loops will obviously serve this need on serial machines. In principle, a construction like the following bizarre fragment could also be utilized,

```
REAL(SP), DIMENSION(n,n) :: mat
REAL(SP), DIMENSION(n*n) :: arr
REAL(SP), DIMENSION(n) :: diag
...
arr = reshape(mat, shape(arr))
diag = arr(1:n*n:n+1)
```

which extracts every  $(n + 1)$ st element from a one-dimensional array derived by reshaping the input matrix. However, it is unlikely that any foreseeable parallel compiler will implement the above fragment without a prohibitive amount of unnecessary data movement; and code like the above is also exceedingly slow on all serial machines that we have tried.

In Chapter 23 we will define utility routines `get_diag`, `put_diag`, `diagadd`, `diagmult`, and `unit_matrix` to manipulate diagonal elements, but the implementation given in Fortran 90 will again be strictly serial, with do-loops.

Fortran 95 (see §21.6) will essentially fix Fortran 90's skew sections deficiency. For example, using its `forall` construction, the diagonal elements of an array can be accessed by a statement like

```
forall (j=1:20) diag(j) = arr(j,j)
```

## SIMD vs. MIMD

Recall that we use “SIMD” (single-instruction, multiple data) and “data parallel” as interchangeable terms, and that “MIMD” (multiple-instruction, multiple data) is a more general programming model. (See §22.1.)

You should not be too quick to jump to the conclusion that Fortran 90's data parallel or SIMD model is “bad,” and that MIMD features, absent in Fortran 90, are therefore “good.” On the contrary, Fortran 90's basic data-parallel paradigm has a lot going for it. As we discussed in §22.1, most scientific problems naturally have a “data dimension” across which the time ordering of the calculation is irrelevant. Parallelism across this dimension, which is by nature most often SIMD, frees the mind to think clearly about the computational steps in an algorithm that actually need to be sequential. SIMD code has advantages of clarity and predictability that should not be taken lightly. The general MIMD model of “lots of different things all going on at the same time and communicating data with each other” is a programming and debugging nightmare.

Having said this, we must at the same time admit that a few MIMD features — most notably the ability to go through different logical branches for calculating different data elements in a data-parallel computation — are badly needed in certain programming situations. Fortran 90 is quite weak in this area.

Note that the `where . . . elsewhere . . . end where` construction is *not* a MIMD construction. Fortran 90 requires that the `where` clause be executed completely before the `elsewhere` is started. (This allows the results of any calculations in the former

clause to be available for use in the latter.) So, this construction cannot be used to allow two logical branches to be calculated in parallel.

Special functions, where one would like to calculate function values for an array of input quantities, are a particularly compelling example of the need for some MIMD access. Indeed, you will find that Chapter B6 contains a number of intricate, and in a few cases truly bizarre, workarounds, using allowed combinations of `merge`, `where`, and `CONTAINS` (the latter, for separating different logical branches into formally different subprograms).

Fortran 95's `ELEMENTAL` and `PURE` constructions, and to some extent also `forall` (whose body will be able to include `PURE` function calls), will go a long way towards providing exactly the kind of MIMD constructions that are most needed. Once Fortran 95 becomes available and widespread, you can expect to see a new version of this volume, with a much-improved Chapter B6.

Conversely, the number of routines outside of Chapter B6 that can be significantly improved by the use of MIMD features is relatively small; this illustrates the underlying viability of the basic data-parallel SIMD model, even in a future language version with useful MIMD features.



# Chapter 23. Numerical Recipes Utility Functions for Fortran 90

## 23.0 Introduction and Summary Listing

This chapter describes and summarizes the Numerical Recipes utility routines that are used throughout the rest of this volume. A complete implementation of these routines in Fortran 90 is listed in Appendix C1.

Why do we need utility routines? Aren't there already enough of them built into the language as Fortran 90 intrinsics? The answers lie in this volume's dual purpose: to implement the Numerical Recipes routines in Fortran 90 code that runs efficiently on fast serial machines, *and* to implement them, wherever possible, with efficient parallel code for multiprocessor machines that will become increasingly common in the future. We have found three kinds of situations where additional utility routines seem desirable:

1. Fortran 90 is a big language, with many high-level constructs — single statements that actually result in a lot of computing. We like this; it gives the language the potential for expressing algorithms very readably, getting them “out of the mud” of microscopic coding. In coding the 350+ Recipes for this volume, we kept a systematic watch for bits of microscopic coding that were repeated in many routines, and that seemed to be at a lower level of coding than that aspired to by good Fortran 90 style. Once these bits were identified, we pulled them out and substituted calls to new utility routines. These are the utilities that arguably ought to be new language intrinsics, equally useful for serial and parallel machines. (A prime example is `swap`.)
2. Fortran 90 contains many highly parallelizable language constructions. But, as we have seen in §22.5, it is also missing a few important constructions. Most parallel machines will provide these missing elements as machine-coded library subroutines. Some of our utility routines are provided simply as a standard interface to these common, but nonstandard, functionalities. Note that it is the nature of these routines that our specific implementation, in Appendix C1, will be serial, and therefore inefficient on parallel machines. If you have a parallel machine, you will need to recode these; this often involves no more than substituting a one-line library function call for the body of our implementation. Utilities in this category will likely become unnecessary over time, either as machine-dependent libraries converge to standard interfaces, or as the utilities get added to future Fortran

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versions. (Indeed, some routines in this category will be unnecessary in Fortran 95, once it is available; see §23.7.)

3. Some tasks should just be done differently in serial, versus parallel, implementation. Linear recurrence relations are a good example (§22.2). These are trivially coded with a do-loop on serial machines, but require a fairly elaborate recursive construction for good parallelization. Rather than provide separate serial and parallel versions of the Numerical Recipes, we have chosen to pull out of the Recipes, and into utility routines, some identifiable tasks of this kind. These are cases where some recoding of our implementation in Appendix C1 might result in improved performance on your particular hardware. Unfortunately, it is not so simple as providing a single “serial implementation” and another single “parallel implementation,” because even the seemingly simple word “serial” hides, at the hardware level, a variety of different degrees of pipelining, wide instructions, and so on. Appendix C1 therefore provides only a single implementation, although with some adjustable parameters that you can customize (by experiment) to maximize performance on your hardware.

The above three cases are not really completely distinct, and it is therefore not possible to assign any single utility routine to exactly one situation. Instead, we organize the rest of this chapter as follows: first, an alphabetical list, with short summary, of all the new utility routines; next, a series of short sections, grouped by functionality, that contain the detailed descriptions of the routines.

### Alphabetical Listing

The following list gives an abbreviated mnemonic for the type, rank, and/or shape of the returned values (as in §21.4), the routine’s calling sequence (optional arguments shown in italics), and a brief, often incomplete, description. The complete description of the routine is given in the later section shown in square brackets.

For each entry, the number shown in parentheses is the approximate number of distinct Recipes in this book that make use of that particular utility function, and is thus a rough guide to that utility’s importance. (There may be multiple invocations of the utility in each such Recipe.) Where this number is small or zero, it is usually because the utility routine is a member of a related family of routines whose total usage was deemed significant enough to include, and we did not want users to have to “guess” which family members were instantiated.

```
call array_copy(src,dest,n_copied,n_not_copied)
    Copy one-dimensional array (whose size is not necessarily known).
    [23.1] (9)
```

```
[Arr] arth(first,increment,n)
    Return an arithmetic progression as an array. [23.4] (55)
```

```
call assert(n1,n2,...,string)
    Exit with error message if any logical arguments are false. [23.3] (50)
```

```
[Int] assert_eq(n1,n2,...,string)
    Exit with error message if all integer arguments are not equal; otherwise
    return common value. [23.3] (133)
```

```
[argTS] cumprod(arr,seed)
```

- Cumulative products of one-dimensional array, with optional seed value. [23.4] (3)
- [argTS] `cumsum(arr, seed)`  
Cumulative sums of one-dimensional array, with optional seed value. [23.4] (9)
- `call diagadd(mat, diag)`  
Adds vector to diagonal of a matrix. [23.7] (4)
- `call diagsmult(mat, diag)`  
Multiplies vector into diagonal of a matrix. [23.7] (2)
- [Arr] `geop(first, factor, n)`  
Return a geometrical progression as an array. [23.4] (7)
- [Arr] `get_diag(mat)`  
Gets diagonal of a matrix. [23.7] (2)
- [Int] `ifirstloc(arr)`  
Location of first true value in a logical array, returned as an integer. [23.2] (3)
- [Int] `imaxloc(arr)`  
Location of array maximum, returned as an integer. [23.2] (11)
- [Int] `iminloc(arr)`  
Location of array minimum, returned as an integer. [23.2] (8)
- [Mat] `lower_triangle(j, k, extra)`  
Returns a lower triangular logical mask. [23.7] (1)
- `call nrerror(string)`  
Exit with error message. [23.3] (96)
- [Mat] `outerand(a, b)`  
Returns the outer logical and of two vectors. [23.5] (1)
- [Mat] `outerdiff(a, b)`  
Returns the outer difference of two vectors. [23.5] (4)
- [Mat] `outerdiv(a, b)`  
Returns the outer quotient of two vectors. [23.5] (0)
- [Mat] `outerprod(a, b)`  
Returns the outer product of two vectors. [23.5] (14)
- [Mat] `outersum(a, b)`  
Returns the outer sum of two vectors. [23.5] (0)
- [argTS] `poly(x, coeffs, mask)`  
Evaluate a polynomial  $P(x)$  for one or more values  $x$ , with optional mask. [23.4] (15)
- [argTS] `poly_term(a, x)`  
Returns partial cumulants of a polynomial, equivalent to synthetic

- division. [23.4] (4)
- call `put_diag(diag,mat)`  
Sets diagonal of a matrix. [23.7] (0)
- [Ptr] `realloc(p,n,m,...)`  
Reallocate pointer to new size, preserving its contents. [23.1] (5)
- call `scatter_add(dest,source,dest_index)`  
Scatter-adds source vector to specified components of destination vector. [23.6] (2)
- call `scatter_max(dest,source,dest_index)`  
Scatter-max source vector to specified components of destination vector. [23.6] (0)
- call `swap(a,b,mask)`  
Swap corresponding elements of a and b. [23.1] (24)
- call `unit_matrix(mat)`  
Sets matrix to be a unit matrix. [23.7] (6)
- [Mat] `upper_triangle(j,k,extra)`  
Returns an upper triangular logical mask. [23.7] (4)
- [Real] `vabs(v)`  
Length of a vector in  $L_2$  norm. [23.8] (6)
- [CArr] `zroots_unity(n,nn)`  
Returns nn consecutive powers of the complex nth root of unity. [23.4] (4)

### Comment on Relative Frequencies of Use

We find it interesting to compare our frequency of using the `nrutil` utility routines, with our most used language intrinsics (see §21.4). On this basis, the following routines are as useful to us as the *top 10* language intrinsics: `arith`, `assert`, `assert_eq`, `outerprod`, `poly`, and `swap`. We strongly recommend that the X3J3 standards committee, as well as individual compiler library implementors, consider the inclusion of new language intrinsics (or library routines) that subsume the capabilities of at least these routines. In the next tier of importance, we would put some further cumulative operations (`geop`, `cumsum`), some other “outer” operations on vectors (e.g., `outerdiff`), basic operations on the diagonals of matrices (`get_diag`, `put_diag`, `diag_add`), and some means of access to an array of unknown size (`array_copy`).

## 23.1 Routines That Move Data

To describe our utility routines, we introduce two items of Fortran 90 pseudocode: We use the symbol **T** to denote some type and rank declaration (including

scalar rank, i.e., zero); and when we append a colon to a type specification, as in `INTEGER(I4B) (:)`, for example, we denote an array of the given type.

The routines `swap`, `array_copy`, and `reallocate` simply move data around in useful ways.

\* \* \*

**swap** (swaps corresponding elements)

*User interface (or, "USE nrutil"):*

```
SUBROUTINE swap(a,b,mask)
  T, INTENT(INOUT) :: a,b
  LOGICAL(LGT), INTENT(IN), OPTIONAL :: mask
END SUBROUTINE swap
```

*Applicable types and ranks:*

**T**  $\equiv$  any type, any rank

*Types and ranks implemented (overloaded) in nrutil:*

```
T  $\equiv$  INTEGER(I4B), REAL(SP), REAL(SP) (:), REAL(DP),
      COMPLEX(SPC), COMPLEX(SPC) (:), COMPLEX(SPC) (:,:),
      COMPLEX(DPC), COMPLEX(DPC) (:), COMPLEX(DPC) (:,:)
```

*Action:*

Swaps the corresponding elements of `a` and `b`. If `mask` is present, performs the swap only where `mask` is true. (Following code is the unmasked case. For speed at run time, the masked case is implemented by overloading, not by testing for the optional argument.)

*Reference implementation:*

```
T :: dum
dum=a
a=b
b=dum
```

\* \* \*

**array\_copy** (copy one-dimensional array)

*User interface (or, "USE nrutil"):*

```
SUBROUTINE array_copy(src,dest,n_copied,n_not_copied)
  T, INTENT(IN) :: src
  T, INTENT(OUT) :: dest
  INTEGER(I4B), INTENT(OUT) :: n_copied, n_not_copied
END SUBROUTINE array_copy
```

*Applicable types and ranks:*

**T**  $\equiv$  any type, rank 1

*Types and ranks implemented (overloaded) in nrutil:*

```
T  $\equiv$  INTEGER(I4B) (:), REAL(SP) (:), REAL(DP) (:)
```

*Action:*

Copies to a destination array `dest` the one-dimensional array `src`, or as much of `src` as will fit in `dest`. Returns the number of components copied as `n_copied`, and the number of components not copied as `n_not_copied`.

The main use of this utility is where `src` is an expression that returns an array whose size is not known in advance, for example, the value returned by the `pack` intrinsic.

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*Reference implementation:*

```
n_copied=min(size(src),size(dest))
n_not_copied=size(src)-n_copied
dest(1:n_copied)=src(1:n_copied)
```

\* \* \*

**reallocate** (reallocate a pointer, preserving contents)

*User interface (or, "USE nrutil"):*

```
FUNCTION reallocate(p,n[,m,...])
  T, POINTER :: p, reallocate
  INTEGER(I4B), INTENT(IN) :: n[,m,...]
END FUNCTION reallocate
```

*Applicable types and ranks:*

**T** ≡ any type, rank 1 or greater

*Types and ranks implemented (overloaded) in nrutil:*

```
T ≡ INTEGER(I4B)(:), INTEGER(I4B)(:,:), REAL(SP)(:),
      REAL(SP)(:,:), CHARACTER(1)(:)
```

*Action:*

Allocates storage for a new array with shape specified by the integer(s) *n*, *m*, ... (equal in number to the rank of pointer *p*). Then, copies the contents of *p*'s target (or as much as will fit) into the new storage. Then, deallocates *p* and returns a pointer to the new storage.

The typical use is `p=reallocate(p,n[,m,...])`, which has the effect of changing the allocated size of *p* while preserving the contents.

The reference implementation, below, shows only the case of rank 1.

*Reference implementation:*

```
INTEGER(I4B) :: nold,ierr
allocate(reallocate(n),stat=ierr)
if (ierr /= 0) call &
  nrerror('reallocate: problem in attempt to allocate memory')
if (.not. associated(p)) RETURN
nold=size(p)
reallocate(1:min(nold,n))=p(1:min(nold,n))
deallocate(p)
```

## 23.2 Routines Returning a Location

Fortran 90's intrinsics `maxloc` and `minloc` return rank-one arrays. When, in the most frequent usage, their argument is a one-dimensional array, the answer comes back in the inconvenient form of an array containing a single component, which cannot be itself used in a subscript calculation. While there are workaround tricks (e.g., use of the `sum` intrinsic to convert the array to a scalar), it seems clearer to define routines `imaxloc` and `iminloc` that return integers directly.

The routine `ifirstloc` adds a related facility missing among the intrinsics: Return the first true location in a logical array.

\* \* \*

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**imaxloc** (location of array maximum as an integer)

*User interface (or, “USE nrutil”):*

```
FUNCTION imaxloc(arr)
  T, INTENT(IN) :: arr
  INTEGER(I4B) :: imaxloc
END FUNCTION imaxloc
```

*Applicable types and ranks:*

**T** ≡ any integer or real type, rank 1

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ INTEGER(I4B)(:), REAL(SP)(:)

*Action:*

For one-dimensional arrays, identical to the `maxloc` intrinsic, except returns its answer as an integer rather than as `maxloc`'s somewhat awkward rank-one array containing a single component.

*Reference implementation:*

```
INTEGER(I4B), DIMENSION(1) :: imax
imax=maxloc(arr(:))
imaxloc=imax(1)
```

\* \* \*

**iminloc** (location of array minimum as an integer)

*User interface (or, “USE nrutil”):*

```
FUNCTION iminloc(arr)
  T, INTENT(IN) :: arr
  INTEGER(I4B) :: iminloc
END FUNCTION iminloc
```

*Applicable types and ranks:*

**T** ≡ any integer or real type, rank 1

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ REAL(SP)(:)

*Action:*

For one-dimensional arrays, identical to the `minloc` intrinsic, except returns its answer as an integer rather than as `minloc`'s somewhat awkward rank-one array containing a single component.

*Reference implementation:*

```
INTEGER(I4B), DIMENSION(1) :: imin
imin=minloc(arr(:))
iminloc=imin(1)
```

\* \* \*

**ifirstloc** (returns location of first “true” in a logical vector)

*User interface (or, “USE nrutil”):*

```
FUNCTION ifirstloc(mask)
  T, INTENT(IN) :: mask
  INTEGER(I4B) :: ifirstloc
END FUNCTION ifirstloc
```

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*Applicable types and ranks:*

**T**  $\equiv$  any logical type, rank 1

*Types and ranks implemented (overloaded) in nrutil:*

**T**  $\equiv$  LOGICAL(LGT)

*Action:*

Returns the index (subscript value) of the first location, in a one-dimensional logical mask, that has the value `.TRUE.`, or returns `size(mask)+1` if all components of mask are `.FALSE.`

Note that while the reference implementation uses a do-loop, the function is parallelized in `nrutil` by instead using the `merge` and `maxloc` intrinsics.

*Reference implementation:*

```
INTEGER(I4B) :: i
do i=1,size(mask)
  if (mask(i)) then
    ifirstloc=i
    return
  end if
end do
ifirstloc=i
```

## 23.3 Argument Checking and Error Handling

It is good programming practice for a routine to check the assumptions (“assertions”) that it makes about the sizes of input arrays, allowed range of numerical arguments, and so forth. The routines `assert` and `assert_eq` are meant for this kind of use. The routine `nrerror` is our default error reporting routine.

\* \* \*

**assert** (exit with error message if any assertion is false)

*User interface (or, “USE nrutil”):*

```
SUBROUTINE assert(n1,n2,...,string)
CHARACTER(LEN=*) , INTENT(IN) :: string
LOGICAL , INTENT(IN) :: n1,n2,...
END SUBROUTINE assert
```

*Action:*

Embedding program dies gracefully with an error message if any of the logical arguments are false. Typical use is with logical expressions as the actual arguments. `nrutil` implements and overloads forms with 1, 2, 3, and 4 logical arguments, plus a form with a vector logical argument,

```
LOGICAL , DIMENSION(:) , INTENT(IN) :: n
that is checked by the all(n) intrinsic.
```

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*Reference implementation:*

```

if (.not. (n1.and.n2.and...)) then
  write (*,*) 'nrerror: an assertion failed with this tag:', string
  STOP 'program terminated by assert'
end if

```

\* \* \*

**assert\_eq** (exit with error message if integer arguments not all equal)*User interface (or, "USE nrutil"):*

```

FUNCTION assert_eq(n1,n2,n3,...,string)
CHARACTER(LEN=*), INTENT(IN) :: string
INTEGER, INTENT(IN) :: n1,n2,n3,...
INTEGER :: assert_eq
END FUNCTION assert_eq

```

*Action:*

Embedding program dies gracefully with an error message if any of the integer arguments are not equal to the first. Otherwise, return the value of the first argument. Typical use is for enforcing equality on the sizes of arrays passed to a subprogram. `nrutil` implements and overloads forms with 1, 2, 3, and 4 integer arguments, plus a form with a vector integer argument,

```

INTEGER, DIMENSION(:), INTENT(IN) :: n
that is checked by the conditional if (all(nn(2:)==nn(1))).

```

*Reference implementation:*

```

if (n1==n2.and.n2==n3.and...) then
  assert_eq=n1
else
  write (*,*) 'nrerror: an assert_eq failed with this tag:', string
  STOP 'program terminated by assert_eq'
end if

```

\* \* \*

**nrerror** (report error message and stop)*User interface (or, "USE nrutil"):*

```

SUBROUTINE nrerror(string)
CHARACTER(LEN=*), INTENT(IN) :: string
END SUBROUTINE nrerror

```

*Action:*

This is the minimal error handler used in this book. In applications of any complexity, it is intended only as a placeholder for a user's more complicated error handling strategy.

*Reference implementation:*

```

write (*,*) 'nrerror: ',string
STOP 'program terminated by nrerror'

```

## 23.4 Routines for Polynomials and Recurrences

Apart from programming convenience, these routines are designed to allow for nontrivial parallel implementations, as discussed in §22.2 and §22.3.

\* \* \*

**arth** (returns arithmetic progression as an array)

*User interface (or, "USE nrutil"):*

```
FUNCTION arth(first,increment,n)
  T, INTENT(IN) :: first,increment
  INTEGER(I4B), INTENT(IN) :: n
  T, DIMENSION(n) [or, 1 rank higher than T]:: arth
END FUNCTION arth
```

*Applicable types and ranks:*

**T** ≡ any numerical type, any rank

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ INTEGER(I4B), REAL(SP), REAL(DP)

*Action:*

Returns an array of length *n* containing an arithmetic progression whose first value is *first* and whose increment is *increment*. If *first* and *increment* have rank greater than zero, returns an array of one larger rank, with the last subscript having size *n* and indexing the progressions. Note that the following reference implementation (for the scalar case) is definitional only, and neither parallelized nor optimized for roundoff error. See §22.2 and Appendix C1 for implementation by subvector scaling.

*Reference implementation:*

```
INTEGER(I4B) :: k
if (n > 0) arth(1)=first
do k=2,n
  arth(k)=arth(k-1)+increment
end do
```

\* \* \*

**geop** (returns geometric progression as an array)

*User interface (or, "USE nrutil"):*

```
FUNCTION geop(first,factor,n)
  T, INTENT(IN) :: first,factor
  INTEGER(I4B), INTENT(IN) :: n
  T, DIMENSION(n) [or, 1 rank higher than T]:: geop
END FUNCTION geop
```

*Applicable types and ranks:*

**T** ≡ any numerical type, any rank

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ INTEGER(I4B), REAL(SP), REAL(DP), REAL(DP)(:),  
COMPLEX(SPC)

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*Action:*

Returns an array of length *n* containing a geometric progression whose first value is *first* and whose multiplier is *factor*. If *first* and *factor* have rank greater than zero, returns an array of one larger rank, with the last subscript having size *n* and indexing the progression. Note that the following reference implementation (for the scalar case) is definitional only, and neither parallelized nor optimized for roundoff error. See §22.2 and Appendix C1 for implementation by subvector scaling.

*Reference implementation:*

```
INTEGER(I4B) :: k
if (n > 0) geop(1)=first
do k=2,n
  geop(k)=geop(k-1)*factor
end do
```

\* \* \*

**cumsum** (cumulative sum on an array, with optional additive seed)

*User interface (or, "USE nrutil"):*

```
FUNCTION cumsum(arr,seed)
  T, DIMENSION(:), INTENT(IN) :: arr
  T, OPTIONAL, INTENT(IN) :: seed
  T, DIMENSION(size(arr)), INTENT(OUT) :: cumsum
END FUNCTION cumsum
```

*Applicable types and ranks:*

**T** ≡ any numerical type

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ INTEGER(I4B), REAL(SP)

*Action:*

Given the rank 1 array *arr* of type **T**, returns an array of identical type and size containing the cumulative sums of *arr*. If the optional argument *seed* is present, it is added to the first component (and therefore, by cumulation, all components) of the result. See §22.2 for parallelization ideas.

*Reference implementation:*

```
INTEGER(I4B) :: n,j
T :: sd
n=size(arr)
if (n == 0) return
sd=0.0
if (present(seed)) sd=seed
cumsum(1)=arr(1)+sd
do j=2,n
  cumsum(j)=cumsum(j-1)+arr(j)
end do
```

\* \* \*

**cumprod** (cumulative prod on an array, with optional multiplicative seed)

*User interface (or, "USE nrutil"):*

```
FUNCTION cumprod(arr,seed)
  T, DIMENSION(:), INTENT(IN) :: arr
  T, OPTIONAL, INTENT(IN) :: seed
  T, DIMENSION(size(arr)), INTENT(OUT) :: cumprod
END FUNCTION cumprod
```

*Applicable types and ranks:*

**T**  $\equiv$  any numerical type

*Types and ranks implemented (overloaded) in nrutil:*

**T**  $\equiv$  REAL(SP)

*Action:*

Given the rank 1 array **arr** of type **T**, returns an array of identical type and size containing the cumulative products of **arr**. If the optional argument **seed** is present, it is multiplied into the first component (and therefore, by cumulation, into all components) of the result. See §22.2 for parallelization ideas.

*Reference implementation:*

```

INTEGER(I4B) :: n, j
T :: sd
n=size(arr)
if (n == 0) return
sd=1.0
if (present(seed)) sd=seed
cumprod(1)=arr(1)*sd
do j=2,n
    cumprod(j)=cumprod(j-1)*arr(j)
end do

```

\* \* \*

## **poly** (polynomial evaluation)

*User interface (or, "USE nrutil"):*

```

FUNCTION poly(x, coeffs, mask)
T, , DIMENSION(:,...), INTENT(IN) :: x
T, DIMENSION(:), INTENT(IN) :: coeffs
LOGICAL(LGT), DIMENSION(:,...), OPTIONAL, INTENT(IN) :: mask
T :: poly
END FUNCTION poly

```

*Applicable types and ranks:*

**T**  $\equiv$  any numerical type (**x** may be scalar or have any rank; **x** and **coeffs** may have different numerical types)

*Types and ranks implemented (overloaded) in nrutil:*

**T**  $\equiv$  various combinations of REAL(SP), REAL(SP)(:), REAL(DP), REAL(DP)(:), COMPLEX(SPC) (see Appendix C1 for details)

*Action:*

Returns a scalar value or array with the same type and shape as **x**, containing the result of evaluating the polynomial with one-dimensional coefficient vector **coeffs** on each component of **x**. The optional argument **mask**, if present, has the same shape as **x**, and suppresses evaluation of the polynomial where its components are **.false..** The following reference code shows the case where **mask** is not present. (The other case can be included by overloading.)

*Reference implementation:*

```

INTEGER(I4B) :: i,n
n=size(coeffs)
if (n <= 0) then
  poly=0.0
else
  poly=coeffs(n)
  do i=n-1,1,-1
    poly=x*poly+coeffs(i)
  end do
end if

```

\* \* \*

**poly\_term** (partial cumulants of a polynomial)

*User interface (or, "USE nrutil"):*

```

FUNCTION poly_term(a,x)
T, DIMENSION(:), INTENT(IN) :: a
T, INTENT(IN) :: x
T, DIMENSION(size(a)) :: poly_term
END FUNCTION poly_term

```

*Applicable types and ranks:*

**T** ≡ any numerical type

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ REAL(SP), COMPLEX(SPC)

*Action:*

Returns an array of type and size the same as the one-dimensional array *a*, containing the partial cumulants of the polynomial with coefficients *a* (arranged from highest-order to lowest-order coefficients, n.b.) evaluated at *x*. This is equivalent to synthetic division, and can be parallelized. See §22.3. Note that the order of arguments is reversed in *poly* and *poly\_term* — each routine returns a value with the size and shape of the *first* argument, the usual Fortran 90 convention.

*Reference implementation:*

```

INTEGER(I4B) :: n,j
n=size(a)
if (n <= 0) return
poly_term(1)=a(1)
do j=2,n
  poly_term(j)=a(j)+x*poly_term(j-1)
end do

```

\* \* \*

**roots\_unity** (returns powers of complex *n*th root of unity)

*User interface (or, "USE nrutil"):*

```

FUNCTION roots_unity(n,nn)
INTEGER(I4B), INTENT(IN) :: n,nn
COMPLEX(SPC), DIMENSION(nn) :: roots_unity
END FUNCTION roots_unity

```

*Action:*

Returns a complex array containing *nn* consecutive powers of the *n*th complex root of unity. Note that the following reference implementation is definitional only, and neither parallelized nor optimized for roundoff error. See Appendix C1 for implementation by subvector scaling.

*Reference implementation:*

```

INTEGER(I4B) :: k
REAL(SP) :: theta
if (nn==0) return
zroots_unity(1)=1.0
if (nn==1) return
theta=TWOPI/n
zroots_unity(2)=cplx(cos(theta),sin(theta))
do k=3,nn
  zroots_unity(k)=zroots_unity(k-1)*zroots_unity(2)
end do

```

## 23.5 Routines for Outer Operations on Vectors

Outer operations on vectors take two vectors as input, and return a matrix as output. One dimension of the matrix is the size of the first vector, the other is the size of the second vector. Our convention is always the standard one,

$$\text{result}(i,j) = \text{first\_operand}(i) \text{ (op) } \text{second\_operand}(j)$$

where (*op*) is any of addition, subtraction, multiplication, division, and logical and. The reason for coding these as utility routines is that Fortran 90's native construction, with two spreads (cf. §22.1), is difficult to read and thus prone to programmer errors.

\* \* \*

### **outerprod** (outer product)

*User interface (or, "USE nrutil"):*

```

FUNCTION outerprod(a,b)
  T, DIMENSION(:), INTENT(IN) :: a,b
  T, DIMENSION(size(a),size(b)) :: outerprod
END FUNCTION outerprod

```

*Applicable types and ranks:*

**T** ≡ any numerical type

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ REAL(SP), REAL(DP)

*Action:*

Returns a matrix that is the outer product of two vectors.

*Reference implementation:*

```

outerprod = spread(a,dim=2,ncopies=size(b)) * &
  spread(b,dim=1,ncopies=size(a))

```

\* \* \*

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**outerdiv** (outer quotient)*User interface (or, "USE nrutil"):*

```

FUNCTION outerdiv(a,b)
  T, DIMENSION(:), INTENT(IN) :: a,b
  T, DIMENSION(size(a),size(b)) :: outerdiv
END FUNCTION outerdiv

```

*Applicable types and ranks:***T** ≡ any numerical type*Types and ranks implemented (overloaded) in nrutil:***T** ≡ REAL (SP)*Action:*

Returns a matrix that is the outer quotient of two vectors.

*Reference implementation:*

```

outerdiv = spread(a,dim=2,ncopies=size(b)) / &
  spread(b,dim=1,ncopies=size(a))

```

\* \* \*

**outersum** (outer sum)*User interface (or, "USE nrutil"):*

```

FUNCTION outersum(a,b)
  T, DIMENSION(:), INTENT(IN) :: a,b
  T, DIMENSION(size(a),size(b)) :: outersum
END FUNCTION outersum

```

*Applicable types and ranks:***T** ≡ any numerical type*Types and ranks implemented (overloaded) in nrutil:***T** ≡ REAL (SP)*Action:*

Returns a matrix that is the outer sum of two vectors.

*Reference implementation:*

```

outersum = spread(a,dim=2,ncopies=size(b)) + &
  spread(b,dim=1,ncopies=size(a))

```

\* \* \*

**outerdiff** (outer difference)*User interface (or, "USE nrutil"):*

```

FUNCTION outerdiff(a,b)
  T, DIMENSION(:), INTENT(IN) :: a,b
  T, DIMENSION(size(a),size(b)) :: outerdiff
END FUNCTION outerdiff

```

*Applicable types and ranks:***T** ≡ any numerical type*Types and ranks implemented (overloaded) in nrutil:***T** ≡ INTEGER (I4B), REAL (SP), REAL (DP)*Action:*

Returns a matrix that is the outer difference of two vectors.

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*Reference implementation:*

```
outerdiff = spread(a,dim=2,ncopies=size(b)) - &
           spread(b,dim=1,ncopies=size(a))
```

\* \* \*

**outerand** (outer logical and)

*User interface (or, "USE nrutil"):*

```
FUNCTION outerand(a,b)
  LOGICAL(LGT), DIMENSION(:), INTENT(IN) :: a,b
  LOGICAL(LGT), DIMENSION(size(a),size(b)) :: outerand
END FUNCTION outerand
```

*Applicable types and ranks:*

**T** ≡ any logical type

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ LOGICAL(LGT)

*Action:*

Returns a matrix that is the outer logical and of two vectors.

*Reference implementation:*

```
outerand = spread(a,dim=2,ncopies=size(b)) .and. &
           spread(b,dim=1,ncopies=size(a))
```

## 23.6 Routines for Scatter with Combine

These are common parallel functions that Fortran 90 simply doesn't provide a means for implementing. If you have a parallel machine, you should substitute library routines specific to your hardware.

\* \* \*

**scatter\_add** (scatter-add source to specified components of destination)

*User interface (or, "USE nrutil"):*

```
SUBROUTINE scatter_add(dest,source,dest_index)
  T, DIMENSION(:), INTENT(OUT) :: dest
  T, DIMENSION(:), INTENT(IN) :: source
  INTEGER(I4B), DIMENSION(:), INTENT(IN) :: dest_index
END SUBROUTINE scatter_add
```

*Applicable types and ranks:*

**T** ≡ any numerical type

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ REAL(SP), REAL(DP)

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*Action:*

Adds each component of the array *source* into a component of *dest* specified by the index array *dest\_index*. (The user will usually have zeroed *dest* before the call to this routine.) Note that *dest\_index* has the size of *source*, but must contain values in the range from 1 to *size(dest)*, inclusive. Out-of-range values are ignored. There is no parallel implementation of this routine accessible from Fortran 90; most parallel machines supply an implementation as a library routine.

*Reference implementation:*

```

INTEGER(I4B) :: m,n,j,i
n=assert_eq(size(source),size(dest_index),'scatter_add')
m=size(dest)
do j=1,n
  i=dest_index(j)
  if (i > 0 .and. i <= m) dest(i)=dest(i)+source(j)
end do

```

\* \* \*

**scatter\_max** (scatter-max source to specified components of destination)*User interface (or, "USE nrutil"):*

```

SUBROUTINE scatter_max(dest,source,dest_index)
  T, DIMENSION(:), INTENT(OUT) :: dest
  T, DIMENSION(:), INTENT(IN) :: source
  INTEGER(I4B), DIMENSION(:), INTENT(IN) :: dest_index
END SUBROUTINE scatter_max

```

*Applicable types and ranks:*

**T** ≡ any integer or real type

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ REAL(SP), REAL(DP)

*Action:*

Takes the max operation between each component of the array *source* and a component of *dest* specified by the index array *dest\_index*, replacing that component of *dest* with the value obtained ("maxing into" operation). (The user will often want to fill the array *dest* with the value *-huge* before the call to this routine.) Note that *dest\_index* has the size of *source*, but must contain values in the range from 1 to *size(dest)*, inclusive. Out-of-range values are ignored. There is no parallel implementation of this routine accessible from Fortran 90; most parallel machines supply an implementation as a library routine.

*Reference implementation:*

```

INTEGER(I4B) :: m,n,j,i
n=assert_eq(size(source),size(dest_index),'scatter_max')
m=size(dest)
do j=1,n
  i=dest_index(j)
  if (i > 0 .and. i <= m) dest(i)=max(dest(i),source(j))
end do

```

## 23.7 Routines for Skew Operations on Matrices

These are also missing parallel capabilities in Fortran 90. In Appendix C1 they are coded serially, with one or more do-loops.

\* \* \*

**diagadd** (adds vector to diagonal of a matrix)

*User interface (or, "USE nrutil"):*

```
SUBROUTINE diagadd(mat,diag)
  T, DIMENSION(:,,:), INTENT(INOUT) :: mat
  T, DIMENSION(:), INTENT(IN) :: diag
END SUBROUTINE diagadd
```

*Applicable types and ranks:*

**T** ≡ any numerical type

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ REAL (SP)

*Action:*

The argument *diag*, either a scalar or else a vector whose size must be the smaller of the two dimensions of matrix *mat*, is added to the diagonal of the matrix *mat*. The following shows an implementation where *diag* is a vector; the scalar case can be overloaded (see Appendix C1).

*Reference implementation:*

```
INTEGER(I4B) :: j,n
n = assert_eq(size(diag),min(size(mat,1),size(mat,2)), 'diagadd')
do j=1,n
  mat(j,j)=mat(j,j)+diag(j)
end do
```

\* \* \*

**diagmult** (multiplies vector into diagonal of a matrix)

*User interface (or, "USE nrutil"):*

```
SUBROUTINE diagmult(mat,diag)
  T, DIMENSION(:,,:), INTENT(INOUT) :: mat
  T, DIMENSION(:), INTENT(IN) :: diag
END SUBROUTINE diagmult
```

*Applicable types and ranks:*

**T** ≡ any numerical type

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ REAL (SP)

*Action:*

The argument *diag*, either a scalar or else a vector whose size must be the smaller of the two dimensions of matrix *mat*, is multiplied onto the diagonal of the matrix *mat*. The following shows an implementation where *diag* is a vector; the scalar case can be overloaded (see Appendix C1).

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*Reference implementation:*

```

INTEGER(I4B) :: j,n
n = assert_eq(size(diag),min(size(mat,1),size(mat,2)), 'diagmult')
do j=1,n
  mat(j,j)=mat(j,j)*diag(j)
end do

```

\* \* \*

**get\_diag** (gets diagonal of matrix)

*User interface (or, "USE nrutil"):*

```

FUNCTION get_diag(mat)
T, DIMENSION(:,:), INTENT(IN) :: mat
T, DIMENSION(min(size(mat,1),size(mat,2))) :: get_diag
END FUNCTION get_diag

```

*Applicable types and ranks:*

**T** ≡ any type

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ REAL (SP), REAL (DP)

*Action:*

Returns a vector containing the diagonal values of the matrix mat.

*Reference implementation:*

```

INTEGER(I4B) :: j
do j=1,min(size(mat,1),size(mat,2))
  get_diag(j)=mat(j,j)
end do

```

\* \* \*

**put\_diag** (sets the diagonal elements of a matrix)

*User interface (or, "USE nrutil"):*

```

SUBROUTINE put_diag(diag,mat)
T, DIMENSION(:), INTENT(IN) :: diag
T, DIMENSION(:,:), INTENT(INOUT) :: mat
END SUBROUTINE put_diag

```

*Applicable types and ranks:*

**T** ≡ any type

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ REAL (SP)

*Action:*

Sets the diagonal of matrix mat equal to the argument diag, either a scalar or else a vector whose size must be the smaller of the two dimensions of matrix mat. The following shows an implementation where diag is a vector; the scalar case can be overloaded (see Appendix C1).

*Reference implementation:*

```

INTEGER(I4B) :: j,n
n=assert_eq(size(diag),min(size(mat,1),size(mat,2)), 'put_diag')
do j=1,n
  mat(j,j)=diag(j)
end do

```

\* \* \*

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**unit\_matrix** (returns a unit matrix)

*User interface (or, "USE nrutil"):*

```
SUBROUTINE unit_matrix(mat)
  T, DIMENSION(:, :), INTENT(OUT) :: mat
END SUBROUTINE unit_matrix
```

*Applicable types and ranks:*

**T** ≡ any numerical type

*Types and ranks implemented (overloaded) in nrutil:*

**T** ≡ REAL (SP)

*Action:*

Sets the diagonal components of **mat** to unity, all other components to zero. When **mat** is square, this will be the unit matrix; otherwise, a unit matrix with appended rows or columns of zeros.

*Reference implementation:*

```
INTEGER(I4B) :: i,n
n=min(size(mat,1),size(mat,2))
mat(:, :)=0.0
do i=1,n
  mat(i,i)=1.0
end do
```

\* \* \*

**upper\_triangle** (returns an upper triangular mask)

*User interface (or, "USE nrutil"):*

```
FUNCTION upper_triangle(j,k,extra)
  INTEGER(I4B), INTENT(IN) :: j,k
  INTEGER(I4B), OPTIONAL, INTENT(IN) :: extra
  LOGICAL(LGT), DIMENSION(j,k) :: upper_triangle
END FUNCTION upper_triangle
```

*Action:*

When the optional argument **extra** is zero or absent, returns a logical mask of shape  $(j, k)$  whose values are true above and to the right of the diagonal, false elsewhere (including on the diagonal). When **extra** is present and positive, a corresponding number of additional (sub-)diagonals are returned as true. (**extra** = 1 makes the main diagonal return true.) When **extra** is present and negative, it suppresses a corresponding number of superdiagonals.

*Reference implementation:*

```
INTEGER(I4B) :: n,jj,kk
n=0
if (present(extra)) n=extra
do jj=1,j
  do kk=1,k
    upper_triangle(jj,kk)= (jj-kk < n)
  end do
end do
```

\* \* \*

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**lower\_triangle** (returns a lower triangular mask)

*User interface (or, “USE nrutil”):*

```
FUNCTION lower_triangle(j,k,extra)
  INTEGER(I4B), INTENT(IN) :: j,k
  INTEGER(I4B), OPTIONAL, INTENT(IN) :: extra
  LOGICAL(LGT), DIMENSION(j,k) :: lower_triangle
END FUNCTION lower_triangle
```

*Action:*

When the optional argument `extra` is zero or absent, returns a logical mask of shape  $(j, k)$  whose values are true below and to the left of the diagonal, false elsewhere (including on the diagonal). When `extra` is present and positive, a corresponding number of additional (super-)diagonals are returned as true. (`extra = 1` makes the main diagonal return true.) When `extra` is present and negative, it suppresses a corresponding number of subdiagonals.

*Reference implementation:*

```
INTEGER(I4B) :: n,jj,kk
n=0
if (present(extra)) n=extra
do jj=1,j
  do kk=1,k
    lower_triangle(jj,kk)= (kk-jj < n)
  end do
end do
```

Fortran 95’s `forall` construction will make the parallel implementation of all our skew operations utilities extremely simple. For example, the `do-loop` in `diagadd` will collapse to

```
forall (j=1:n) mat(j,j)=mat(j,j)+diag(j)
```

In fact, this implementation is so simple as to raise the question of whether a separate utility like `diagadd` will be needed at all. There are valid arguments on both sides of this question: The “con” argument, against a routine like `diagadd`, is that it is just another reserved name that you have to remember (if you want to use it). The “pro” argument is that a separate routine avoids the “index pollution” (the opposite disease from “index loss” discussed in §22.1) of introducing a superfluous variable `j`, and that a separate utility allows for additional error checking on the sizes and compatibility of its arguments. We expect that different programmers will have differing tastes.

The argument for keeping a routine like `upper_triangle` or `lower_triangle`, once Fortran 95’s `masked forall` constructions become available, is less persuasive. We recommend that you consider these two routines as placeholders for “remember to recode this in Fortran 95, someday.”

## 23.8 Other Routine(s)

You might argue that we don’t really need a routine for the idiom

```
sqrt(dot_product(v,v))
```

You might be right. The ability to overload the complex case, with its additional complex conjugate, is an argument in its favor, however.

\* \* \*

**vabs** ( $L_2$  norm of a vector)

*User interface (or, "USE nrutil"):*

```
FUNCTION vabs(v)
  T, DIMENSION(:), INTENT(IN) :: v
  T :: vabs
END FUNCTION vabs
```

*Applicable types and ranks:*

**T**  $\equiv$  any real or complex type

*Types and ranks implemented (overloaded) in nrutil:*

**T**  $\equiv$  REAL (SP)

*Action:*

Returns the length of a vector  $v$  in  $L_2$  norm, that is, the square root of the sum of the squares of the components. (For complex types, the `dot_product` should be between the vector and its complex conjugate.)

*Reference implementation:*

```
vabs=sqrt(dot_product(v,v))
```

## Fortran 90 Code Chapters B1–B20

Fortran 90 versions of all the Numerical Recipes routines appear in the following Chapters B1 through B20, numbered in correspondence with Chapters 1 through 20 in Volume 1. Within each chapter, the routines appear in the same order as in Volume 1, but not broken out separately by section number within Volume 1's chapters.

There are commentaries accompanying many of the routines, generally following the printed listing of the routine to which they apply. These are of two kinds: issues related to parallelizing the algorithm in question, and issues related to the Fortran 90 implementation. To distinguish between these two, rather different, kinds of discussions, we use the two icons,



the left icon (above) indicating a “parallel note,” and the right icon denoting a “Fortran 90 tip.” Specific code segments of the routine that are discussed in these commentaries are singled out by reproducing some of the code as an “index line” next to the icon, or at the beginning of subsequent paragraphs if there are several items that are commented on.

`d=merge(FPMIN,d,abs(d)<FPMIN)` This would be the start of a discussion of code that begins at the line in the listing containing the indicated code fragment.

\* \* \*

A row of stars, like the above, is used between unrelated routines, or at the beginning and end of related groups of routines.

Some chapters contain discussions that are more general than commentary on individual routines, but that were deemed too specific for inclusion in Chapters 21 through 23. Here are some highlights of this additional material:

- Approximations to roots of orthogonal polynomials for parallel computation of Gaussian quadrature formulas (Chapter B4)
- Difficulty of, and tricks for, parallel calculation of special function values in a SIMD model of computation (Chapter B6)
- Parallel random number generation (Chapter B7)
- Fortran 90 tricks for dealing with ties in sorted arrays, counting things in boxes, etc. (Chapter B14)
- Use of recursion in implementing multigrid elliptic PDE solvers (Chapter B19)

## Chapter B1. Preliminaries

```
SUBROUTINE flmoon(n,nph,jd,frac)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n,nph
INTEGER(I4B), INTENT(OUT) :: jd
REAL(SP), INTENT(OUT) :: frac

Our programs begin with an introductory comment summarizing their purpose and explain-
ing their calling sequence. This routine calculates the phases of the moon. Given an integer
n and a code nph for the phase desired (nph = 0 for new moon, 1 for first quarter, 2 for
full, 3 for last quarter), the routine returns the Julian Day Number jd, and the fractional
part of a day frac to be added to it, of the nth such phase since January, 1900. Greenwich
Mean Time is assumed.

REAL(SP), PARAMETER :: RAD=PI/180.0_sp
INTEGER(I4B) :: i
REAL(SP) :: am,as,c,t,t2,xtra
c=n+nph/4.0_sp
t=c/1236.85_sp
t2=t**2
as=359.2242_sp+29.105356_sp*c
am=306.0253_sp+385.816918_sp*c+0.010730_sp*t2
jd=2415020+28*n+7*nph
xtra=0.75933_sp+1.53058868_sp*c+(1.178e-4_sp-1.55e-7_sp*t)*t2
select case(nph)
case(0,2)
xtra=xtra+(0.1734_sp-3.93e-4_sp*t)*sin(RAD*as)-0.4068_sp*sin(RAD*am)
case(1,3)
xtra=xtra+(0.1721_sp-4.0e-4_sp*t)*sin(RAD*as)-0.6280_sp*sin(RAD*am)
case default
call nrerror('flmoon: nph is unknown')
end select
i=int(merge(xtra,xtra-1.0_sp, xtra >= 0.0))
jd=jd+i
frac=xtra-i
END SUBROUTINE flmoon
```

**f**<sub>90</sub> select case(nph)...case(0,2)...end select Fortran 90 includes a case construction that executes at most one of several blocks of code, depending on the value of an integer, logical, or character expression. Ideally, the case construction will execute more efficiently than a long sequence of cascaded if...else if...else if... constructions. C programmers should note that the Fortran 90 construction, perhaps mercifully, does not have C's “drop-through” feature.

merge(xtra,xtra-1.0\_sp, xtra >= 0.0) The merge construction in Fortran 90, while intended primarily for use with vector arguments, is also a convenient way of generating conditional scalar expressions, that is, expressions with one value, or another, depending on the result of a logical test.

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When the arguments of a merge are vectors, parallelization by the compiler is straightforward as an array parallel operation (see p. 964).

Less obvious is how the scalar case, as above, is handled. For small-scale parallel (SSP) machines, the natural gain is via speculative evaluation of both of the first two arguments simultaneously with evaluation of the test.

A good compiler should not penalize a scalar machine for use of either the scalar or vector merge construction. The Fortran 90 standard states that “it is not necessary for a processor to evaluate all of the operands of an expression, or to evaluate entirely each operand, if the value of the expression can be determined otherwise.” Therefore, for each test on a scalar machine, only one or the other of the first two argument components need be evaluated.

\* \* \*

```

FUNCTION julday(mm,id,iyyy)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: mm,id,iyyy
INTEGER(I4B) :: julday
    In this routine julday returns the Julian Day Number that begins at noon of the calendar
    date specified by month mm, day id, and year iyyy, all integer variables. Positive year
    signifies A.D.; negative, B.C. Remember that the year after 1 B.C. was 1 A.D.
INTEGER(I4B), PARAMETER :: IGREG=15+31*(10+12*1582)    Gregorian Calendar adopted
INTEGER(I4B) :: ja,jm,jy                                Oct. 15, 1582.
jy=iyyy
if (jy == 0) call nrerror('julday: there is no year zero')
if (jy < 0) jy=jy+1
if (mm > 2) then                                       Here is an example of a block IF-structure.
    jm=mm+1
else
    jy=jy-1
    jm=mm+13
end if
julday=int(365.25_sp*jy)+int(30.6001_sp*jm)+id+1720995
if (id+31*(mm+12*iyyy) >= IGREG) then                Test whether to change to Gregorian Cal-
    ja=int(0.01_sp*jy)                                endar.
    julday=julday+2-ja+int(0.25_sp*ja)
end if
END FUNCTION julday

```

\* \* \*

```

PROGRAM badluk
USE nrtype
USE nr, ONLY : flmoon,julday
IMPLICIT NONE
INTEGER(I4B) :: ic,icon,idwk,ifrac,im,iyyy,jd,jday,n
INTEGER(I4B) :: iybeg=1900,iyend=2000    The range of dates to be searched.
REAL(SP) :: frac
REAL(SP), PARAMETER :: TIMZON=-5.0_sp/24.0_sp
    Time zone -5 is Eastern Standard Time.
write (*,'(1x,a,i5,a,i5)') 'Full moons on Friday the 13th from',&
    iybeg,' to',iyend
do iyyy=iybeg,iyend                                  Loop over each year,
do im=1,12                                           and each month.
    jday=julday(im,13,iyyy)                          Is the 13th a Friday?
    idwk=mod(jday+1,7)

```

```

if (idwk == 5) then
  n=12.37_sp*(iyyy-1900+(im-0.5_sp)/12.0_sp)
  This value n is a first approximation to how many full moons have occurred
  since 1900. We will feed it into the phase routine and adjust it up or down until
  we determine that our desired 13th was or was not a full moon. The variable
  icon signals the direction of adjustment.
  icon=0
  do
    call flmoon(n,2,jd,frac)      Get date of full moon n.
    ifrac=nint(24.0_sp*(frac+TIMZON))  Convert to hours in correct time
    if (ifrac < 0) then          zone.
      jd=jd-1                    Convert from Julian Days beginning at noon
      ifrac=ifrac+24             to civil days beginning at midnight.
    end if
    if (ifrac > 12) then
      jd=jd+1
      ifrac=ifrac-12
    else
      ifrac=ifrac+12
    end if
    if (jd == jday) then        Did we hit our target day?
      write (*,'(1x,i2,a,i2,a,i4)') im,'/',13,'/',iyyy
      write (*,'(1x,a,i2,a)') 'Full moon ',ifrac,&
        ' hrs after midnight (EST).'
      Don't worry if you are unfamiliar with FORTRAN's esoteric input/output
      statements; very few programs in this book do any input/output.
      exit                      Part of the break-structure, case of a match.
    else
      Didn't hit it.
      ic=isign(1,jday-jd)
      if (ic == -icon) exit      Another break, case of no match.
      icon=ic
      n=n+ic
    end if
  end do
end if
end do
END PROGRAM badluk

```

**f90** ...IGREG=15+31\*(10+12\*1582) (in julday), ...TIMZON=-5.0\_sp/24.0\_sp (in badluk) These are two examples of initialization expressions for “named constants” (that is, PARAMETERS). Because the initialization expressions will generally be evaluated at compile time, Fortran 90 puts some restrictions on what kinds of intrinsic functions they can contain. Although the evaluation of a real expression like  $-5.0\_sp/24.0\_sp$  *ought* to give identical results at compile time and at execution time, all the way down to the least significant bit, in our opinion the conservative programmer shouldn't count on strict identity at the level of floating-point roundoff error. (In the special case of *cross*-compilers, such roundoff-level discrepancies between compile time and run time are almost inevitable.)

\* \* \*

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```

SUBROUTINE caldat(julian,mm,id,iyyy)
USE nrtype
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: julian
INTEGER(I4B), INTENT(OUT) :: mm,id,iyyy
    Inverse of the function julday given above. Here julian is input as a Julian Day Number,
    and the routine outputs mm,id, and iyyy as the month, day, and year on which the specified
    Julian Day started at noon.
INTEGER(I4B) :: ja,jalpha,jb,jc,jd,je
INTEGER(I4B), PARAMETER :: IGREG=2299161
if (julian >= IGREG) then          Cross-over to Gregorian Calendar produces this
    jalpha=int(((julian-1867216)-0.25_sp)/36524.25_sp)    correction.
    ja=julian+1+jalpha-int(0.25_sp*jalpha)
else if (julian < 0) then          Make day number positive by adding integer num-
    ja=julian+36525*(1-julian/36525)    ber of Julian centuries, then subtract them
else                                off at the end.
    ja=julian
end if
jb=ja+1524
jc=int(6680.0_sp+((jb-2439870)-122.1_sp)/365.25_sp)
jd=365*jc+int(0.25_sp*jc)
je=int((jb-jd)/30.6001_sp)
id=jb-jd-int(30.6001_sp*je)
mm=je-1
if (mm > 12) mm=mm-12
iyyy=jc-4715
if (mm > 2) iyyy=iyyy-1
if (iyyy <= 0) iyyy=iyyy-1
if (julian < 0) iyyy=iyyy-100*(1-julian/36525)
END SUBROUTINE caldat

```

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## Chapter B2. Solution of Linear Algebraic Equations

```

SUBROUTINE gaussj(a,b)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror,outerand,outerprod,swap
IMPLICIT NONE
REAL(SP), DIMENSION(:,:) , INTENT(INOUT) :: a,b
  Linear equation solution by Gauss-Jordan elimination, equation (2.1.1). a is an  $N \times N$  input
  coefficient matrix. b is an  $N \times M$  input matrix containing  $M$  right-hand-side vectors. On
  output, a is replaced by its matrix inverse, and b is replaced by the corresponding set of
  solution vectors.
INTEGER(I4B), DIMENSION(size(a,1)) :: ipiv,indxr,indx
  These arrays are used for bookkeeping on the pivoting.
LOGICAL(LGT), DIMENSION(size(a,1)) :: lpiv
REAL(SP) :: pivinv
REAL(SP), DIMENSION(size(a,1)) :: dumc
INTEGER(I4B), TARGET :: irc(2)
INTEGER(I4B) :: i,1,n
INTEGER(I4B), POINTER :: irow,icol
n=assert_eq(size(a,1),size(a,2),size(b,1),'gaussj')
irow => irc(1)
icol => irc(2)
ipiv=0
do i=1,n
  Main loop over columns to be reduced.
  lpiv = (ipiv == 0)      Begin search for a pivot element.
  irc=maxloc(abs(a),outerand(lpiv,lpiv))
  ipiv(icol)=ipiv(icol)+1
  if (ipiv(icol) > 1) call nrerror('gaussj: singular matrix (1)')
  We now have the pivot element, so we interchange rows, if needed, to put the pivot
  element on the diagonal. The columns are not physically interchanged, only relabeled:
  indx(i), the column of the ith pivot element, is the ith column that is reduced, while
  indxr(i) is the row in which that pivot element was originally located. If indxr(i)  $\neq$ 
  indx(i) there is an implied column interchange. With this form of bookkeeping, the
  solution b's will end up in the correct order, and the inverse matrix will be scrambled
  by columns.
  if (irow /= icol) then
    call swap(a(irow,:),a(icol,:))
    call swap(b(irow,:),b(icol,:))
  end if
  indxr(i)=irow      We are now ready to divide the pivot row by the pivot
  indx(i)=icol      element, located at irow and icol.
  if (a(icol,icol) == 0.0) &
    call nrerror('gaussj: singular matrix (2)')
  pivinv=1.0_sp/a(icol,icol)
  a(icol,icol)=1.0
  a(icol,:)=a(icol,:)*pivinv
  b(icol,:)=b(icol,:)*pivinv
  dumc=a(:,icol)
  Next, we reduce the rows, except for the pivot one, of
  a(:,icol)=0.0      course.
end do

```

```

a(icol,icol)=pivinv
a(1:icol-1,:)=a(1:icol-1,)-outerprod(dumc(1:icol-1),a(icol,:))
b(1:icol-1,:)=b(1:icol-1,)-outerprod(dumc(1:icol-1),b(icol,:))
a(icol+1,:)=a(icol+1,)-outerprod(dumc(icol+1:),a(icol,:))
b(icol+1,:)=b(icol+1,)-outerprod(dumc(icol+1:),b(icol,:))
end do
It only remains to unscramble the solution in view of the column interchanges. We do this
by interchanging pairs of columns in the reverse order that the permutation was built up.
do l=n,1,-1
  call swap(a(:,indxr(l)),a(:,indxc(l)))
end do
END SUBROUTINE gaussj

```

**f90** `irow => irc(1) ... icol => irc(2)` The `maxloc` intrinsic returns the location of the maximum value of an array as an integer array, in this case of size 2. Pre-pointing pointer variables to components of the array that will be thus set makes possible convenient references to the desired row and column positions.

`irc=maxloc(abs(a),outerand(lpiv,lpiv))` The combination of `maxloc` and one of the `outer...` routines from `nrutil` allows for a very concise formulation. If this task is done with loops, it becomes the ungainly “flying vee,”

```

aa=0.0
do i=1,n
  if (lpiv(i)) then
    do j=1,n
      if (lpiv(j)) then
        if (abs(a(i,j)) > aa) then
          aa=abs(a(i,j))
          irow=i
          icol=j
        endif
      endif
    end do
  end do
end do

```

`call swap(a(irow,:),a(icol,:))` The `swap` routine (in `nrutil`) is concise and convenient. Fortran 90’s ability to overload multiple routines onto a single name is vital here: Much of the convenience would vanish if we had to remember variant routine names for each variable type and rank of object that might be swapped.

Even better, here, than overloading would be if Fortran 90 allowed user-written *elemental* procedures (procedures with unspecified or arbitrary rank and shape), like the intrinsic elemental procedures built into the language. Fortran 95 will, but Fortran 90 doesn’t.



One quick (if superficial) test for how much parallelism is achieved in a Fortran 90 routine is to count its `do`-loops, and compare that number to the number of `do`-loops in the Fortran 77 version of the same routine. Here, in `gaussj`, 13 `do`-loops are reduced to 2.

```

a(1:icol-1,:)=... b(1:icol-1,:)=...
a(icol+1,:)=... b(icol+1,:)=...

```

Here the same operation is applied to every row of *a*, and to every row of *b*, *except* row number *icol*. On a massively multiprocessor (MMP) machine it would be better to use a logical mask and do all of *a* in a single statement, all of *b* in another one. For a small-scale parallel (SSP) machine, the lines as written should saturate the machine's concurrency, and they avoid the additional overhead of testing the mask.

This would be a good place to point out, however, that linear algebra routines written in Fortran 90 are likely *never* to be competitive with the hand-coded library routines that are generally supplied as part of MMP programming environments. If you are using our routines instead of library routines written specifically for your architecture, you are wasting cycles!

\* \* \*

```


SUBROUTINE ludcmp(a,indx,d)
USE nrtype; USE nrutil, ONLY : assert_eq,imaxloc,nrerror,outerprod,swap
IMPLICIT NONE
REAL(SP), DIMENSION(:, :), INTENT(INOUT) :: a
INTEGER(I4B), DIMENSION(:), INTENT(OUT) :: indx
REAL(SP), INTENT(OUT) :: d
    Given an  $N \times N$  input matrix a, this routine replaces it by the LU decomposition of a
    rowwise permutation of itself. On output, a is arranged as in equation (2.3.14); indx is an
    output vector of length N that records the row permutation effected by the partial pivoting;
    d is output as  $\pm 1$  depending on whether the number of row interchanges was even or odd,
    respectively. This routine is used in combination with lubksb to solve linear equations or
    invert a matrix.
REAL(SP), DIMENSION(size(a,1)) :: vv          vv stores the implicit scaling of each row.
REAL(SP), PARAMETER :: TINY=1.0e-20_sp       A small number.
INTEGER(I4B) :: j,n,imax
n=assert_eq(size(a,1),size(a,2),size(indx),'ludcmp')
d=1.0                                          No row interchanges yet.
vv=maxval(abs(a),dim=2)                       Loop over rows to get the implicit scaling
if (any(vv == 0.0)) call nrerror('singular matrix in ludcmp') information.
    There is a row of zeros.
vv=1.0_sp/vv                                  Save the scaling.
do j=1,n
    imax=(j-1)+imaxloc(vv(j:n)*abs(a(j:n,j))) Find the pivot row.
    if (j /= imax) then                       Do we need to interchange rows?
        call swap(a(imax,:),a(j,:))         Yes, do so...
        d=-d                                 ...and change the parity of d.
        vv(imax)=vv(j)                       Also interchange the scale factor.
    end if
    indx(j)=imax
    if (a(j,j) == 0.0) a(j,j)=TINY
        If the pivot element is zero the matrix is singular (at least to the precision of the al-
        gorithm). For some applications on singular matrices, it is desirable to substitute TINY
        for zero.
    a(j+1:n,j)=a(j+1:n,j)/a(j,j)             Divide by the pivot element.
    a(j+1:n,j+1:n)=a(j+1:n,j+1:n)-outerprod(a(j+1:n,j),a(j,j+1:n))
        Reduce remaining submatrix.
end do
END SUBROUTINE ludcmp

```

**f90** `vv=maxval(abs(a),dim=2)` A single statement finds the maximum absolute value in each row. Fortran 90 intrinsics like `maxval` generally “do their thing” in the dimension specified by *dim* and return a result with a shape corresponding to the *other* dimensions. Thus, here, *vv*'s size is that of the *first* dimension of *a*.

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`imax=(j-1)+imaxloc(vv(j:n)*abs(a(j:n,j)))` Here we see why the `nutil` routine `imaxloc` is handy: We want the index, in the range `1:n` of a quantity to be searched for only in the limited range `j:n`. Using `imaxloc`, we just add back the proper offset of `j-1`. (Using only Fortran 90 intrinsics, we could write `imax=(j-1)+sum(maxloc(vv(j:n)*abs(a(j:n,j))))`, but the use of `sum` just to turn an array of length 1 into a scalar seems sufficiently confusing as to be avoided.)



`a(j+1:n,j+1:n)=a(j+1:n,j+1:n)-outerprod(a(j+1:n,j),a(j,j+1:n))`  
The Fortran 77 version of `ludcmp`, using Crout's algorithm for the reduction, does not parallelize well: The elements are updated by  $O(N^2)$  separate dot product operations in a particular order. Here we use a slightly different reduction, termed "outer product Gaussian elimination" by Golub and Van Loan [1], that requires just  $N$  steps of matrix-parallel reduction. (See their §3.2.3 and §3.2.9 for the algorithm, and their §3.4.1 to understand how the pivoting is performed.)

We use `nutil`'s routine `outerprod` instead of the more cumbersome pure Fortran 90 construction:


```
spread(a(j+1:n,j),dim=2,ncopies=n-j)*spread(a(j,j+1:n),dim=1,ncopies=n-j)
```

```
SUBROUTINE lubksb(a,indx,b)
USE nrtype; USE nutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:, :), INTENT(IN) :: a
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: indx
REAL(SP), DIMENSION(:), INTENT(INOUT) :: b
  Solves the set of  $N$  linear equations  $A \cdot X = B$ . Here the  $N \times N$  matrix a is input, not
  as the original matrix  $A$ , but rather as its  $LU$  decomposition, determined by the routine
  ludcmp. indx is input as the permutation vector of length  $N$  returned by ludcmp. b is
  input as the right-hand-side vector  $B$ , also of length  $N$ , and returns with the solution vector
   $X$ . a and indx are not modified by this routine and can be left in place for successive calls
  with different right-hand sides b. This routine takes into account the possibility that b will
  begin with many zero elements, so it is efficient for use in matrix inversion.
INTEGER(I4B) :: i,n,ii,ll
REAL(SP) :: summ
n=assert_eq(size(a,1),size(a,2),size(indx),'lubksb')
ii=0
do i=1,n
  ll=indx(i)
  summ=b(ll)
  b(ll)=b(i)
  if (ii /= 0) then
    summ=summ-dot_product(a(i,ii:i-1),b(ii:i-1))
  else if (summ /= 0.0) then
    ii=i
  end if
  b(i)=summ
end do
do i=n,1,-1
  b(i) = (b(i)-dot_product(a(i,i+1:n),b(i+1:n)))/a(i,i)
end do
END SUBROUTINE lubksb
```

When `ii` is set to a positive value, it will become the index of the first nonvanishing element of `b`. We now do the forward substitution, equation (2.3.6). The only new wrinkle is to unscramble the permutation as we go.

A nonzero element was encountered, so from now on we will have to do the dot product above.

Now we do the backsubstitution, equation (2.3.7).



Conceptually, the search for the first nonvanishing element of `b` (index `ii`) should be moved out of the first `do`-loop. However, in practice, the need to unscramble the permutation, and also considerations of performance

on scalar machines, cause us to write this very scalar-looking code. The performance penalty on parallel machines should be minimal.

\* \* \*

Serial and parallel algorithms for tridiagonal problems are quite different. We therefore provide separate routines `tridag_ser` and `tridag_par`. In the MODULE `nr` interface file, one or the other of these (your choice) is given the generic name `tridag`. Of course, *either* version will work correctly on any computer; it is only a question of efficiency. See §22.2 for the numbering of the equation coefficients, and for a description of the parallel algorithm.

```

SUBROUTINE tridag_ser(a,b,c,r,u)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: a,b,c,r
REAL(SP), DIMENSION(:), INTENT(OUT) :: u
    Solves for a vector u of size N the tridiagonal linear set given by equation (2.4.1) using a
    serial algorithm. Input vectors b (diagonal elements) and r (right-hand sides) have size N,
    while a and c (off-diagonal elements) are size N - 1.
REAL(SP), DIMENSION(size(b)) :: gam      One vector of workspace, gam is needed.
INTEGER(I4B) :: n,j
REAL(SP) :: bet
n=assert_eq((/size(a)+1,size(b),size(c)+1,size(r),size(u)/),'tridag_ser')
bet=b(1)
if (bet == 0.0) call nrerror('tridag_ser: Error at code stage 1')
    If this happens then you should rewrite your equations as a set of order N - 1, with u2
    trivially eliminated.
u(1)=r(1)/bet
do j=2,n                                Decomposition and forward substitution.
    gam(j)=c(j-1)/bet
    bet=b(j)-a(j-1)*gam(j)
    if (bet == 0.0) &                    Algorithm fails; see below routine in Vol. 1.
        call nrerror('tridag_ser: Error at code stage 2')
    u(j)=(r(j)-a(j-1)*u(j-1))/bet
end do
do j=n-1,1,-1                            Backsubstitution.
    u(j)=u(j)-gam(j+1)*u(j+1)
end do
END SUBROUTINE tridag_ser

RECURSIVE SUBROUTINE tridag_par(a,b,c,r,u)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
USE nr, ONLY : tridag_ser
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: a,b,c,r
REAL(SP), DIMENSION(:), INTENT(OUT) :: u
    Solves for a vector u of size N the tridiagonal linear set given by equation (2.4.1) using a
    parallel algorithm. Input vectors b (diagonal elements) and r (right-hand sides) have size
    N, while a and c (off-diagonal elements) are size N - 1.
INTEGER(I4B), PARAMETER :: NPAR_TRIDAG=4    Determines when serial algorithm is in-
INTEGER(I4B) :: n,n2,nm,nx                  voked.
REAL(SP), DIMENSION(size(b)/2) :: y,q,piva
REAL(SP), DIMENSION(size(b)/2-1) :: x,z
REAL(SP), DIMENSION(size(a)/2) :: pivc
n=assert_eq((/size(a)+1,size(b),size(c)+1,size(r),size(u)/),'tridag_par')
if (n < NPAR_TRIDAG) then
    call tridag_ser(a,b,c,r,u)
else
    if (maxval(abs(b(1:n))) == 0.0) &        Algorithm fails; see below routine in Vol. 1.

```

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```

    call nrerror('tridag_par: possible singular matrix')
    n2=size(y)
    nm=size(pivc)
    nx=size(x)
    piva = a(1:n-1:2)/b(1:n-1:2)           Zero the odd a's and even c's, giving x,
    pivc = c(2:n-1:2)/b(3:n:2)             y, z, q.
    y(1:nm) = b(2:n-1:2)-piva(1:nm)*c(1:n-2:2)-pivc*a(2:n-1:2)
    q(1:nm) = r(2:n-1:2)-piva(1:nm)*r(1:n-2:2)-pivc*r(3:n:2)
    if (nm < n2) then
        y(n2) = b(n)-piva(n2)*c(n-1)
        q(n2) = r(n)-piva(n2)*r(n-1)
    end if
    x = -piva(2:n2)*a(2:n-2:2)
    z = -pivc(1:nx)*c(3:n-1:2)
    call tridag_par(x,y,z,q,u(2:n:2))      Recurse and get even u's.
    u(1) = (r(1)-c(1)*u(2))/b(1)          Substitute and get odd u's.
    u(3:n-1:2) = (r(3:n-1:2)-a(2:n-2:2)*u(2:n-2:2) &
        -c(3:n-1:2)*u(4:n:2))/b(3:n-1:2)
    if (nm == n2) u(n)=(r(n)-a(n-1)*u(n-1))/b(n)
end if
END SUBROUTINE tridag_par

```

**f90** The serial version `tridag_ser` is called when the routine has recursed its way down to sufficiently small subproblems. The point at which this occurs is determined by the parameter `NPAR_TRIDAG` whose optimal value is likely machine-dependent. Notice that `tridag_ser` must here be called by its specific name, not by the generic `tridag` (which might itself be overloaded with either `tridag_ser` or `tridag_par`).

\* \* \*

```

SUBROUTINE banmul(a,m1,m2,x,b)
USE nrtype; USE nrutil, ONLY : assert_eq, arth
IMPLICIT NONE
REAL(SP), DIMENSION(:, :), INTENT(IN) :: a
INTEGER(I4B), INTENT(IN) :: m1, m2
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(OUT) :: b
    Matrix multiply  $\mathbf{b} = \mathbf{A} \cdot \mathbf{x}$ , where  $\mathbf{A}$  is band diagonal with  $m1$  rows below the diagonal and  $m2$  rows above. If the input vector  $\mathbf{x}$  and output vector  $\mathbf{b}$  are of length  $N$ , then the array  $\mathbf{a}(1:N, 1:m1+m2+1)$  stores  $\mathbf{A}$  as follows: The diagonal elements are in  $\mathbf{a}(1:N, m1+1)$ . Subdiagonal elements are in  $\mathbf{a}(j:N, 1:m1)$  (with  $j > 1$  appropriate to the number of elements on each subdiagonal). Superdiagonal elements are in  $\mathbf{a}(1:j, m1+2:m1+m2+1)$  with  $j < N$  appropriate to the number of elements on each superdiagonal.
INTEGER(I4B) :: m, n
n=assert_eq(size(a,1),size(b),size(x),'banmul: n')
m=assert_eq(size(a,2),m1+m2+1,'banmul: m')
b=sum(a*eoshift(spread(x,dim=2,ncopies=m), &
    dim=1,shift=arth(-m1,1,m)),dim=2)
END SUBROUTINE banmul

```

**f90** `b=sum(a*eoshift(spread(x,dim=2,ncopies=m), &`  
`dim=1,shift=arth(-m1,1,m)),dim=2)`

This is a good example of Fortran 90 at both its best and its worst: best, because it allows quite subtle combinations of fully parallel operations to be built up; worst, because the resulting code is virtually incomprehensible!

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What is going on becomes clearer if we imagine a temporary array  $y$  with a declaration like `REAL(SP), DIMENSION(size(a,1),size(a,2)) :: y`. Then, the above single line decomposes into

```
y=spread(x,dim=2,ncopies=m)           [Duplicate x into columns of y.]
y=eoshift(y,dim=1,shift=arth(-m1,1,m)) [Shift columns by a linear progression.]
b=sum(a*y,dim=2)                       [Multiply by the band-diagonal elements,
                                         and sum.]
```

We use here a relatively rare subcase of the `eoshift` intrinsic, using a vector value for the `shift` argument to accomplish the simultaneous shifting of a bunch of columns, by different amounts (here specified by the linear progression returned by `arth`).

If you still don't see how this accomplishes the multiplication of a band diagonal matrix by a vector, work through a simple example by hand.

```
SUBROUTINE bandec(a,m1,m2,al,indx,d)
USE nrtype; USE nrutil, ONLY : assert_eq,imaxloc,swap,arth
IMPLICIT NONE
REAL(SP), DIMENSION(:,,:), INTENT(INOUT) :: a
INTEGER(I4B), INTENT(IN) :: m1,m2
REAL(SP), DIMENSION(:,,:), INTENT(OUT) :: al
INTEGER(I4B), DIMENSION(:), INTENT(OUT) :: indx
REAL(SP), INTENT(OUT) :: d
REAL(SP), PARAMETER :: TINY=1.0e-20_sp
  Given an  $N \times N$  band diagonal matrix  $A$  with  $m1$  subdiagonal rows and  $m2$  superdiagonal
  rows, compactly stored in the array  $a(1:N, 1:m1+m2+1)$  as described in the comment for
  routine banmul, this routine constructs an  $LU$  decomposition of a rowwise permutation of
   $A$ . The upper triangular matrix replaces  $a$ , while the lower triangular matrix is returned in
   $al(1:N, 1:m1)$ .  $indx$  is an output vector of length  $N$  that records the row permutation
  effected by the partial pivoting;  $d$  is output as  $\pm 1$  depending on whether the number of
  row interchanges was even or odd, respectively. This routine is used in combination with
  banbks to solve band-diagonal sets of equations.
INTEGER(I4B) :: i,k,l,mdum,mm,n
REAL(SP) :: dum
n=assert_eq(size(a,1),size(al,1),size(indx),'bandec: n')
mm=assert_eq(size(a,2),m1+m2+1,'bandec: mm')
mdum=assert_eq(size(al,2),m1,'bandec: mdum')
a(1:m1,:)=eoshift(a(1:m1,:),dim=2,shift=arth(m1,-1,m1))  Rearrange the storage a
d=1.0                                                     bit.
do k=1,n
  For each row...
  l=min(m1+k,n)
  i=imaxloc(abs(a(k:l,1)))+k-1  Find the pivot element.
  dum=a(i,1)
  if (dum == 0.0) a(k,1)=TINY
  Matrix is algorithmically singular, but proceed anyway with TINY pivot (desirable in some
  applications).
  indx(k)=i
  if (i /= k) then  Interchange rows.
    d=-d
    call swap(a(k,1:mm),a(i,1:mm))
  end if
  do i=k+1,l  Do the elimination.
    dum=a(i,1)/a(k,1)
    al(k,i-k)=dum
    a(i,1:mm-1)=a(i,2:mm)-dum*a(k,2:mm)
    a(i,mm)=0.0
  end do
end do
END SUBROUTINE bandec
```

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`a(1:m1,:)=eoshift(a(1:m1,:),...` See similar discussion of `eoshift` for `banmul`, just above.

`i=imaxloc(abs(a(k:l,1)))+k-1` See discussion of `imaxloc` on p. 1017.



Notice that the above is *not* well parallelized for MMP machines: the outer do-loop is done  $N$  times, where  $N$ , the diagonal length, is potentially the largest dimension in the problem. Small-scale parallel (SSP) machines, and scalar machines, are not disadvantaged, because the parallelism of order  $mm=m1+m2+1$  in the inner loops can be enough to saturate their concurrency.

We don't know of an  $N$ -parallel algorithm for decomposing band diagonal matrices, at least one that has any reasonably concise expression in Fortran 90. Conceptually, one can view a band diagonal matrix as a *block tridiagonal* matrix, and then apply the same recursive strategy as was used in `tridag_par`. However, the implementation details of this are daunting. (We would welcome a user-contributed routine, clear, concise, and with parallelism of order  $N$ .)

```

SUBROUTINE banbks(a,m1,m2,al,indx,b)
USE nrtype; USE nrutil, ONLY : assert_eq,swap
IMPLICIT NONE
REAL(SP), DIMENSION(:,:) , INTENT(IN) :: a,al
INTEGER(I4B), INTENT(IN) :: m1,m2
INTEGER(I4B), DIMENSION(:) , INTENT(IN) :: indx
REAL(SP), DIMENSION(:) , INTENT(INOUT) :: b
    Given the arrays a, al, and indx as returned from bandec, and given a right-hand-side
    vector b, solves the band diagonal linear equations  $A \cdot x = b$ . The solution vector x overwrites
    b. The other input arrays are not modified, and can be left in place for successive calls with
    different right-hand sides.
INTEGER(I4B) :: i,k,l,mdum,mm,n
n=assert_eq(size(a,1),size(al,1),size(b),size(indx),'banbks: n')
mm=assert_eq(size(a,2),m1+m2+1,'banbks: mm')
mdum=assert_eq(size(al,2),m1,'banbks: mdum')
do k=1,n
    Forward substitution, unscrambling the permuted rows as we
    l=min(n,m1+k)
    go.
    i=indx(k)
    if (i /= k) call swap(b(i),b(k))
    b(k+1:l)=b(k+1:l)-al(k,1:l-k)*b(k)
end do
do i=n,1,-1
    Backsubstitution.
    l=min(mm,n-i+1)
    b(i)=(b(i)-dot_product(a(i,2:l),b(1+i:i+1-1)))/a(i,1)
end do
END SUBROUTINE banbks

```



As for `bandec`, the routine `banbks` is not parallelized on the large dimension  $N$ , though it does give the compiler the opportunity for ample small-scale parallelization inside the loops.

\* \* \*

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```

SUBROUTINE mprove(a,alud,indx,b,x)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : lubksb
IMPLICIT NONE
REAL(SP), DIMENSION(:, :), INTENT(IN) :: a,alud
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: indx
REAL(SP), DIMENSION(:), INTENT(IN) :: b
REAL(SP), DIMENSION(:), INTENT(OUT) :: x
  Improves a solution vector x of the linear set of equations  $A \cdot X = B$ . The  $N \times N$  matrix a
  and the  $N$ -dimensional vectors b and x are input. Also input is alud, the LU decomposition
  of a as returned by ludcmp, and the  $N$ -dimensional vector indx also returned by that
  routine. On output, only x is modified, to an improved set of values.
INTEGER(I4B) :: ndum
REAL(SP), DIMENSION(size(a,1)) :: r
ndum=assert_eq(/size(a,1),size(a,2),size(alud,1),size(alud,2),size(b),&
  size(x),size(indx)/),'mprove')
r=matmul(real(a,dp),real(x,dp))-real(b,dp)
  Calculate the right-hand side, accumulating the residual in double precision.
call lubksb(alud,indx,r)      Solve for the error term,
x=x-r                        and subtract it from the old solution.
END SUBROUTINE mprove

```

**f90** `assert_eq(/.../,'mprove')` This overloaded version of the `nrutil` routine `assert_eq` makes use of a trick for passing a variable number of scalar arguments to a routine: Put them into an array constructor, `(/.../)`, and pass the array. The receiving routine can use the `size` intrinsic to count them. The technique has some obvious limitations: All the arguments in the array must be of the same type; and the arguments are passed, in effect, by *value*, not by address, so they must be, in effect, `INTENT(IN)`.

`r=matmul(real(a,dp),real(x,dp))-real(b,dp)` Since Fortran 90's elemental intrinsics operate with the type of their arguments, we can use the `real(...,dp)`'s to force the `matmul` matrix multiplication to be done in double precision, which is what we want. In Fortran 77, we would have to do the matrix multiplication with temporary double precision variables, both inconvenient and (since Fortran 77 has no dynamic memory allocation) a waste of memory.

\* \* \*

```

SUBROUTINE svbksb_sp(u,w,v,b,x)
USE nrtype; USE nrutil, ONLY : assert_eq
REAL(SP), DIMENSION(:, :), INTENT(IN) :: u,v
REAL(SP), DIMENSION(:), INTENT(IN) :: w,b
REAL(SP), DIMENSION(:), INTENT(OUT) :: x
  Solves  $A \cdot X = B$  for a vector X, where A is specified by the arrays u, v, w as returned
  by svdcmp. Here u is  $M \times N$ , v is  $N \times N$ , and w is of length N. b is the M-dimensional
  input right-hand side. x is the N-dimensional output solution vector. No input quantities
  are destroyed, so the routine may be called sequentially with different b's.
INTEGER(I4B) :: mdum,ndum
REAL(SP), DIMENSION(size(x)) :: tmp
mdum=assert_eq(size(u,1),size(b),'svbksb_sp: mdum')
ndum=assert_eq(/size(u,2),size(v,1),size(v,2),size(w),size(x)/),&
  'svbksb_sp: ndum')
where (w /= 0.0)
  tmp=matmul(b,u)/w      Calculate  $\text{diag}(1/w_j)U^T B$ ,
elsewhere
  tmp=0.0                but replace  $1/w_j$  by zero if  $w_j = 0$ .
end where

```

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```
x=matmul(v,tmp)           Matrix multiply by V to get answer.
END SUBROUTINE svbksb_sp
```

**f90** where (w /= 0.0)...tmp=...elsewhere...tmp= Normally, when a where ...elsewhere construction is used to set a variable (here tmp) to one or another value, we like to replace it with a merge expression. Here, however, the where is required to guarantee that a division by zero doesn't occur. The rule is that where will *never* evaluate expressions that are excluded by the mask in the where line, but other constructions, like merge, *might* perform speculative evaluation of more than one possible outcome before selecting the applicable one.

Because singular value decomposition is something that one often wants to do in double precision, we include a double-precision version. In nr, the single- and double-precision versions are overloaded onto the name svbksb.

```
SUBROUTINE svbksb_dp(u,w,v,b,x)
USE nrtype; USE nrutil, ONLY : assert_eq
REAL(DP), DIMENSION(:,:) , INTENT(IN) :: u,v
REAL(DP), DIMENSION(:) , INTENT(IN) :: w,b
REAL(DP), DIMENSION(:) , INTENT(OUT) :: x
INTEGER(I4B) :: mdum,ndum
REAL(DP), DIMENSION(size(x)) :: tmp
mdum=assert_eq(size(u,1),size(b),'svbksb_dp: mdum')
ndum=assert_eq(/size(u,2),size(v,1),size(v,2),size(w),size(x)/,&
'svbksb_dp: ndum')
where (w /= 0.0)
tmp=matmul(b,u)/w
elsewhere
tmp=0.0
end where
x=matmul(v,tmp)
END SUBROUTINE svbksb_dp
```

```
SUBROUTINE svdcmp_sp(a,w,v)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror,outerprod
USE nr, ONLY : pythag
IMPLICIT NONE
REAL(SP), DIMENSION(:,:) , INTENT(INOUT) :: a
REAL(SP), DIMENSION(:) , INTENT(OUT) :: w
REAL(SP), DIMENSION(:,:) , INTENT(OUT) :: v
```

Given an  $M \times N$  matrix  $a$ , this routine computes its singular value decomposition,  $A = U \cdot W \cdot V^T$ . The matrix  $U$  replaces  $a$  on output. The diagonal matrix of singular values  $W$  is output as the  $N$ -dimensional vector  $w$ . The  $N \times N$  matrix  $V$  (not the transpose  $V^T$ ) is output as  $v$ .

```
INTEGER(I4B) :: i,its,j,k,l,m,n,nm
REAL(SP) :: anorm,c,f,g,h,s,scale,x,y,z
REAL(SP), DIMENSION(size(a,1)) :: tempm
REAL(SP), DIMENSION(size(a,2)) :: rv1,tempn
m=size(a,1)
n=assert_eq(size(a,2),size(v,1),size(v,2),size(w),'svdcmp_sp')
g=0.0
scale=0.0
do i=1,n
l=i+1
rv1(i)=scale*g
g=0.0
scale=0.0
if (i <= m) then
```

Householder reduction to bidiagonal form.

```

    scale=sum(abs(a(i:m,i)))
    if (scale /= 0.0) then
        a(i:m,i)=a(i:m,i)/scale
        s=dot_product(a(i:m,i),a(i:m,i))
        f=a(i,i)
        g=-sign(sqrt(s),f)
        h=f*g-s
        a(i,i)=f-g
        tempn(1:n)=matmul(a(i:m,i),a(i:m,1:n))/h
        a(i:m,1:n)=a(i:m,1:n)+outerprod(a(i:m,i),tempn(1:n))
        a(i:m,i)=scale*a(i:m,i)
    end if
end if
w(i)=scale*g
g=0.0
scale=0.0
if ((i <= m) .and. (i /= n)) then
    scale=sum(abs(a(i,1:n)))
    if (scale /= 0.0) then
        a(i,1:n)=a(i,1:n)/scale
        s=dot_product(a(i,1:n),a(i,1:n))
        f=a(i,1)
        g=-sign(sqrt(s),f)
        h=f*g-s
        a(i,1)=f-g
        rv1(1:n)=a(i,1:n)/h
        tempm(1:m)=matmul(a(1:m,1:n),a(i,1:n))
        a(1:m,1:n)=a(1:m,1:n)+outerprod(tempm(1:m),rv1(1:n))
        a(i,1:n)=scale*a(i,1:n)
    end if
end if
end do
anorm=maxval(abs(w)+abs(rv1))
do i=n,1,-1
    Accumulation of right-hand transformations.
    if (i < n) then
        if (g /= 0.0) then
            v(1:n,i)=(a(i,1:n)/a(i,1))/g      Double division to avoid possible under-
            tempn(1:n)=matmul(a(i,1:n),v(1:n,1:n))      flow.
            v(1:n,1:n)=v(1:n,1:n)+outerprod(v(1:n,i),tempn(1:n))
        end if
        v(i,1:n)=0.0
        v(1:n,i)=0.0
    end if
    v(i,i)=1.0
    g=rv1(i)
    l=i
end do
do i=min(m,n),1,-1
    Accumulation of left-hand transformations.
    l=i+1
    g=w(i)
    a(i,1:n)=0.0
    if (g /= 0.0) then
        g=1.0_sp/g
        tempn(1:n)=(matmul(a(1:m,i),a(1:m,1:n))/a(i,i))*g
        a(i:m,1:n)=a(i:m,1:n)+outerprod(a(i:m,i),tempn(1:n))
        a(i:m,i)=a(i:m,i)*g
    else
        a(i:m,i)=0.0
    end if
    a(i,i)=a(i,i)+1.0_sp
end do
do k=n,1,-1
    Diagonalization of the bidiagonal form: Loop over
    do its=1,30
        singular values, and over allowed iterations.
        do l=k,1,-1
            Test for splitting.

```

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```

nm=l-1
if ((abs(rv1(1))+anorm) == anorm) exit
  Note that rv1(1) is always zero, so can never fall through bottom of loop.
if ((abs(w(nm))+anorm) == anorm) then
  c=0.0          Cancellation of rv1(1), if l > 1.
  s=1.0
  do i=l,k
    f=s*rv1(i)
    rv1(i)=c*rv1(i)
    if ((abs(f)+anorm) == anorm) exit
    g=w(i)
    h=pythag(f,g)
    w(i)=h
    h=1.0_sp/h
    c= (g*h)
    s=- (f*h)
    tempm(1:m)=a(1:m,nm)
    a(1:m,nm)=a(1:m,nm)*c+a(1:m,i)*s
    a(1:m,i)=-tempm(1:m)*s+a(1:m,i)*c
  end do
  exit
end if
end do
z=w(k)
if (l == k) then          Convergence.
  if (z < 0.0) then      Singular value is made nonnegative.
    w(k)=-z
    v(1:n,k)=-v(1:n,k)
  end if
  exit
end if
if (its == 30) call nrerror('svdcmp_sp: no convergence in svdcmp')
x=w(1)          Shift from bottom 2-by-2 minor.
nm=k-1
y=w(nm)
g=rv1(nm)
h=rv1(k)
f=((y-z)*(y+z)+(g-h)*(g+h))/(2.0_sp*h*y)
g=pythag(f,1.0_sp)
f=((x-z)*(x+z)+h*((y/(f+sign(g,f)))-h))/x
c=1.0          Next QR transformation:
s=1.0
do j=l,nm
  i=j+1
  g=rv1(i)
  y=w(i)
  h=s*g
  g=c*g
  z=pythag(f,h)
  rv1(j)=z
  c=f/z
  s=h/z
  f= (x*c)+(g*s)
  g=-(x*s)+(g*c)
  h=y*s
  y=y*c
  tempn(1:n)=v(1:n,j)
  v(1:n,j)=v(1:n,j)*c+v(1:n,i)*s
  v(1:n,i)=-tempn(1:n)*s+v(1:n,i)*c
  z=pythag(f,h)
  w(j)=z
  if (z /= 0.0) then
    z=1.0_sp/z
    c=f*z
    Rotation can be arbitrary if z = 0.

```

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```

        s=h*z
      end if
      f= (c*g)+(s*y)
      x=-(s*g)+(c*y)
      tempm(1:m)=a(1:m,j)
      a(1:m,j)=a(1:m,j)*c+a(1:m,i)*s
      a(1:m,i)=-tempm(1:m)*s+a(1:m,i)*c
    end do
    rv1(1)=0.0
    rv1(k)=f
    w(k)=x
  end do
end do
END SUBROUTINE svdcmp_sp

```



The SVD algorithm implemented above does not parallelize very well. There are two parts to the algorithm. The first, reduction to bidiagonal form, can be parallelized. The second, the iterative diagonalization of the bidiagonal form, uses QR transformations that are intrinsically serial. There have been proposals for parallel SVD algorithms [2], but we do not have sufficient experience with them yet to recommend them over the well-established serial algorithm.

tempn(1:n)=matmul...a(i:m,1:n)=...outerprod... Here is an example of an update as in equation (22.1.6). In this case  $b_i$  is independent of  $i$ : It is simply  $1/h$ . The lines beginning tempm(1:m)=matmul about 16 lines down are of a similar form, but with the terms in the opposite order in the matmul.



As with svbksb, single- and double-precision versions of the routines are overloaded onto the name svdcmp in nr.

```

SUBROUTINE svdcmp_dp(a,w,v)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror,outerprod
USE nr, ONLY : pythag
IMPLICIT NONE
REAL(DP), DIMENSION(:,:) , INTENT(INOUT) :: a
REAL(DP), DIMENSION(:) , INTENT(OUT) :: w
REAL(DP), DIMENSION(:,:) , INTENT(OUT) :: v
INTEGER(I4B) :: i,its,j,k,l,m,n,nm
REAL(DP) :: anorm,c,f,g,h,s,scale,x,y,z
REAL(DP), DIMENSION(size(a,1)) :: tempm
REAL(DP), DIMENSION(size(a,2)) :: rv1,tempn
m=size(a,1)
n=assert_eq(size(a,2),size(v,1),size(v,2),size(w),'svdcmp_dp')
g=0.0
scale=0.0
do i=1,n
  l=i+1
  rv1(i)=scale*g
  g=0.0
  scale=0.0
  if (i <= m) then
    scale=sum(abs(a(i:m,i)))
    if (scale /= 0.0) then
      a(i:m,i)=a(i:m,i)/scale
      s=dot_product(a(i:m,i),a(i:m,i))
      f=a(i,i)
      g=-sign(sqrt(s),f)

```



```

        h=f*g-s
        a(i,i)=f-g
        tempn(1:n)=matmul(a(i:m,i),a(i:m,1:n))/h
        a(i:m,1:n)=a(i:m,1:n)+outerprod(a(i:m,i),tempn(1:n))
        a(i:m,i)=scale*a(i:m,i)
    end if
end if
w(i)=scale*g
g=0.0
scale=0.0
if ((i <= m) .and. (i /= n)) then
    scale=sum(abs(a(i,1:n)))
    if (scale /= 0.0) then
        a(i,1:n)=a(i,1:n)/scale
        s=dot_product(a(i,1:n),a(i,1:n))
        f=a(i,1)
        g=-sign(sqrt(s),f)
        h=f*g-s
        a(i,1)=f-g
        rv1(1:n)=a(i,1:n)/h
        tempm(1:m)=matmul(a(1:m,1:n),a(i,1:n))
        a(1:m,1:n)=a(1:m,1:n)+outerprod(tempm(1:m),rv1(1:n))
        a(i,1:n)=scale*a(i,1:n)
    end if
end if
end do
anorm=maxval(abs(w)+abs(rv1))
do i=n,1,-1
    if (i < n) then
        if (g /= 0.0) then
            v(1:n,i)=(a(i,1:n)/a(i,1))/g
            tempn(1:n)=matmul(a(i,1:n),v(1:n,1:n))
            v(1:n,1:n)=v(1:n,1:n)+outerprod(v(1:n,i),tempn(1:n))
        end if
        v(i,1:n)=0.0
        v(1:n,i)=0.0
    end if
    v(i,i)=1.0
    g=rv1(i)
    l=i
end do
do i=min(m,n),1,-1
    l=i+1
    g=w(i)
    a(i,1:n)=0.0
    if (g /= 0.0) then
        g=1.0_dp/g
        tempn(1:n)=(matmul(a(1:m,i),a(1:m,1:n))/a(i,i))*g
        a(i:m,1:n)=a(i:m,1:n)+outerprod(a(i:m,i),tempn(1:n))
        a(i:m,i)=a(i:m,i)*g
    else
        a(i:m,i)=0.0
    end if
    a(i,i)=a(i,i)+1.0_dp
end do
do k=n,1,-1
    do its=1,30
        do l=k,1,-1
            nm=l-1
            if ((abs(rv1(l))+anorm) == anorm) exit
            if ((abs(w(nm))+anorm) == anorm) then
                c=0.0
                s=1.0
                do i=1,k

```

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```

        f=s*rv1(i)
        rv1(i)=c*rv1(i)
        if ((abs(f)+anorm) == anorm) exit
        g=w(i)
        h=pythag(f,g)
        w(i)=h
        h=1.0_dp/h
        c= (g*h)
        s=-(f*h)
        tempm(1:m)=a(1:m,nm)
        a(1:m,nm)=a(1:m,nm)*c+a(1:m,i)*s
        a(1:m,i)=-tempm(1:m)*s+a(1:m,i)*c
    end do
    exit
end if
end do
z=w(k)
if (l == k) then
    if (z < 0.0) then
        w(k)=-z
        v(1:n,k)=-v(1:n,k)
    end if
    exit
end if
if (its == 30) call nrerror('svdcmp_dp: no convergence in svdcmp')
x=w(l)
nm=k-1
y=w(nm)
g=rv1(nm)
h=rv1(k)
f=((y-z)*(y+z)+(g-h)*(g+h))/(2.0_dp*h*y)
g=pythag(f,1.0_dp)
f=((x-z)*(x+z)+h*((y/(f+sign(g,f)))-h))/x
c=1.0
s=1.0
do j=l,nm
    i=j+1
    g=rv1(i)
    y=w(i)
    h=s*g
    g=c*g
    z=pythag(f,h)
    rv1(j)=z
    c=f/z
    s=h/z
    f= (x*c)+(g*s)
    g=- (x*s)+(g*c)
    h=y*s
    y=y*c
    tempn(1:n)=v(1:n,j)
    v(1:n,j)=v(1:n,j)*c+v(1:n,i)*s
    v(1:n,i)=-tempn(1:n)*s+v(1:n,i)*c
    z=pythag(f,h)
    w(j)=z
    if (z /= 0.0) then
        z=1.0_dp/z
        c=f*z
        s=h*z
    end if
    f= (c*g)+(s*y)
    x=- (s*g)+(c*y)
    tempm(1:m)=a(1:m,j)
    a(1:m,j)=a(1:m,j)*c+a(1:m,i)*s
    a(1:m,i)=-tempm(1:m)*s+a(1:m,i)*c
end do

```

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```

        end do
        rv1(1)=0.0
        rv1(k)=f
        w(k)=x
    end do
end do
END SUBROUTINE svdcmp_dp

```

```

FUNCTION pythag_sp(a,b)
USE nrtype
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP) :: pythag_sp
    Computes  $(a^2 + b^2)^{1/2}$  without destructive underflow or overflow.
REAL(SP) :: absa,absb
absa=abs(a)
absb=abs(b)
if (absa > absb) then
    pythag_sp=absa*sqrt(1.0_sp+(absb/absa)**2)
else
    if (absb == 0.0) then
        pythag_sp=0.0
    else
        pythag_sp=absb*sqrt(1.0_sp+(absa/absb)**2)
    end if
end if
END FUNCTION pythag_sp

```

```

FUNCTION pythag_dp(a,b)
USE nrtype
IMPLICIT NONE
REAL(DP), INTENT(IN) :: a,b
REAL(DP) :: pythag_dp
REAL(DP) :: absa,absb
absa=abs(a)
absb=abs(b)
if (absa > absb) then
    pythag_dp=absa*sqrt(1.0_dp+(absb/absa)**2)
else
    if (absb == 0.0) then
        pythag_dp=0.0
    else
        pythag_dp=absb*sqrt(1.0_dp+(absa/absb)**2)
    end if
end if
END FUNCTION pythag_dp

```

\* \* \*

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```

SUBROUTINE cyclic(a,b,c,alpha,beta,r,x)
USE nrtype; USE nrutil, ONLY : assert,assert_eq
USE nr, ONLY : tridag
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN):: a,b,c,r
REAL(SP), INTENT(IN) :: alpha,beta
REAL(SP), DIMENSION(:), INTENT(OUT):: x
  Solves the "cyclic" set of linear equations given by equation (2.7.9). a, b, c, and r are
  input vectors, while x is the output solution vector, all of the same size. alpha and beta
  are the corner entries in the matrix. The input is not modified.
INTEGER(I4B) :: n
REAL(SP) :: fact,gamma
REAL(SP), DIMENSION(size(x)) :: bb,u,z
n=assert_eq((/size(a),size(b),size(c),size(r),size(x)/),'cyclic')
call assert(n > 2, 'cyclic arg')
gamma=-b(1)                               Avoid subtraction error in forming bb(1).
bb(1)=b(1)-gamma                           Set up the diagonal of the modified tridiag-
bb(n)=b(n)-alpha*beta/gamma                 onal system.
bb(2:n-1)=b(2:n-1)
call tridag(a(2:n),bb,c(1:n-1),r,x)         Solve  $A \cdot x = r$ .
u(1)=gamma                                  Set up the vector u.
u(n)=alpha
u(2:n-1)=0.0
call tridag(a(2:n),bb,c(1:n-1),u,z)         Solve  $A \cdot z = u$ .
fact=(x(1)+beta*x(n)/gamma)/(1.0_sp+z(1)+beta*z(n)/gamma)   Form  $v \cdot x / (1 + v \cdot z)$ .
x=x-fact*z                                  Now get the solution vector x.
END SUBROUTINE cyclic

```



The parallelism in `cyclic` is in `tridag`. Users with multiprocessor machines will want to be sure that, in `nrutil`, they have set the name `tridag` to be overloaded with `tridag_par` instead of `tridag_ser`.

\* \* \*

The routines `sprsin`, `spr sax`, `sprstx`, `sprstp`, and `sprsdia` give roughly equivalent functionality to the corresponding Fortran 77 routines, but they are *not* plug compatible. Instead, they take advantage of (and illustrate) several Fortran 90 features that are not present in Fortran 77.

In the module `nrtype` we define a TYPE `sprs2_sp` for two-dimensional sparse, square, matrices, in single precision, as follows

```

TYPE sprs2_sp
  INTEGER(I4B) :: n,len
  REAL(SP), DIMENSION(:), POINTER :: val
  INTEGER(I4B), DIMENSION(:), POINTER :: irow
  INTEGER(I4B), DIMENSION(:), POINTER :: jcol
END TYPE sprs2_sp

```

This has much less structure to it than the “row-indexed sparse storage mode” used in Volume 1. Here, a sparse matrix is just a list of values, and corresponding lists giving the row and column number that each value is in. Two integers `n` and `len` give, respectively, the underlying size (number of rows or columns) in the full matrix, and the number of stored nonzero values. While the previously used row-indexed scheme can be somewhat more efficient for serial machines, it does not parallelize conveniently, while this one does (though with some caveats; see below).

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```

SUBROUTINE sprsin_sp(a,thresh,sa)
USE nrtype; USE nrutil, ONLY : arth,assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:,:) , INTENT(IN) :: a
REAL(SP), INTENT(IN) :: thresh
TYPE(sprs2_sp), INTENT(OUT) :: sa
    Converts a square matrix a to sparse storage format as sa. Only elements of a with mag-
    nitude  $\geq$  thresh are retained.
INTEGER(I4B) :: n,len
LOGICAL(LGT), DIMENSION(size(a,1),size(a,2)) :: mask
n=assert_eq(size(a,1),size(a,2),'sprsin_sp')
mask=abs(a)>thresh
len=count(mask)           How many elements to store?
allocate(sa%val(len),sa%irow(len),sa%jcol(len))
sa%n=n
sa%len=len
sa%val=pack(a,mask)       Grab the values, row, and column numbers.
sa%irow=pack(spread(arth(1,1,n),2,n),mask)
sa%jcol=pack(spread(arth(1,1,n),1,n),mask)
END SUBROUTINE sprsin_sp

```

```

SUBROUTINE sprsin_dp(a,thresh,sa)
USE nrtype; USE nrutil, ONLY : arth,assert_eq
IMPLICIT NONE
REAL(DP), DIMENSION(:,:) , INTENT(IN) :: a
REAL(DP), INTENT(IN) :: thresh
TYPE(sprs2_dp), INTENT(OUT) :: sa
INTEGER(I4B) :: n,len
LOGICAL(LGT), DIMENSION(size(a,1),size(a,2)) :: mask
n=assert_eq(size(a,1),size(a,2),'sprsin_dp')
mask=abs(a)>thresh
len=count(mask)
allocate(sa%val(len),sa%irow(len),sa%jcol(len))
sa%n=n
sa%len=len
sa%val=pack(a,mask)
sa%irow=pack(spread(arth(1,1,n),2,n),mask)
sa%jcol=pack(spread(arth(1,1,n),1,n),mask)
END SUBROUTINE sprsin_dp

```

**f**<sub>90</sub> Note that the routines `sprsin_sp` and `sprsin_dp` — single and double precision versions of the same algorithm — are overloaded onto the name `sprsin` in module `nr`. We supply both forms because the routine `linbcg`, below, works in double precision.

`sa%irow=pack(spread(arth(1,1,n),2,n),mask)` The trick here is to use the same `mask`, `abs(a)>thresh`, in three consecutive `pack` expressions, thus guaranteeing that the corresponding elements of the array argument get selected for packing. The first time, we get the desired matrix element values. The second time (above code fragment), we construct a matrix with each element having the value of its *row* number. The third time, we construct a matrix with each element having the value of its *column* number.

```


SUBROUTINE sprsax_sp(sa,x,b)
USE nrtype; USE nrutil, ONLY : assert_eq,scatter_add
IMPLICIT NONE
TYPE(sprs2_sp), INTENT(IN) :: sa
REAL(SP), DIMENSION (:), INTENT(IN) :: x
REAL(SP), DIMENSION (:), INTENT(OUT) :: b
    Multiply a matrix sa in sparse matrix format by a vector x, giving a vector b.
INTEGER(I4B) :: ndum
ndum=assert_eq(sa%n,size(x),size(b),'sprsax_sp')
b=0.0_sp
call scatter_add(b,sa%val*x(sa%jcol),sa%irow)
    Each sparse matrix entry adds a term to some component of b.
END SUBROUTINE sprsax_sp

```

```

SUBROUTINE sprsax_dp(sa,x,b)
USE nrtype; USE nrutil, ONLY : assert_eq,scatter_add
IMPLICIT NONE
TYPE(sprs2_dp), INTENT(IN) :: sa
REAL(DP), DIMENSION (:), INTENT(IN) :: x
REAL(DP), DIMENSION (:), INTENT(OUT) :: b
INTEGER(I4B) :: ndum
ndum=assert_eq(sa%n,size(x),size(b),'sprsax_dp')
b=0.0_dp
call scatter_add(b,sa%val*x(sa%jcol),sa%irow)
END SUBROUTINE sprsax_dp

```



call scatter\_add(b,sa%val\*x(sa%jcol),sa%irow) Since more than one component of the middle vector argument will, in general, need to be added into the same component of b, we must resort to a call to the nrutil routine scatter\_add to achieve parallelism. *However*, this parallelism is achieved only if a parallel version of scatter\_add is available! As we have discussed previously (p. 984), Fortran 90 does not provide any scatter-with-combine (here, scatter-with-add) facility, insisting instead that indexed operations yield non-colliding addresses. Luckily, almost all parallel machines do provide such a facility as a library program. In HPF, for example, the equivalent of scatter\_add is SUM\_SCATTER.

The call to scatter\_add above is equivalent to the do-loop

```

b=0.0
do k=1,sa%len
    b(sa%irow(k))=b(sa%irow(k))+sa%val(k)*x(sa%jcol(k))
end do

```

```

SUBROUTINE sprstx_sp(sa,x,b)
USE nrtype; USE nrutil, ONLY : assert_eq,scatter_add
IMPLICIT NONE
TYPE(sprs2_sp), INTENT(IN) :: sa
REAL(SP), DIMENSION (:), INTENT(IN) :: x
REAL(SP), DIMENSION (:), INTENT(OUT) :: b
    Multiply the transpose of a matrix sa in sparse matrix format by a vector x, giving a vector b.
INTEGER(I4B) :: ndum
ndum=assert_eq(sa%n,size(x),size(b),'sprstx_sp')
b=0.0_sp
call scatter_add(b,sa%val*x(sa%irow),sa%jcol)
    Each sparse matrix entry adds a term to some component of b.
END SUBROUTINE sprstx_sp

```

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```

SUBROUTINE sprstx_dp(sa,x,b)
USE nrtype; USE nrutil, ONLY : assert_eq,scatter_add
IMPLICIT NONE
TYPE(sprs2_dp), INTENT(IN) :: sa
REAL(DP), DIMENSION (:), INTENT(IN) :: x
REAL(DP), DIMENSION (:), INTENT(OUT) :: b
INTEGER(I4B) :: ndum
ndum=assert_eq(sa%n,size(x),size(b),'sprstx_dp')
b=0.0_dp
call scatter_add(b,sa%val*x(sa%irow),sa%jcol)
END SUBROUTINE sprstx_dp

```



Precisely the same comments as for sprsax apply to sprstx. The call to scatter\_add is here equivalent to

```

b=0.0
do k=1,sa%len
  b(sa%jcol(k))=b(sa%jcol(k))+sa%val(k)*x(sa%irow(k))
end do

```

```

SUBROUTINE sprstp(sa)
USE nrtype
IMPLICIT NONE
TYPE(sprs2_sp), INTENT(INOUT) :: sa
  Replaces sa, in sparse matrix format, by its transpose.
INTEGER(I4B), DIMENSION(:), POINTER :: temp
temp=>sa%irow      We need only swap the row and column pointers.
sa%irow=>sa%jcol
sa%jcol=>temp
END SUBROUTINE sprstp

```

```

SUBROUTINE sprsdiag_sp(sa,b)
USE nrtype; USE nrutil, ONLY : array_copy,assert_eq
IMPLICIT NONE
TYPE(sprs2_sp), INTENT(IN) :: sa
REAL(SP), DIMENSION(:), INTENT(OUT) :: b
  Extracts the diagonal of a matrix sa in sparse matrix format into a vector b.
REAL(SP), DIMENSION(size(b)) :: val
INTEGER(I4B) :: k,l,ndum,nerr
INTEGER(I4B), DIMENSION(size(b)) :: i
LOGICAL(LGT), DIMENSION(:), ALLOCATABLE :: mask
ndum=assert_eq(sa%n,size(b),'sprsdiag_sp')
l=sa%len
allocate(mask(l))
mask = (sa%irow(1:l) == sa%jcol(1:l))  Find diagonal elements.
call array_copy(pack(sa%val(1:l),mask),val,k,nerr)  Grab the values...
i(1:k)=pack(sa%irow(1:l),mask)  ...and their locations.
deallocate(mask)
b=0.0  Zero b because zero values not stored in sa.
b(i(1:k))=val(1:k)  Scatter values into correct slots.
END SUBROUTINE sprsdiag_sp

```

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```

SUBROUTINE sprsdia_dp(sa,b)
USE nrtype; USE nrutil, ONLY : array_copy,assert_eq
IMPLICIT NONE
TYPE(sprs2_dp), INTENT(IN) :: sa
REAL(DP), DIMENSION(:), INTENT(OUT) :: b
REAL(DP), DIMENSION(size(b)) :: val
INTEGER(I4B) :: k,l,ndum,nerr
INTEGER(I4B), DIMENSION(size(b)) :: i
LOGICAL(LGT), DIMENSION(:), ALLOCATABLE :: mask
ndum=assert_eq(sa%n,size(b),'sprsdia_dp')
l=sa%len
allocate(mask(l))
mask = (sa%irow(1:l) == sa%jcol(1:l))
call array_copy(pack(sa%val(1:l),mask),val,k,nerr)
i(1:k)=pack(sa%irow(1:l),mask)
deallocate(mask)
b=0.0
b(i(1:k))=val(1:k)
END SUBROUTINE sprsdia_dp

```

**f**<sub>90</sub> call array\_copy(pack(sa%val(1:l),mask),val,k,nerr) We use the nrutil routine array\_copy because we don't know in advance how many nonzero diagonal elements will be selected by mask. Of course we could count them with a count (mask), but this is an extra step, and inefficient on scalar machines.

i(1:k)=pack(sa%irow(1:l),mask) Using the same mask, we pick out the corresponding locations of the diagonal elements. No need to use array\_copy now, since we know the value of k.

b(i(1:k))=val(1:k) Finally, we can put each element in the right place. Notice that if the sparse matrix is ill-formed, with more than one value stored for the same diagonal element (which should not happen!) then the vector subscript i(1:k) is a “many-one section” and its use on the left-hand side is illegal.

\* \* \*

```

SUBROUTINE linbcg(b,x,itol,tol,itmax,iter,err)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
USE nr, ONLY : atimes,asolve,snmr
IMPLICIT NONE
REAL(DP), DIMENSION(:), INTENT(IN) :: b           Double precision is a good idea in this
REAL(DP), DIMENSION(:), INTENT(INOUT) :: x        routine.
INTEGER(I4B), INTENT(IN) :: itol,itmax
REAL(DP), INTENT(IN) :: tol
INTEGER(I4B), INTENT(OUT) :: iter
REAL(DP), INTENT(OUT) :: err
REAL(DP), PARAMETER :: EPS=1.0e-14_dp

```

Solves  $A \cdot x = b$  for  $x$ , given  $b$  of the same length, by the iterative biconjugate gradient method. On input  $x$  should be set to an initial guess of the solution (or all zeros);  $itol$  is 1,2,3, or 4, specifying which convergence test is applied (see text);  $itmax$  is the maximum number of allowed iterations; and  $tol$  is the desired convergence tolerance. On output,  $x$  is reset to the improved solution,  $iter$  is the number of iterations actually taken, and  $err$  is the estimated error. The matrix  $A$  is referenced only through the user-supplied routines  $atimes$ , which computes the product of either  $A$  or its transpose on a vector; and  $asolve$ ,

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which solves  $\tilde{\mathbf{A}} \cdot \mathbf{x} = \mathbf{b}$  or  $\tilde{\mathbf{A}}^T \cdot \mathbf{x} = \mathbf{b}$  for some preconditioner matrix  $\tilde{\mathbf{A}}$  (possibly the trivial diagonal part of  $\mathbf{A}$ ).

```

INTEGER(I4B) :: n
REAL(DP) :: ak,akden,bk,bkden,bknum,bnrm,dxnrm,xnrm,zm1nrm,znrm
REAL(DP), DIMENSION(size(b)) :: p,pp,r,rr,z,zz
n=assert_eq(size(b),size(x),'linbcg')
iter=0
call atimes(x,r,0)           Calculate initial residual. Input to atimes is
r=b-r                       x(1:n), output is r(1:n); the final 0
rr=r                         indicates that the matrix (not its transpose)
! call atimes(r,rr,0)        is to be used.
    Uncomment this line to get the "minimum residual" variant of the algorithm.
select case(itol)           Calculate norms for use in stopping criterion,
case(1)                     and initialize z.
    bnrn=snrm(b,itol)
    call asolve(r,z,0)       Input to asolve is r(1:n), output is z(1:n);
case(2)                     the final 0 indicates that the matrix  $\tilde{\mathbf{A}}$ 
    call asolve(b,z,0)       (not its transpose) is to be used.
    bnrn=snrm(z,itol)
    call asolve(r,z,0)
case(3:4)
    call asolve(b,z,0)
    bnrn=snrm(z,itol)
    call asolve(r,z,0)
    znrm=snrm(z,itol)
case default
    call nrrror('illegal itol in linbcg')
end select
do                           Main loop.
    if (iter > itmax) exit
    iter=iter+1
    call asolve(rr,zz,1)     Final 1 indicates use of transpose matrix  $\tilde{\mathbf{A}}^T$ .
    bknum=dot_product(z,rr) Calculate coefficient bk and direction vectors
    if (iter == 1) then      p and pp.
        p=z
        pp=zz
    else
        bk=bknum/bkden
        p=bk*p+z
        pp=bk*pp+zz
    end if
    bkden=bknum             Calculate coefficient ak, new iterate x, and
    call atimes(p,z,0)      new residuals r and rr.
    akden=dot_product(z,pp)
    ak=bknum/akden
    call atimes(pp,zz,1)
    x=x+ak*p
    r=r-ak*z
    rr=rr-ak*zz
    call asolve(r,z,0)     Solve  $\tilde{\mathbf{A}} \cdot \mathbf{z} = \mathbf{r}$  and check stopping criterion.
select case(itol)
case(1)
    err=snrm(r,itol)/bnrm
case(2)
    err=snrm(z,itol)/bnrm
case(3:4)
    zm1nrm=znrm
    znrm=snrm(z,itol)
    if (abs(zm1nrm-znrm) > EPS*znrm) then
        dxnrm=abs(ak)*snrm(p,itol)
        err=znrm/abs(zm1nrm-znrm)*dxnrm
    else
        err=znrm/bnrm
    cycle
end do

```

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```

        end if
        xnorm=snrm(x,itol)
        if (err <= 0.5_dp*xnorm) then
            err=err/xnorm
        else
            err=znorm/bnorm           Error may not be accurate, so loop again.
            cycle
        end if
    end select
    write (*,*) ' iter=',iter,' err=',err
    if (err <= tol) exit
end do
END SUBROUTINE linbcg

```



case default...call nrerror('illegal itol in linbcg') It's *always* a good idea to trap errors when the value of a case construction is supplied externally to the routine, as here.

```

FUNCTION snrm(sx,itol)
USE nrtype
IMPLICIT NONE
REAL(DP), DIMENSION(:), INTENT(IN) :: sx
INTEGER(I4B), INTENT(IN) :: itol
REAL(DP) :: snrm
    Compute one of two norms for a vector sx, as signaled by itol. Used by linbcg.
if (itol <= 3) then
    snrm=sqrt(dot_product(sx,sx))           Vector magnitude norm.
else
    snrm=maxval(abs(sx))                   Largest component norm.
end if
END FUNCTION snrm

```

```

SUBROUTINE atimes(x,r,itrnsp)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : sprsax,sprstx           DOUBLE PRECISION versions of sprsax and sprstx.
USE xlinbcg_data                       The matrix is accessed through this module.
REAL(DP), DIMENSION(:), INTENT(IN) :: x
REAL(DP), DIMENSION(:), INTENT(OUT) :: r
INTEGER(I4B), INTENT(IN) :: itrnsp
INTEGER(I4B) :: n
n=assert_eq(size(x),size(r),'atimes')
if (itrnsp == 0) then
    call sprsax(sa,x,r)
else
    call sprstx(sa,x,r)
end if
END SUBROUTINE atimes

```

```

SUBROUTINE asolve(b,x,itrnsp)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
USE nr, ONLY : sprsdia          DOUBLE PRECISION version of sprsdia.
USE xlinbcg_data               The matrix is accessed through this module.
REAL(DP), DIMENSION(:), INTENT(IN) :: b
REAL(DP), DIMENSION(:), INTENT(OUT) :: x
INTEGER(I4B), INTENT(IN) :: itrnsp
INTEGER(I4B) :: ndum
ndum=assert_eq(size(b),size(x),'asolve')
call sprsdia(sa,x)
  The matrix A is taken to be the diagonal part of A. Since the transpose matrix has the same
  diagonal, the flag itrnsp is not used.
if (any(x == 0.0)) call nrerror('asolve: singular diagonal matrix')
x=b/x
END SUBROUTINE asolve

```

**f90** The routines *atimes* and *asolve* are examples of user-supplied routines that interface *linbcg* to a user-supplied method for multiplying the user's sparse matrix by a vector, and for solving the preconditioner matrix equation. Here, we have used these routines to connect *linbcg* to the sparse matrix machinery developed above. If we were instead using the different sparse matrix machinery of Volume 1, we would modify *atimes* and *asolve* accordingly.

USE *xlinbcg\_data* This user-supplied module is assumed to have *sa* (the sparse matrix) in it.

\* \* \*

```

FUNCTION vander(x,q)
USE nrtype; USE nrutil, ONLY : assert_eq,outerdiff
IMPLICIT NONE
REAL(DP), DIMENSION(:), INTENT(IN) :: x,q
REAL(DP), DIMENSION(size(x)) :: vander
  Solves the Vandermonde linear system  $\sum_{i=1}^N x_i^{k-1} w_i = q_k$  ( $k = 1, \dots, N$ ). Input consists
  of the vectors x and q of length N. The solution w (also of length N) is returned in vander.
REAL(DP), DIMENSION(size(x)) :: c
REAL(DP), DIMENSION(size(x),size(x)) :: a
INTEGER(I4B) :: i,n
n=assert_eq(size(x),size(q),'vander')
if (n == 1) then
  vander(1)=q(1)
else
  c(:)=0.0                               Initialize array.
  c(n)=-x(1)                             Coefficients of the master polynomial are found
  do i=2,n                                by recursion.
    c(n+1-i:n-1)=c(n+1-i:n-1)-x(i)*c(n+2-i:n)
    c(n)=c(n)-x(i)
  end do
  a(:,:)=outerdiff(x,x)                  Make vector  $w_j = \prod_{n \neq j} (x_j - x_n)$ .
  vander(:)=product(a,dim=2,mask=(a /= 0.0))
  Now do synthetic division by  $x - x_j$ . The division for all  $x_j$  can be done in parallel (on
  a parallel machine), since the : in the loop below is over j.
  a(:,1)=-c(1)/x(:)
  do i=2,n
    a(:,i)=-c(i)-a(:,i-1))/x(:)
  end do
  vander(:)=matmul(a,q)/vander(:)        Solve linear system and supply denomina-
end if                                     tor.
END FUNCTION vander

```

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`a=outerdiff...w=product...` Here is an example of the coding of equation (22.1.4). Since in this case the product is over the second index ( $n$  in  $x_j - x_n$ ), we have `dim=2` in the product.

```

FUNCTION toeplz(r,y)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: r,y
REAL(SP), DIMENSION(size(y)) :: toeplz
  Solves the Toeplitz system  $\sum_{j=1}^N R_{(N+i-j)}x_j = y_i$  ( $i = 1, \dots, N$ ). The Toeplitz matrix
  need not be symmetric. y (of length  $N$ ) and r (of length  $2N - 1$ ) are input arrays; the
  solution x (of length  $N$ ) is returned in toeplz.
INTEGER(I4B) :: m,m1,n,ndum
REAL(SP) :: sd,sgd,sgn,shn,sxn
REAL(SP), DIMENSION(size(y)) :: g,h,t
n=size(y)
ndum=assert_eq(2*n-1,size(r),'toeplz: ndum')
if (r(n) == 0.0) call nrerror('toeplz: initial singular minor')
toeplz(1)=y(1)/r(n)                                Initialize for the recursion.
if (n == 1) RETURN
g(1)=r(n-1)/r(n)
h(1)=r(n+1)/r(n)
do m=1,n                                           Main loop over the recursion.
  m1=m+1
  sxn=-y(m1)+dot_product(r(n+1:n+m),toeplz(m:1:-1))
  Compute numerator and denominator for x,
  sd=-r(n)+dot_product(r(n+1:n+m),g(1:m))
  if (sd == 0.0) exit
  toeplz(m1)=sxn/sd                                whence x.
  toeplz(1:m)=toeplz(1:m)-toeplz(m1)*g(m:1:-1)
  if (m1 == n) RETURN
  sgn=-r(n-m1)+dot_product(r(n-m:n-1),g(1:m))      Compute numerator and denom-
  shn=-r(n+m1)+dot_product(r(n+m:n+1:-1),h(1:m))  inator for G and H,
  sgd=-r(n)+dot_product(r(n-m:n-1),h(m:1:-1))
  if (sd == 0.0 .or. sgd == 0.0) exit
  g(m1)=sgn/sgd                                    whence G and H.
  h(m1)=shn/sd
  t(1:m)=g(1:m)
  g(1:m)=g(1:m)-g(m1)*h(m:1:-1)
  h(1:m)=h(1:m)-h(m1)*t(m:1:-1)
end do                                             Back for another recurrence.
if (m > n) call nrerror('toeplz: sanity check failed in routine')
call nrerror('toeplz: singular principal minor')
END FUNCTION toeplz

```

\* \* \*

```

SUBROUTINE choldc(a,p)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
IMPLICIT NONE
REAL(SP), DIMENSION(:, :), INTENT(INOUT) :: a
REAL(SP), DIMENSION(:), INTENT(OUT) :: p
  Given an  $N \times N$  positive-definite symmetric matrix a, this routine constructs its Cholesky
  decomposition,  $\mathbf{A} = \mathbf{L} \cdot \mathbf{L}^T$ . On input, only the upper triangle of a need be given; it is
  not modified. The Cholesky factor L is returned in the lower triangle of a, except for its
  diagonal elements, which are returned in p, a vector of length  $N$ .
INTEGER(I4B) :: i,n
REAL(SP) :: summ
n=assert_eq(size(a,1),size(a,2),size(p),'choldc')
do i=1,n

```

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```

    summ=a(i,i)-dot_product(a(i,1:i-1),a(i,1:i-1))
    if (summ <= 0.0) call nrerror('choldc failed')      a, with rounding errors, is
    p(i)=sqrt(summ)                                   not positive definite.
    a(i+1:n,i)=(a(i,i+1:n)-matmul(a(i+1:n,1:i-1),a(i,1:i-1)))/p(i)
end do
END SUBROUTINE choldc

```

```

SUBROUTINE cholsl(a,p,b,x)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:, :), INTENT(IN) :: a
REAL(SP), DIMENSION(:), INTENT(IN) :: p,b
REAL(SP), DIMENSION(:), INTENT(INOUT) :: x
  Solves the set of  $N$  linear equations  $\mathbf{A} \cdot \mathbf{x} = \mathbf{b}$ , where  $\mathbf{a}$  is a positive-definite symmetric
  matrix.  $\mathbf{a}$  ( $N \times N$ ) and  $\mathbf{p}$  (of length  $N$ ) are input as the output of the routine choldc.
  Only the lower triangle of  $\mathbf{a}$  is accessed.  $\mathbf{b}$  is the input right-hand-side vector, of length  $N$ .
  The solution vector, also of length  $N$ , is returned in  $\mathbf{x}$ .  $\mathbf{a}$  and  $\mathbf{p}$  are not modified and can be
  left in place for successive calls with different right-hand sides  $\mathbf{b}$ .  $\mathbf{b}$  is not modified unless
  you identify  $\mathbf{b}$  and  $\mathbf{x}$  in the calling sequence, which is allowed.
INTEGER(I4B) :: i,n
n=assert_eq((/size(a,1),size(a,2),size(p),size(b),size(x)/), 'cholsl')
do i=1,n
  Solve  $\mathbf{L} \cdot \mathbf{y} = \mathbf{b}$ , storing  $\mathbf{y}$  in  $\mathbf{x}$ .
  x(i)=(b(i)-dot_product(a(i,1:i-1),x(1:i-1)))/p(i)
end do
do i=n,1,-1
  Solve  $\mathbf{L}^T \cdot \mathbf{x} = \mathbf{y}$ .
  x(i)=(x(i)-dot_product(a(i+1:n,i),x(i+1:n)))/p(i)
end do
END SUBROUTINE cholsl

```

\* \* \*

```

SUBROUTINE qrdcmp(a,c,d,sing)
USE nrtype; USE nrutil, ONLY : assert_eq,outerprod,vabs
IMPLICIT NONE
REAL(SP), DIMENSION(:, :), INTENT(INOUT) :: a
REAL(SP), DIMENSION(:), INTENT(OUT) :: c,d
LOGICAL(LGT), INTENT(OUT) :: sing
  Constructs the  $QR$  decomposition of the  $n \times n$  matrix  $\mathbf{a}$ . The upper triangular matrix  $\mathbf{R}$ 
  is returned in the upper triangle of  $\mathbf{a}$ , except for the diagonal elements of  $\mathbf{R}$ , which are returned
  in the  $n$ -dimensional vector  $\mathbf{d}$ . The orthogonal matrix  $\mathbf{Q}$  is represented as a product of  $n-1$ 
  Householder matrices  $\mathbf{Q}_1 \dots \mathbf{Q}_{n-1}$ , where  $\mathbf{Q}_j = \mathbf{I} - \mathbf{u}_j \otimes \mathbf{u}_j / c_j$ . The  $i$ th component of  $\mathbf{u}_j$ 
  is zero for  $i = 1, \dots, j-1$  while the nonzero components are returned in  $\mathbf{a}(i, j)$  for
   $i = j, \dots, n$ .  $\mathbf{sing}$  returns as true if singularity is encountered during the decomposition,
  but the decomposition is still completed in this case.
INTEGER(I4B) :: k,n
REAL(SP) :: scale,sigma
n=assert_eq(size(a,1),size(a,2),size(c),size(d), 'qrdcmp')
sing=.false.
do k=1,n-1
  scale=maxval(abs(a(k:n,k)))
  if (scale == 0.0) then
    Singular case.
    sing=.true.
    c(k)=0.0
    d(k)=0.0
  else
    Form  $\mathbf{Q}_k$  and  $\mathbf{Q}_k \cdot \mathbf{A}$ .
    a(k:n,k)=a(k:n,k)/scale
    sigma=sign(vabs(a(k:n,k)),a(k,k))
    a(k,k)=a(k,k)+sigma
    c(k)=sigma*a(k,k)
  end if
end do

```

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```

    d(k)=-scale*sigma
    a(k:n,k+1:n)=a(k:n,k+1:n)-outerprod(a(k:n,k), &
        matmul(a(k:n,k), a(k:n,k+1:n)))/c(k)
  end if
end do
d(n)=a(n,n)
if (d(n) == 0.0) sing=.true.
END SUBROUTINE qrdcmp

```



$a(k:n,k+1:n)=a(k:n,k+1:n)-\text{outerprod} \dots \text{matmul} \dots$  See discussion of equation (22.1.6).

```

SUBROUTINE qrsolv(a,c,d,b)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : rsolv
IMPLICIT NONE
REAL(SP), DIMENSION(:, :), INTENT(IN) :: a
REAL(SP), DIMENSION(:), INTENT(IN) :: c,d
REAL(SP), DIMENSION(:), INTENT(INOUT) :: b
  Solves the set of  $n$  linear equations  $\mathbf{A} \cdot \mathbf{x} = \mathbf{b}$ . The  $n \times n$  matrix  $\mathbf{a}$  and the  $n$ -dimensional vectors  $\mathbf{c}$  and  $\mathbf{d}$  are input as the output of the routine qrdcmp and are not modified.  $\mathbf{b}$  is input as the right-hand-side vector of length  $n$ , and is overwritten with the solution vector on output.
INTEGER(I4B) :: j,n
REAL(SP) :: tau
n=assert_eq((/size(a,1),size(a,2),size(b),size(c),size(d)/), 'qrsolv')
do j=1,n-1
  Form  $\mathbf{Q}^T \cdot \mathbf{b}$ .
  tau=dot_product(a(j:n,j),b(j:n))/c(j)
  b(j:n)=b(j:n)-tau*a(j:n,j)
end do
call rsolv(a,d,b)          Solve  $\mathbf{R} \cdot \mathbf{x} = \mathbf{Q}^T \cdot \mathbf{b}$ .
END SUBROUTINE qrsolv

```

```

SUBROUTINE rsolv(a,d,b)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:, :), INTENT(IN) :: a
REAL(SP), DIMENSION(:), INTENT(IN) :: d
REAL(SP), DIMENSION(:), INTENT(INOUT) :: b
  Solves the set of  $n$  linear equations  $\mathbf{R} \cdot \mathbf{x} = \mathbf{b}$ , where  $\mathbf{R}$  is an upper triangular matrix stored in  $\mathbf{a}$  and  $\mathbf{d}$ . The  $n \times n$  matrix  $\mathbf{a}$  and the vector  $\mathbf{d}$  of length  $n$  are input as the output of the routine qrdcmp and are not modified.  $\mathbf{b}$  is input as the right-hand-side vector of length  $n$ , and is overwritten with the solution vector on output.
INTEGER(I4B) :: i,n
n=assert_eq(size(a,1),size(a,2),size(b),size(d), 'rsolv')
b(n)=b(n)/d(n)
do i=n-1,1,-1
  b(i)=(b(i)-dot_product(a(i,i+1:n),b(i+1:n)))/d(i)
end do
END SUBROUTINE rsolv

```

\* \* \*

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```

SUBROUTINE qrupdt(r,qt,u,v)
USE nrtype; USE nrutil, ONLY : assert_eq,ifirstloc
USE nr, ONLY : rotate,pythag
IMPLICIT NONE
REAL(SP), DIMENSION(:, :), INTENT(INOUT) :: r,qt
REAL(SP), DIMENSION(:), INTENT(INOUT) :: u
REAL(SP), DIMENSION(:), INTENT(IN) :: v
  Given the  $QR$  decomposition of some  $n \times n$  matrix, calculates the  $QR$  decomposition of
  the matrix  $Q \cdot (R + u \otimes v)$ . Here  $r$  and  $qt$  are  $n \times n$  matrices,  $u$  and  $v$  are  $n$ -dimensional
  vectors. Note that  $Q^T$  is input and returned in  $qt$ .
INTEGER(I4B) :: i,k,n
n=assert_eq((/size(r,1),size(r,2),size(qt,1),size(qt,2),size(u),&
  size(v)/),'qrupdt')
k=n+1-ifirstloc(u(n:1:-1) /= 0.0)      Find largest k such that  $u(k) \neq 0$ .
if (k < 1) k=1
do i=k-1,1,-1                          Transform  $R + u \otimes v$  to upper Hessenberg.
  call rotate(r,qt,i,u(i),-u(i+1))
  u(i)=pythag(u(i),u(i+1))
end do
r(1,:) = r(1,:) + u(1)*v
do i=1,k-1                              Transform upper Hessenberg matrix to upper
  call rotate(r,qt,i,r(i,i),-r(i+1,i))    triangular.
end do
END SUBROUTINE qrupdt

```



$k=n+1$ -ifirstloc( $u(n:1:-1) \neq 0.0$ ) The function ifirstloc in nrutil returns the first occurrence of .true. in a logical vector. See the discussion of the analogous routine imaxloc on p. 1017.

```

SUBROUTINE rotate(r,qt,i,a,b)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:, :), TARGET, INTENT(INOUT) :: r,qt
INTEGER(I4B), INTENT(IN) :: i
REAL(SP), INTENT(IN) :: a,b
  Given  $n \times n$  matrices  $r$  and  $qt$ , carry out a Jacobi rotation on rows  $i$  and  $i+1$  of each matrix.
   $a$  and  $b$  are the parameters of the rotation:  $\cos \theta = a/\sqrt{a^2 + b^2}$ ,  $\sin \theta = b/\sqrt{a^2 + b^2}$ .
REAL(SP), DIMENSION(size(r,1)) :: temp
INTEGER(I4B) :: n
REAL(SP) :: c,fact,s
n=assert_eq(size(r,1),size(r,2),size(qt,1),size(qt,2),'rotate')
if (a == 0.0) then                      Avoid unnecessary overflow or underflow.
  c=0.0
  s=sign(1.0_sp,b)
else if (abs(a) > abs(b)) then
  fact=b/a
  c=sign(1.0_sp/sqrt(1.0_sp+fact**2),a)
  s=fact*c
else
  fact=a/b
  s=sign(1.0_sp/sqrt(1.0_sp+fact**2),b)
  c=fact*s
end if
temp(i:n)=r(i,i:n)                    Premultiply  $r$  by Jacobi rotation.
r(i,i:n)=c*temp(i:n)-s*r(i+1,i:n)
r(i+1,i:n)=s*temp(i:n)+c*r(i+1,i:n)
temp=qt(i,:)                          Premultiply  $qt$  by Jacobi rotation.
qt(i,:)=c*temp-s*qt(i+1,:)
qt(i+1,:)=s*temp+c*qt(i+1,:)
END SUBROUTINE rotate

```

## CITED REFERENCES AND FURTHER READING:

- Golub, G.H., and Van Loan, C.F. 1989, *Matrix Computations*, 2nd ed. (Baltimore: Johns Hopkins University Press). [1]
- Gu, M., Demmel, J., and Dhillon, I. 1994, LAPACK Working Note #88 (Computer Science Department, University of Tennessee at Knoxville, Preprint UT-CS-94-257; available from Netlib, or as <http://www.cs.utk.edu/~library/TechReports/1994/ut-cs-94-257.ps.Z>). [2] See also discussion after `tq1i` in Chapter B11.

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## Chapter B3. Interpolation and Extrapolation

```

SUBROUTINE polint(xa,ya,x,y,dy)
USE nrtype; USE nrutil, ONLY : assert_eq,iminloc,nrerror
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: xa,ya
REAL(SP), INTENT(IN) :: x
REAL(SP), INTENT(OUT) :: y,dy
    Given arrays xa and ya of length  $N$ , and given a value  $x$ , this routine returns a value  $y$ ,
    and an error estimate  $dy$ . If  $P(x)$  is the polynomial of degree  $N - 1$  such that  $P(xa_i) =$ 
     $ya_i, i = 1, \dots, N$ , then the returned value  $y = P(x)$ .
INTEGER(I4B) :: m,n,ns
REAL(SP), DIMENSION(size(xa)) :: c,d,den,ho
n=assert_eq(size(xa),size(ya),'polint')
c=ya
d=ya
ho=xa-x
ns=iminloc(abs(x-xa))
y=ya(ns)
ns=ns-1
do m=1,n-1
    den(1:n-m)=ho(1:n-m)-ho(1+m:n)
    if (any(den(1:n-m) == 0.0)) &
        call nrerror('polint: calculation failure')
    This error can occur only if two input xa's are (to within roundoff) identical.
    den(1:n-m)=(c(2:n-m+1)-d(1:n-m))/den(1:n-m)
    d(1:n-m)=ho(1+m:n)*den(1:n-m)
    c(1:n-m)=ho(1:n-m)*den(1:n-m)
    Here the c's and d's are updated.
    if (2*ns < n-m) then
        After each column in the tableau is completed, we decide
        dy=c(ns+1)
        which correction, c or d, we want to add to our accu-
    else
        dy=d(ns)
        ns=ns-1
        mending value of y, i.e., which path to take through
    end if
        the tableau—forking up or down. We do this in such a
        y=y+dy
        way as to take the most “straight line” route through the
    end do
        tableau to its apex, updating ns accordingly to keep track
END SUBROUTINE polint
        of where we are. This route keeps the partial approxima-
        tions centered (insofar as possible) on the target x. The
        last dy added is thus the error indication.

```

```

SUBROUTINE ratint(xa,ya,x,y,dy)
USE nrtype; USE nrutil, ONLY : assert_eq,iminloc,nrerror
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: xa,ya
REAL(SP), INTENT(IN) :: x
REAL(SP), INTENT(OUT) :: y,dy
    Given arrays xa and ya of length  $N$ , and given a value of  $x$ , this routine returns a value of  $y$ 
    and an accuracy estimate  $dy$ . The value returned is that of the diagonal rational function,
    evaluated at  $x$ , that passes through the  $N$  points  $(xa_i, ya_i), i = 1 \dots N$ .
INTEGER(I4B) :: m,n,ns
REAL(SP), DIMENSION(size(xa)) :: c,d,dd,h,t

```

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```

REAL(SP), PARAMETER :: TINY=1.0e-25_sp      A small number.
n=assert_eq(size(xa),size(ya),'ratint')
h=xa-x
ns=iminloc(abs(h))
y=ya(ns)
if (x == xa(ns)) then
  dy=0.0
  RETURN
end if
c=ya
d=ya+TINY                                  The TINY part is needed to prevent
ns=ns-1                                    a rare zero-over-zero condition.
do m=1,n-1
  t(1:n-m)=(xa(1:n-m)-x)*d(1:n-m)/h(1+m:n)  h will never be zero, since this was
  dd(1:n-m)=t(1:n-m)-c(2:n-m+1)             tested in the initializing loop.
  if (any(dd(1:n-m) == 0.0)) &
    call nrerror('failure in ratint')        This error condition indicates that
  dd(1:n-m)=(c(2:n-m+1)-d(1:n-m))/dd(1:n-m)  the interpolating function has a
  d(1:n-m)=c(2:n-m+1)*dd(1:n-m)            pole at the requested value of
  c(1:n-m)=t(1:n-m)*dd(1:n-m)              x.
  if (2*ns < n-m) then
    dy=c(ns+1)
  else
    dy=d(ns)
    ns=ns-1
  end if
  y=y+dy
end do
END SUBROUTINE ratint

```

\* \* \*

```

SUBROUTINE spline(x,y,yp1,ypn,y2)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : tridag
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
REAL(SP), INTENT(IN) :: yp1,ypn
REAL(SP), DIMENSION(:), INTENT(OUT) :: y2

```

Given arrays  $x$  and  $y$  of length  $N$  containing a tabulated function, i.e.,  $y_i = f(x_i)$ , with  $x_1 < x_2 < \dots < x_N$ , and given values  $yp1$  and  $ypn$  for the first derivative of the interpolating function at points 1 and  $N$ , respectively, this routine returns an array  $y2$  of length  $N$  that contains the second derivatives of the interpolating function at the tabulated points  $x_i$ . If  $yp1$  and/or  $ypn$  are equal to  $1 \times 10^{30}$  or larger, the routine is signaled to set the corresponding boundary condition for a natural spline, with zero second derivative on that boundary.

```

INTEGER(I4B) :: n
REAL(SP), DIMENSION(size(x)) :: a,b,c,r
n=assert_eq(size(x),size(y),size(y2),'spline')
c(1:n-1)=x(2:n)-x(1:n-1)      Set up the tridiagonal equations.
r(1:n-1)=6.0_sp*((y(2:n)-y(1:n-1))/c(1:n-1))
r(2:n-1)=r(2:n-1)-r(1:n-2)
a(2:n-1)=c(1:n-2)
b(2:n-1)=2.0_sp*(c(2:n-1)+a(2:n-1))
b(1)=1.0
b(n)=1.0
if (yp1 > 0.99e30_sp) then    The lower boundary condition is set either to be "nat-
  r(1)=0.0                    ural"
  c(1)=0.0
else
  or else to have a specified first derivative.
  r(1)=(3.0_sp/(x(2)-x(1)))*((y(2)-y(1))/(x(2)-x(1))-yp1)

```

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```

      c(1)=0.5
end if
if (ypn > 0.99e30_sp) then
  r(n)=0.0
  a(n)=0.0
else
  r(n)=(-3.0_sp/(x(n)-x(n-1)))*((y(n)-y(n-1))/(x(n)-x(n-1))-ypn)
  a(n)=0.5
end if
call tridag(a(2:n),b(1:n),c(1:n-1),r(1:n),y2(1:n))
END SUBROUTINE spline

```

```

FUNCTION splint(xa,ya,y2a,x)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
USE nr, ONLY: locate
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: xa,ya,y2a
REAL(SP), INTENT(IN) :: x
REAL(SP) :: splint

```

Given the arrays *xa* and *ya*, which tabulate a function (with the *xa<sub>i</sub>*'s in increasing or decreasing order), and given the array *y2a*, which is the output from *spline* above, and given a value of *x*, this routine returns a cubic-spline interpolated value. The arrays *xa*, *ya* and *y2a* are all of the same size.

```

INTEGER(I4B) :: khi,klo,n
REAL(SP) :: a,b,h
n=assert_eq(size(xa),size(ya),size(y2a),'splint')
klo=max(min(locate(xa,x),n-1),1)

```

We will find the right place in the table by means of *locate*'s bisection algorithm. This is optimal if sequential calls to this routine are at random values of *x*. If sequential calls are in order, and closely spaced, one would do better to store previous values of *klo* and *khi* and test if they remain appropriate on the next call.

```

khi=klo+1
h=xa(khi)-xa(klo)
if (h == 0.0) call nrerror('bad xa input in splint')
a=(xa(khi)-x)/h
b=(x-xa(klo))/h
splint=a*ya(klo)+b*ya(khi)+((a**3-a)*y2a(klo)+(b**3-b)*y2a(khi))*(h**2)/6.0_sp
END FUNCTION splint

```

**f90** *klo*=max(min(*locate*(*xa*,*x*),*n*-1),1) In the Fortran 77 version of *splint*, there is in-line code to find the location in the table by bisection. Here we prefer an explicit call to *locate*, which performs the bisection. On some massively multiprocessor (MMP) machines, one might substitute a different, more parallel algorithm (see next note).

\* \* \*

```

FUNCTION locate(xx,x)
USE nrtype
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: xx
REAL(SP), INTENT(IN) :: x
INTEGER(I4B) :: locate

```

Given an array *xx*(1:*N*), and given a value *x*, returns a value *j* such that *x* is between *xx*(*j*) and *xx*(*j*+1). *xx* must be monotonic, either increasing or decreasing. *j* = 0 or *j* = *N* is returned to indicate that *x* is out of range.

```

INTEGER(I4B) :: n,jl,jm,ju
LOGICAL :: ascnd

```

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```

n=size(xx)
ascnd = (xx(n) >= xx(1))      True if ascending order of table, false otherwise.
j1=0                          Initialize lower
ju=n+1                        and upper limits.
do
  if (ju-j1 <= 1) exit        Repeat until this condition is satisfied.
  jm=(ju+j1)/2               Compute a midpoint,
  if (ascnd .eqv. (x >= xx(jm))) then
    j1=jm                    and replace either the lower limit
  else
    ju=jm                    or the upper limit, as appropriate.
  end if
end do
if (x == xx(1)) then         Then set the output, being careful with the endpoints.
  locate=1
else if (x == xx(n)) then
  locate=n-1
else
  locate=j1
end if
END FUNCTION locate

```



The use of bisection is perhaps a sin on a genuinely parallel machine, but (since the process takes only logarithmically many sequential steps) it is at most a *small* sin. One can imagine a “fully parallel” implementation like,

```

k=iminloc(abs(x-xx))
if ((x < xx(k)) .eqv. (xx(1) < xx(n))) then
  locate=k-1
else
  locate=k
end if

```

Problem is, unless the number of *physical* (not logical) processors participating in the `iminloc` is larger than  $N$ , the length of the array, this “parallel” code turns a  $\log N$  algorithm into one scaling as  $N$ , quite an unacceptable inefficiency. So we prefer to be small sinners and bisect.

```

SUBROUTINE hunt(xx,x,jlo)
USE nrtype
IMPLICIT NONE
INTEGER(I4B), INTENT(INOUT) :: jlo
REAL(SP), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(IN) :: xx
  Given an array xx(1:N), and given a value x, returns a value jlo such that x is between
  xx(jlo) and xx(jlo+1). xx must be monotonic, either increasing or decreasing. jlo = 0
  or jlo = N is returned to indicate that x is out of range. jlo on input is taken as the
  initial guess for jlo on output.
INTEGER(I4B) :: n,inc,jhi,jm
LOGICAL :: ascnd
n=size(xx)
ascnd = (xx(n) >= xx(1))      True if ascending order of table, false otherwise.
if (jlo <= 0 .or. jlo > n) then
  jlo=0                      Input guess not useful. Go immediately to bisection.
  jhi=n+1
else
  inc=1                      Set the hunting increment.
  if (x >= xx(jlo) .eqv. ascnd) then
    Hunt up:
    do
      jhi=jlo+inc
      if (jhi > n) then      Done hunting, since off end of table.

```

```

        jhi=n+1
        exit
    else
        if (x < xx(jhi) .eqv. ascnd) exit
        jlo=jhi          Not done hunting,
        inc=inc+inc      so double the increment
    end if
end do                    and try again.
else                      Hunt down:
    jhi=jlo
    do
        jlo=jhi-inc
        if (jlo < 1) then    Done hunting, since off end of table.
            jlo=0
            exit
        else
            if (x >= xx(jlo) .eqv. ascnd) exit
            jhi=jlo          Not done hunting,
            inc=inc+inc      so double the increment
        end if
    end do                and try again.
end if
end if                    Done hunting, value bracketed.
do                      Hunt is done, so begin the final bisection phase:
    if (jhi-jlo <= 1) then
        if (x == xx(n)) jlo=n-1
        if (x == xx(1)) jlo=1
        exit
    else
        jm=(jhi+jlo)/2
        if (x >= xx(jm) .eqv. ascnd) then
            jlo=jm
        else
            jhi=jm
        end if
    end if
end do
END SUBROUTINE hunt

```

\* \* \*

```

FUNCTION polcoe(x,y)
USE nrtype; USE nrutil, ONLY : assert_eq,outerdiff
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
REAL(SP), DIMENSION(size(x)) :: polcoe
    Given same-size arrays x and y containing a tabulated function  $y_i = f(x_i)$ , this routine
    returns a same-size array of coefficients  $c_j$ , such that  $y_i = \sum_j c_j x_i^{j-1}$ .
INTEGER(I4B) :: i,k,n
REAL(SP), DIMENSION(size(x)) :: s
REAL(SP), DIMENSION(size(x),size(x)) :: a
n=assert_eq(size(x),size(y),'polcoe')
s=0.0          Coefficients  $s_i$  of the master polynomial  $P(x)$  are found by
s(n)=-x(1)    recurrence.
do i=2,n
    s(n+1-i:n-1)=s(n+1-i:n-1)-x(i)*s(n+2-i:n)
    s(n)=s(n)-x(i)
end do
a=outerdiff(x,x)      Make vector  $w_j = \prod_{j \neq n} (x_j - x_n)$ , using polcoe for tempo-
polcoe=product(a,dim=2,mask=a /= 0.0)    rary storage.


```

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```

Now do synthetic division by  $x - x_j$ . The division for all  $x_j$  can be done in parallel (on a
parallel machine), since the  $:$  in the loop below is over  $j$ .
a(:,1)=-s(1)/x(:)
do k=2,n
  a(:,k)=-s(k)-a(:,k-1))/x(:)
end do
s=y/polcoe
polcoe=matmul(s,a)          Solve linear system.
END FUNCTION polcoe

```



For a description of the coding here, see §22.3, especially equation (22.3.9). You might also want to compare the coding here with the Fortran 77 version, and also look at the description of the method on p. 84 in Volume 1. The Fortran 90 implementation here is in fact much closer to that description than is the Fortran 77 method, which goes through some acrobatics to roll the synthetic division and matrix multiplication into a single set of two nested loops. The price we pay, here, is storage for the matrix  $a$ . Since the degree of any useful polynomial is not a very large number, this is essentially no penalty.

Also worth noting is the way that parallelism is brought to the required synthetic division. For a *single* such synthetic division (e.g., as accomplished by the `nrutil` routine `poly_term`), parallelism can be obtained only by recursion. Here things are much simpler, because we need a whole bunch of simultaneous and independent synthetic divisions; so we can just do them in the obvious, data-parallel, way.

```

FUNCTION polcof(xa,ya)
USE nrtype; USE nrutil, ONLY : assert_eq,iminloc
USE nr, ONLY : polint
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: xa,ya
REAL(SP), DIMENSION(size(xa)) :: polcof
  Given same-size arrays xa and ya containing a tabulated function  $ya_i = f(xa_i)$ , this routine
  returns a same-size array of coefficients  $c_j$  such that  $ya_i = \sum_j c_j xa_i^{j-1}$ .
INTEGER(I4B) :: j,k,m,n
REAL(SP) :: dy
REAL(SP), DIMENSION(size(xa)) :: x,y
n=assert_eq(size(xa),size(ya),'polcof')
x=xa
y=ya
do j=1,n
  m=n+1-j
  call polint(x(1:m),y(1:m),0.0_sp,polcof(j),dy)
  Use the polynomial interpolation routine of §3.1 to extrapolate to  $x = 0$ .
  k=iminloc(abs(x(1:m)))      Find the remaining  $x_k$  of smallest absolute value,
  where  $(x(1:m) /= 0.0)$   $y(1:m)=(y(1:m)-polcof(j))/x(1:m)$  reduce all the terms,
   $y(k:m-1)=y(k+1:m)$  and eliminate  $x_k$ .
  x(k:m-1)=x(k+1:m)
end do
END FUNCTION polcof

```

\* \* \*

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```

SUBROUTINE polin2(x1a,x2a,ya,x1,x2,y,dy)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : polint
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x1a,x2a
REAL(SP), DIMENSION(:, :), INTENT(IN) :: ya
REAL(SP), INTENT(IN) :: x1,x2
REAL(SP), INTENT(OUT) :: y,dy
    Given arrays x1a of length  $M$  and x2a of length  $N$  of independent variables, and an  $M \times N$ 
    array of function values ya, tabulated at the grid points defined by x1a and x2a, and given
    values x1 and x2 of the independent variables, this routine returns an interpolated function
    value y, and an accuracy indication dy (based only on the interpolation in the x1 direction,
    however).
INTEGER(I4B) :: j,m,ndum
REAL(SP), DIMENSION(size(x1a)) :: ymtmp
REAL(SP), DIMENSION(size(x2a)) :: yntmp
m=assert_eq(size(x1a),size(ya,1),'polin2: m')
ndum=assert_eq(size(x2a),size(ya,2),'polin2: ndum')
do j=1,m
    yntmp=ya(j,:)
    call polint(x2a,yntmp,x2,ymtmp(j),dy)
end do
call polint(x1a,ymtmp,x1,y,dy)
END SUBROUTINE polin2

```

\* \* \*

```

SUBROUTINE bcucuf(y,y1,y2,y12,d1,d2,c)
USE nrtype
IMPLICIT NONE
REAL(SP), INTENT(IN) :: d1,d2
REAL(SP), DIMENSION(4), INTENT(IN) :: y,y1,y2,y12
REAL(SP), DIMENSION(4,4), INTENT(OUT) :: c
    Given arrays y, y1, y2, and y12, each of length 4, containing the function, gradients, and
    cross derivative at the four grid points of a rectangular grid cell (numbered counterclockwise
    from the lower left), and given d1 and d2, the length of the grid cell in the 1- and 2-
    directions, this routine returns the  $4 \times 4$  table c that is used by routine bcuint for bicubic
    interpolation.
REAL(SP), DIMENSION(16) :: x
REAL(SP), DIMENSION(16,16) :: wt
DATA wt /1,0,-3,2,4*0,-3,0,9,-6,2,0,-6,4,&
    8*0,3,0,-9,6,-2,0,6,-4,10*0,9,-6,2*0,-6,4,2*0,3,-2,6*0,-9,6,&
    2*0,6,-4,4*0,1,0,-3,2,-2,0,6,-4,1,0,-3,2,8*0,-1,0,3,-2,1,0,-3,&
    2,10*0,-3,2,2*0,3,-2,6*0,3,-2,2*0,-6,4,2*0,3,-2,0,1,-2,1,5*0,&
    -3,6,-3,0,2,-4,2,9*0,3,-6,3,0,-2,4,-2,10*0,-3,3,2*0,2,-2,2*0,&
    -1,1,6*0,3,-3,2*0,-2,2,5*0,1,-2,1,0,-2,4,-2,0,1,-2,1,9*0,-1,2,&
    -1,0,1,-2,1,10*0,1,-1,2*0,-1,1,6*0,-1,1,2*0,2,-2,2*0,-1,1/
x(1:4)=y
x(5:8)=y1*d1
x(9:12)=y2*d2
x(13:16)=y12*d1*d2
x=matmul(wt,x)
c=reshape(x,(/4,4/),order=(/2,1/))
END SUBROUTINE bcucuf

```

\* \* \*

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Matrix multiply by the stored table.  
 Unpack the result into the output table.

**f90** `x=matmul(wt,x) ... c=reshape(x,(/4,4/),order=(/2,1/))` It is a powerful technique to combine the `matmul` intrinsic with `reshape`'s of the input or output. The idea is to use `matmul` whenever the calculation can be cast into the form of a linear mapping between input and output objects. Here the `order=(/2,1/)` parameter specifies that we want the packing to be by rows, not by Fortran's default of columns. (In this two-dimensional case, it's the equivalent of applying `transpose`.)

```

SUBROUTINE bcuint(y,y1,y2,y12,x1l,x1u,x2l,x2u,x1,x2,ansy,ansy1,ansy2)
USE nrtype; USE nrutil, ONLY : nrerror
USE nr, ONLY : bcucof
IMPLICIT NONE
REAL(SP), DIMENSION(4), INTENT(IN) :: y,y1,y2,y12
REAL(SP), INTENT(IN) :: x1l,x1u,x2l,x2u,x1,x2
REAL(SP), INTENT(OUT) :: ansy,ansy1,ansy2
  Bicubic interpolation within a grid square. Input quantities are y,y1,y2,y12 (as described
  in bcucof); x1l and x1u, the lower and upper coordinates of the grid square in the 1-
  direction; x2l and x2u likewise for the 2-direction; and x1,x2, the coordinates of the
  desired point for the interpolation. The interpolated function value is returned as ansy,
  and the interpolated gradient values as ansy1 and ansy2. This routine calls bcucof.
INTEGER(I4B) :: i
REAL(SP) :: t,u
REAL(SP), DIMENSION(4,4) :: c
call bcucof(y,y1,y2,y12,x1u-x1l,x2u-x2l,c)      Get the c's.
if (x1u == x1l .or. x2u == x2l) call &
  nrerror('bcuint: problem with input values - boundary pair equal?')
t=(x1-x1l)/(x1u-x1l)                            Equation (3.6.4).
u=(x2-x2l)/(x2u-x2l)
ansy=0.0
ansy2=0.0
ansy1=0.0
do i=4,1,-1                                     Equation (3.6.6).
  ansy=t*ansy+((c(i,4)*u+c(i,3))*u+c(i,2))*u+c(i,1)
  ansy2=t*ansy2+(3.0_sp*c(i,4)*u+2.0_sp*c(i,3))*u+c(i,2)
  ansy1=u*ansy1+(3.0_sp*c(4,i)*t+2.0_sp*c(3,i))*t+c(2,i)
end do
ansy1=ansy1/(x1u-x1l)
ansy2=ansy2/(x2u-x2l)
END SUBROUTINE bcuint

```

\* \* \*

```

SUBROUTINE splie2(x1a,x2a,ya,y2a)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : spline
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x1a,x2a
REAL(SP), DIMENSION(:,), INTENT(IN) :: ya
REAL(SP), DIMENSION(:,), INTENT(OUT) :: y2a
  Given an  $M \times N$  tabulated function ya, and  $N$  tabulated independent variables x2a, this
  routine constructs one-dimensional natural cubic splines of the rows of ya and returns the
  second derivatives in the  $M \times N$  array y2a. (The array x1a is included in the argument
  list merely for consistency with routine splin2.)
INTEGER(I4B) :: j,m,ndum
m=assert_eq(size(x1a),size(ya,1),size(y2a,1),'splie2: m')
ndum=assert_eq(size(x2a),size(ya,2),size(y2a,2),'splie2: ndum')
do j=1,m
  call spline(x2a,ya(j,:),1.0e30_sp,1.0e30_sp,y2a(j,:))

```

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```

      Values  $1 \times 10^{30}$  signal a natural spline.
end do
END SUBROUTINE splie2

FUNCTION splin2(x1a,x2a,ya,y2a,x1,x2)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : spline,splint
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x1a,x2a
REAL(SP), DIMENSION(:,:), INTENT(IN) :: ya,y2a
REAL(SP), INTENT(IN) :: x1,x2
REAL(SP) :: splin2
  Given x1a, x2a, ya as described in splie2 and y2a as produced by that routine; and given
  a desired interpolating point x1,x2; this routine returns an interpolated function value by
  bicubic spline interpolation.
INTEGER(I4B) :: j,m,ndum
REAL(SP), DIMENSION(size(x1a)) :: yytmp,y2tmp2
m=assert_eq(size(x1a),size(ya,1),size(y2a,1),'splin2: m')
ndum=assert_eq(size(x2a),size(ya,2),size(y2a,2),'splin2: ndum')
do j=1,m
  yytmp(j)=splint(x2a,ya(j,:),y2a(j,:),x2)
  Perform m evaluations of the row splines constructed by splie2, using the one-dimensional
  spline evaluator splint.
end do
call spline(x1a,yytmp,1.0e30_sp,1.0e30_sp,y2tmp2)
  Construct the one-dimensional column spline and evaluate it.
splin2=splint(x1a,yytmp,y2tmp2,x1)
END FUNCTION splin2

```

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## Chapter B4. Integration of Functions

```

SUBROUTINE trapzd(func,a,b,s,n)
USE nrtype; USE nrutil, ONLY : arth
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP), INTENT(INOUT) :: s
INTEGER(I4B), INTENT(IN) :: n
INTERFACE
  FUNCTION func(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: func
  END FUNCTION func
END INTERFACE

```

This routine computes the  $n$ th stage of refinement of an extended trapezoidal rule. `func` is input as the name of the function to be integrated between limits `a` and `b`, also input. When called with  $n=1$ , the routine returns as `s` the crudest estimate of  $\int_a^b f(x)dx$ . Subsequent calls with  $n=2,3,\dots$  (in that sequential order) will improve the accuracy of `s` by adding  $2^{n-2}$  additional interior points. `s` should not be modified between sequential calls.

```

REAL(SP) :: del,fsum
INTEGER(I4B) :: it
if (n == 1) then
  s=0.5_sp*(b-a)*sum(func( (/ a,b /) ))
else
  it=2**(n-2)
  del=(b-a)/it
  fsum=sum(func(arth(a+0.5_sp*del,del,it)))
  s=0.5_sp*(s+del*fsum)
end if
END SUBROUTINE trapzd

```

**f90** While most of the quadrature routines in this chapter are coded as functions, `trapzd` is a subroutine because the argument `s` that returns the function value must also be supplied as an input parameter. We could change the subroutine into a function by declaring `s` to be a local variable with the `SAVE` attribute. However, this would prevent us from being able to use the routine recursively to do multidimensional quadrature (see `quad3d` on p. 1065). When `s` is left as an argument, a fresh copy is created on each recursive call. As a `SAVE`'d variable, by contrast, its value would get overwritten on each call, and the code would not be properly “re-entrant.”

`s=0.5_sp*(b-a)*sum(func( (/ a,b /) ))` Note how we use the `(/.../)` construct to supply a set of scalar arguments to a vector function.

\* \* \*

```

FUNCTION qtrap(func,a,b)
USE nrtype; USE nrutil, ONLY : nrerror
USE nr, ONLY : trapzd
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP) :: qtrap
INTERFACE
  FUNCTION func(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: func
  END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: JMAX=20
REAL(SP), PARAMETER :: EPS=1.0e-6_sp, UNLIKELY=-1.0e30_sp
  Returns the integral of the function func from a to b. The parameter EPS should be set to
  the desired fractional accuracy and JMAX so that 2 to the power JMAX-1 is the maximum
  allowed number of steps. Integration is performed by the trapezoidal rule.
REAL(SP) :: olds
INTEGER(I4B) :: j
olds=UNLIKELY
do j=1,JMAX
  call trapzd(func,a,b,qtrap,j)
  if (j > 5) then
    Avoid spurious early convergence.
    if (abs(qtrap-olds) < EPS*abs(olds) .or. &
      (qtrap == 0.0 .and. olds == 0.0)) RETURN
  end if
  olds=qtrap
end do
call nrerror('qtrap: too many steps')
END FUNCTION qtrap

```

\* \* \*

```

FUNCTION qsimp(func,a,b)
USE nrtype; USE nrutil, ONLY : nrerror
USE nr, ONLY : trapzd
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP) :: qsimp
INTERFACE
  FUNCTION func(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: func
  END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: JMAX=20
REAL(SP), PARAMETER :: EPS=1.0e-6_sp, UNLIKELY=-1.0e30_sp
  Returns the integral of the function func from a to b. The parameter EPS should be set to
  the desired fractional accuracy and JMAX so that 2 to the power JMAX-1 is the maximum
  allowed number of steps. Integration is performed by Simpson's rule.
INTEGER(I4B) :: j
REAL(SP) :: os,ost,st
ost=UNLIKELY
os= UNLIKELY
do j=1,JMAX
  call trapzd(func,a,b,st,j)
  qsimp=(4.0_sp*st-ost)/3.0_sp
  Compare equation (4.2.4).
  if (j > 5) then
    Avoid spurious early convergence.
    if (abs(qsimp-os) < EPS*abs(os) .or. &
      (qsimp == 0.0 .and. os == 0.0)) RETURN
  end if
  os=qsimp
end do

```

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```

    ost=st
end do
call nrerror('qsimp: too many steps')
END FUNCTION qsimp

```

\* \* \*

```

FUNCTION qromb(func,a,b)
USE nrtype; USE nrutil, ONLY : nrerror
USE nr, ONLY : polint,trapzd
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP) :: qromb
INTERFACE
  FUNCTION func(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: func
  END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: JMAX=20, JMAXP=JMAX+1, K=5, KM=K-1
REAL(SP), PARAMETER :: EPS=1.0e-6_sp

```

Returns the integral of the function `func` from `a` to `b`. Integration is performed by Romberg's method of order  $2K$ , where, e.g.,  $K=2$  is Simpson's rule.

Parameters: `EPS` is the fractional accuracy desired, as determined by the extrapolation error estimate; `JMAX` limits the total number of steps; `K` is the number of points used in the extrapolation.

```

REAL(SP), DIMENSION(JMAXP) :: h,s           These store the successive trapezoidal ap-
REAL(SP) :: dqromb                          proximations and their relative stepsizes.
INTEGER(I4B) :: j
h(1)=1.0
do j=1,JMAX
  call trapzd(func,a,b,s(j),j)
  if (j >= K) then
    call polint(h(j-KM:j),s(j-KM:j),0.0_sp,qromb,dqromb)
    if (abs(dqromb) <= EPS*abs(qromb)) RETURN
  end if
  s(j+1)=s(j)
  h(j+1)=0.25_sp*h(j)
end do
call nrerror('qromb: too many steps')
END FUNCTION qromb

```

This is a key step: The factor is 0.25 even though the stepsize is decreased by only 0.5. This makes the extrapolation a polynomial in  $h^2$  as allowed by equation (4.2.1), not just a polynomial in  $h$ .

\* \* \*

```

SUBROUTINE midpnt(func,a,b,s,n)
USE nrtype; USE nrutil, ONLY : arth
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP), INTENT(INOUT) :: s
INTEGER(I4B), INTENT(IN) :: n
INTERFACE
  FUNCTION func(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: func
  END FUNCTION func
END INTERFACE

```

This routine computes the  $n$ th stage of refinement of an extended midpoint rule. `func` is input as the name of the function to be integrated between limits `a` and `b`, also input. When

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called with  $n=1$ , the routine returns as  $s$  the crudest estimate of  $\int_a^b f(x)dx$ . Subsequent calls with  $n=2,3,\dots$  (in that sequential order) will improve the accuracy of  $s$  by adding  $(2/3) \times 3^{n-1}$  additional interior points.  $s$  should not be modified between sequential calls.

```

REAL(SP) :: del
INTEGER(I4B) :: it
REAL(SP), DIMENSION(2*3**(n-2)) :: x
if (n == 1) then
  s=(b-a)*sum(func( (/0.5_sp*(a+b)/ )) )
else
  it=3**(n-2)
  del=(b-a)/(3.0_sp*it)
  x(1:2*it-1:2)=arth(a+0.5_sp*del,3.0_sp*del,it)
  x(2:2*it:2)=x(1:2*it-1:2)+2.0_sp*del
  s=s/3.0_sp+del*sum(func(x))
end if
END SUBROUTINE midpnt

```

The added points alternate in spacing between  $del$  and  $2*del$ .

The new sum is combined with the old integral to give a refined integral.



`midpnt` is a subroutine and not a function for the same reasons as `trapzd`. This is also true for the other `mid...` routines below.

`s=(b-a)*sum(func( (/0.5_sp*(a+b)/ )) )` Here we use `(/.../)` to pass a single scalar argument to a vector function.

\* \* \*

```

FUNCTION qromo(func,a,b,choose)
USE nrtype; USE nrutil, ONLY : nrerror
USE nr, ONLY : polint
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP) :: qromo
INTERFACE
  FUNCTION func(x)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), DIMENSION(:), INTENT(IN) :: x
  REAL(SP), DIMENSION(size(x)) :: func
  END FUNCTION func
  SUBROUTINE choose(funk,aa,bb,s,n)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: aa,bb
  REAL(SP), INTENT(INOUT) :: s
  INTEGER(I4B), INTENT(IN) :: n
  INTERFACE
    FUNCTION funk(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: funk
    END FUNCTION funk
  END INTERFACE
END SUBROUTINE choose
END INTERFACE
INTEGER(I4B), PARAMETER :: JMAX=14,JMAXP=JMAX+1,K=5,KM=K-1
REAL(SP), PARAMETER :: EPS=1.0e-6

```

Romberg integration on an open interval. Returns the integral of the function `func` from  $a$  to  $b$ , using any specified integrating subroutine `choose` and Romberg's method. Normally `choose` will be an open formula, not evaluating the function at the endpoints. It is assumed that `choose` triples the number of steps on each call, and that its error series contains only

```

even powers of the number of steps. The routines midpnt, midinf, midsql, midsqu,
and midexp are possible choices for choose. The parameters have the same meaning as
in qromb.
REAL(SP), DIMENSION(JMAXP) :: h,s
REAL(SP) :: dqromo
INTEGER(I4B) :: j
h(1)=1.0
do j=1,JMAX
  call choose(func,a,b,s(j),j)
  if (j >= K) then
    call polint(h(j-KM:j),s(j-KM:j),0.0_sp,qromo,dqromo)
    if (abs(dqromo) <= EPS*abs(qromo)) RETURN
  end if
  s(j+1)=s(j)
  h(j+1)=h(j)/9.0_sp      This is where the assumption of step tripling and an even
end do                    error series is used.
call nrerror('qromo: too many steps')
END FUNCTION qromo

```

\* \* \*

```

SUBROUTINE midinf(funk,aa,bb,s,n)
USE nrtype; USE nrutil, ONLY : arth,assert
IMPLICIT NONE
REAL(SP), INTENT(IN) :: aa,bb
REAL(SP), INTENT(INOUT) :: s
INTEGER(I4B), INTENT(IN) :: n
INTERFACE
  FUNCTION funk(x)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: x
  REAL(SP), DIMENSION(size(x)) :: funk
  END FUNCTION funk
END INTERFACE
This routine is an exact replacement for midpnt, i.e., returns as s the nth stage of refinement
of the integral of funk from aa to bb, except that the function is evaluated at evenly spaced
points in 1/x rather than in x. This allows the upper limit bb to be as large and positive
as the computer allows, or the lower limit aa to be as large and negative, but not both.
aa and bb must have the same sign.
REAL(SP) :: a,b,del
INTEGER(I4B) :: it
REAL(SP), DIMENSION(2*3**(n-2)) :: x
call assert(aa*bb > 0.0, 'midinf args')
b=1.0_sp/aa      These two statements change the limits of integration ac-
a=1.0_sp/bb      cordingly.
if (n == 1) then  From this point on, the routine is exactly identical to midpnt.
  s=(b-a)*sum(func( (/0.5_sp*(a+b)/ )) )
else
  it=3**(n-2)
  del=(b-a)/(3.0_sp*it)
  x(1:2*it-1:2)=arth(a+0.5_sp*del,3.0_sp*del,it)
  x(2:2*it:2)=x(1:2*it-1:2)+2.0_sp*del
  s=s/3.0_sp+del*sum(func(x))
end if
CONTAINS
  FUNCTION func(x)      This internal function effects the change of variable.
  REAL(SP), DIMENSION(:), INTENT(IN) :: x
  REAL(SP), DIMENSION(size(x)) :: func
  func=funk(1.0_sp/x)/x**2
  END FUNCTION func
END SUBROUTINE midinf

```

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**f90** FUNCTION `func(x)` The change of variable could have been effected by a statement function in `midinf` itself. However, the statement function is a Fortran 77 feature that is deprecated in Fortran 90 because it does not allow the benefits of having an explicit interface, i.e., a complete set of specification statements. Statement functions can always be coded as internal subprograms instead.

```

SUBROUTINE midsql(funk,aa,bb,s,n)
USE nrtype; USE nrutil, ONLY : arth
IMPLICIT NONE
REAL(SP), INTENT(IN) :: aa,bb
REAL(SP), INTENT(INOUT) :: s
INTEGER(I4B), INTENT(IN) :: n
INTERFACE
  FUNCTION funk(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: funk
  END FUNCTION funk
END INTERFACE
  This routine is an exact replacement for midpnt, i.e., returns as s the nth stage of refinement of the integral of funk from aa to bb, except that it allows for an inverse square-root singularity in the integrand at the lower limit aa.
REAL(SP) :: a,b,del
INTEGER(I4B) :: it
REAL(SP), DIMENSION(2*3**(n-2)) :: x
b=sqrt(bb-aa)      These two statements change the limits of integration accordingly.
a=0.0
if (n == 1) then  From this point on, the routine is exactly identical to midpnt.
  s=(b-a)*sum(func( (/0.5_sp*(a+b)/ )) )
else
  it=3**(n-2)
  del=(b-a)/(3.0_sp*it)
  x(1:2*it-1:2)=arth(a+0.5_sp*del,3.0_sp*del,it)
  x(2:2*it:2)=x(1:2*it-1:2)+2.0_sp*del
  s=s/3.0_sp+del*sum(func(x))
end if
CONTAINS
  FUNCTION func(x)      This internal function effects the change of variable.
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: funk
    func=2.0_sp*x*funk(aa+x**2)
  END FUNCTION func
END SUBROUTINE midsql

```

```

SUBROUTINE midsqu(funk,aa,bb,s,n)
USE nrtype; USE nrutil, ONLY : arth
IMPLICIT NONE
REAL(SP), INTENT(IN) :: aa,bb
REAL(SP), INTENT(INOUT) :: s
INTEGER(I4B), INTENT(IN) :: n
INTERFACE
  FUNCTION funk(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: funk
  END FUNCTION funk
END INTERFACE
  This routine is an exact replacement for midpnt, i.e., returns as s the nth stage of refinement of the integral of funk from aa to bb, except that it allows for an inverse square-root singularity in the integrand at the upper limit bb.
REAL(SP) :: a,b,del

```

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```

INTEGER(I4B) :: it
REAL(SP), DIMENSION(2*3**(n-2)) :: x
b=sqrt(bb-aa)           These two statements change the limits of integration ac-
a=0.0                   cordingly.
if (n == 1) then       From this point on, the routine is exactly identical to midpnt.
    s=(b-a)*sum(func( (/0.5_sp*(a+b)/) ))
else
    it=3**(n-2)
    del=(b-a)/(3.0_sp*it)
    x(1:2*it-1:2)=arth(a+0.5_sp*del,3.0_sp*del,it)
    x(2:2*it:2)=x(1:2*it-1:2)+2.0_sp*del
    s=s/3.0_sp+del*sum(func(x))
end if
CONTAINS
    FUNCTION func(x)    This internal function effects the change of variable.
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: func
    func=2.0_sp*x*funk(bb-x**2)
    END FUNCTION func
END SUBROUTINE midsqu

```

```

SUBROUTINE midexp(funk,aa,bb,s,n)
USE nrtype; USE nrutil, ONLY : arth
IMPLICIT NONE
REAL(SP), INTENT(IN) :: aa,bb
REAL(SP), INTENT(INOUT) :: s
INTEGER(I4B), INTENT(IN) :: n
INTERFACE
    FUNCTION funk(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: funk
    END FUNCTION funk
END INTERFACE
This routine is an exact replacement for midpnt, i.e., returns as s the nth stage of refinement
of the integral of funk from aa to bb, except that bb is assumed to be infinite (value passed
not actually used). It is assumed that the function funk decreases exponentially rapidly at
infinity.
REAL(SP) :: a,b,del
INTEGER(I4B) :: it
REAL(SP), DIMENSION(2*3**(n-2)) :: x
b=exp(-aa)           These two statements change the limits of integration ac-
a=0.0                   cordingly.
if (n == 1) then       From this point on, the routine is exactly identical to midpnt.
    s=(b-a)*sum(func( (/0.5_sp*(a+b)/) ))
else
    it=3**(n-2)
    del=(b-a)/(3.0_sp*it)
    x(1:2*it-1:2)=arth(a+0.5_sp*del,3.0_sp*del,it)
    x(2:2*it:2)=x(1:2*it-1:2)+2.0_sp*del
    s=s/3.0_sp+del*sum(func(x))
end if
CONTAINS
    FUNCTION func(x)    This internal function effects the change of variable.
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: func
    func=funk(-log(x))/x
    END FUNCTION func
END SUBROUTINE midexp

```

\* \* \*

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```

SUBROUTINE gauleg(x1,x2,x,w)
USE nrtype; USE nrutil, ONLY : arth,assert_eq,nrerror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x1,x2
REAL(SP), DIMENSION(:), INTENT(OUT) :: x,w
REAL(DP), PARAMETER :: EPS=3.0e-14_dp

  Given the lower and upper limits of integration x1 and x2, this routine returns arrays x and w
  of length N containing the abscissas and weights of the Gauss-Legendre N-point quadrature
  formula. The parameter EPS is the relative precision. Note that internal computations are
  done in double precision.

  INTEGER(I4B) :: its,j,m,n
  INTEGER(I4B), PARAMETER :: MAXIT=10
  REAL(DP) :: x1,xm
  REAL(DP), DIMENSION((size(x)+1)/2) :: p1,p2,p3,pp,z,z1
  LOGICAL(LGT), DIMENSION((size(x)+1)/2) :: unfinished
  n=assert_eq(size(x),size(w),'gauleg')
  m=(n+1)/2
  xm=0.5_dp*(x2+x1)
  x1=0.5_dp*(x2-x1)
  z=cos(PI_D*(arth(1,1,m)-0.25_dp)/(n+0.5_dp))
  unfinished=.true.
  do its=1,MAXIT
    where (unfinished)
      p1=1.0
      p2=0.0
    end where
    do j=1,n
      where (unfinished)
        p3=p2
        p2=p1
        p1=((2.0_dp*j-1.0_dp)*z*p2-(j-1.0_dp)*p3)/j
      end where
    end do
    p1 now contains the desired Legendre polynomials. We next compute pp, the derivatives,
    by a standard relation involving also p2, the polynomials of one lower order.
    where (unfinished)
      pp=n*(z*p1-p2)/(z*z-1.0_dp)
      z1=z
      z=z1-p1/pp
      unfinished=(abs(z-z1) > EPS)
    end where
    if (.not. any(unfinished)) exit
  end do
  if (its == MAXIT+1) call nrerror('too many iterations in gauleg')
  x(1:m)=xm-x1*z
  x(n-m+1:-1)=xm+x1*z
  w(1:m)=2.0_dp*x1/((1.0_dp-z**2)*pp**2)
  w(n-m+1:-1)=w(1:m)
END SUBROUTINE gauleg

```

The roots are symmetric in the interval, so we only have to find half of them.

Initial approximations to the roots.

Newton's method carried out simultaneously on the roots.

Loop up the recurrence relation to get the Legendre polynomials evaluated at z.

Newton's method.

Scale the root to the desired interval, and put in its symmetric counterpart.

Compute the weight and its symmetric counterpart.

**f** Often we have an iterative procedure that has to be applied until all components of a vector have satisfied a convergence criterion. Some components of the vector might converge sooner than others, and it is inefficient on a small-scale parallel (SSP) machine to continue iterating on those components. The general structure we use for such an iteration is exemplified by the following lines from `gauleg`:

```

LOGICAL(LGT), DIMENSION((size(x)+1)/2) :: unfinished
...
unfinished=.true.
do its=1,MAXIT

```

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```

      where (unfinished)
      ...
      unfinished=(abs(z-z1) > EPS)
    end where
    if (.not. any(unfinished)) exit
  end do
  if (its == MAXIT+1) call nrerror('too many iterations in gauleg')

```

We use the logical mask `unfinished` to control which vector components are processed inside the `where`. The mask gets updated on each iteration by testing whether any further vector components have converged. When all have converged, we exit the iteration loop. Finally, we check the value of `its` to see whether the maximum allowed number of iterations was exceeded before all components converged.

The logical expression controlling the `where` block (in this case `unfinished`) gets evaluated completely on entry into the `where`, and it is then perfectly fine to modify it inside the block. The modification affects only the *next* execution of the `where`.

On a strictly *serial* machine, there is of course some penalty associated with the above scheme: after a vector component converges, its corresponding component in `unfinished` is redundantly tested on each further iteration, until the slowest-converging component is done. If the number of iterations required does not vary too greatly from component to component, this is a minor, often negligible, penalty. However, one should be on the alert against algorithms whose worst-case convergence could differ from typical convergence by orders of magnitude. For these, one would need to implement a more complicated packing-unpacking scheme. (See discussion in Chapter B6, especially introduction, p. 1083, and notes for `factrl`, p. 1087.)

```

SUBROUTINE gaulag(x,w,alf)
USE nrtype; USE nrutil, ONLY : arth,assert_eq,nrerror
USE nr, ONLY : gammaln
IMPLICIT NONE
REAL(SP), INTENT(IN) :: alf
REAL(SP), DIMENSION(:), INTENT(OUT) :: x,w
REAL(DP), PARAMETER :: EPS=3.0e-13_dp
  Given alf, the parameter  $\alpha$  of the Laguerre polynomials, this routine returns arrays x and w
  of length N containing the abscissas and weights of the N-point Gauss-Laguerre quadrature
  formula. The abscissas are returned in ascending order. The parameter EPS is the relative
  precision. Note that internal computations are done in double precision.
INTEGER(I4B) :: its,j,n
INTEGER(I4B), PARAMETER :: MAXIT=10
REAL(SP) :: anu
REAL(SP), PARAMETER :: C1=9.084064e-01_sp,C2=5.214976e-02_sp,&
  C3=2.579930e-03_sp,C4=3.986126e-03_sp
REAL(SP), DIMENSION(size(x)) :: rhs,r2,r3,theta
REAL(DP), DIMENSION(size(x)) :: p1,p2,p3,pp,z,z1
LOGICAL(LGT), DIMENSION(size(x)) :: unfinished
n=assert_eq(size(x),size(w),'gauleg')
anu=4.0_sp*n+2.0_sp*alf+2.0_sp      Initial approximations to the roots go into z.
rhs=arth(4*n-1,-4,n)*PI/anu
r3=rhs**(1.0_sp/3.0_sp)
r2=r3**2
theta=r3*(C1+r2*(C2+r2*(C3+r2*C4)))
z=anu*cos(theta)**2
unfinished=.true.
do its=1,MAXIT
  where (unfinished)
    Newton's method carried out simultaneously on
    the roots.

```

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```

      p1=1.0
      p2=0.0
end where
do j=1,n
      where (unfinished)
      p3=p2
      p2=p1
      p1=((2.0_dp*j-1.0_dp+alf-z)*p2-(j-1.0_dp+alf)*p3)/j
      end where
end do
      p1 now contains the desired Laguerre polynomials. We next compute pp, the derivatives,
      by a standard relation involving also p2, the polynomials of one lower order.
      where (unfinished)
      pp=(n*p1-(n+alf)*p2)/z
      z1=z
      z=z1-p1/pp
      unfinished=(abs(z-z1) > EPS*z)
      end where
      if (.not. any(unfinished)) exit
end do
if (its == MAXIT+1) call nrerror('too many iterations in gaulag')
x=z
w=-exp(gammln(alf+n)-gammln(real(n,sp)))/(pp*n*p2)
END SUBROUTINE gaulag

```



The key difficulty in parallelizing this routine starting from the Fortran 77 version is that the initial guesses for the roots of the Laguerre polynomials were given in terms of previously determined roots. This prevents one from finding all the roots simultaneously. The solution is to come up with a new approximation to the roots that is a simple explicit formula, like the formula we used for the Legendre roots in `gaulag`.

We start with the approximation to  $L_n^\alpha(x)$  given in equation (10.15.8) of [1]. We keep only the first term and ask when it is zero. This gives the following prescription for the  $k$ th root  $x_k$  of  $L_n^\alpha(x)$ : Solve for  $\theta$  the equation

$$2\theta - \sin 2\theta = \frac{4n - 4k + 3}{4n + 2\alpha + 2} \pi \quad (\text{B4.1})$$

Since  $1 \leq k \leq n$  and  $\alpha > -1$ , we can always find a value such that  $0 < \theta < \pi/2$ . Then the approximation to the root is

$$x_k = (4n + 2\alpha + 2) \cos^2 \theta \quad (\text{B4.2})$$

This typically gives 3-digit accuracy, more than enough for the Newton iteration to be able to refine the root. Unfortunately equation (B4.1) is not an explicit formula for  $\theta$ . (You may recognize it as being of the same form as Kepler's equation in mechanics.) If we call the right-hand side of (B4.1)  $y$ , then we can get an explicit formula by working out the power series for  $y^{1/3}$  near  $\theta = 0$  (using a computer algebra program). Next invert the series to give  $\theta$  as a function of  $y^{1/3}$ . Finally, economize the series (see §5.11). The result is the concise approximation

$$\theta = 0.9084064y^{1/3} + 5.214976 \times 10^{-2}y + 2.579930 \times 10^{-3}y^{5/3} + 3.986126 \times 10^{-3}y^{7/3} \quad (\text{B4.3})$$

```

SUBROUTINE gauher(x,w)
USE nrtype; USE nrutil, ONLY : arth,assert_eq,nrerror
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(OUT) :: x,w
REAL(DP), PARAMETER :: EPS=3.0e-13_dp,PIM4=0.7511255444649425_dp
  This routine returns arrays x and w of length N containing the abscissas and weights of
  the N-point Gauss-Hermite quadrature formula. The abscissas are returned in descending
  order. Note that internal computations are done in double precision.
  Parameters: EPS is the relative precision, PIM4 = 1/π1/4.
INTEGER(I4B) :: its,j,m,n
INTEGER(I4B), PARAMETER :: MAXIT=10
REAL(SP) :: anu
REAL(SP), PARAMETER :: C1=9.084064e-01_sp,C2=5.214976e-02_sp,&
  C3=2.579930e-03_sp,C4=3.986126e-03_sp
REAL(SP), DIMENSION((size(x)+1)/2) :: rhs,r2,r3,theta
REAL(DP), DIMENSION((size(x)+1)/2) :: p1,p2,p3,pp,z,z1
LOGICAL(LGT), DIMENSION((size(x)+1)/2) :: unfinished
n=assert_eq(size(x),size(w),'gauher')
m=(n+1)/2
  The roots are symmetric about the origin, so we have to
  find only half of them.
anu=2.0_sp*n+1.0_sp
rhs=arth(3,4,m)*PI/anu
r3=rhs**(1.0_sp/3.0_sp)
r2=r3**2
theta=r3*(C1+r2*(C2+r2*(C3+r2*C4)))
z=sqrt(anu)*cos(theta)
  Initial approximations to the roots.
unfinished=.true.
do its=1,MAXIT
  Newton's method carried out simultaneously on the roots.
  where (unfinished)
    p1=PIM4
    p2=0.0
  end where
  do j=1,n
    Loop up the recurrence relation to get the Hermite poly-
    nomials evaluated at z.
    where (unfinished)
      p3=p2
      p2=p1
      p1=z*sqrt(2.0_dp/j)*p2-sqrt(real(j-1,dp)/real(j,dp))*p3
    end where
  end do
  p1 now contains the desired Hermite polynomials. We next compute pp, the derivatives,
  by the relation (4.5.21) using p2, the polynomials of one lower order.
  where (unfinished)
    pp=sqrt(2.0_dp*n)*p2
    z1=z
    z=z1-p1/pp
    Newton's formula.
    unfinished=(abs(z-z1) > EPS)
  end where
  if (.not. any(unfinished)) exit
end do
if (its == MAXIT+1) call nrerror('too many iterations in gauher')
x(1:m)=z
  Store the root
  and its symmetric counterpart.
x(n:n-m+1:-1)=-z
w(1:m)=2.0_dp/pp**2
  Compute the weight
w(n:n-m+1:-1)=w(1:m)
  and its symmetric counterpart.
END SUBROUTINE gauher

```



Once again we need an explicit approximation for the polynomial roots, this time for  $H_n(x)$ . We can use the same approximation scheme as for  $L_n^\alpha(x)$ , since

$$H_{2m}(x) \propto L_m^{-1/2}(x^2), \quad H_{2m+1}(x) \propto xL_m^{1/2}(x^2) \quad (\text{B4.4})$$

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Equations (B4.1) and (B4.2) become

$$2\theta - \sin 2\theta = \frac{4k-1}{2n+1}\pi \quad (\text{B4.5})$$

$$x_k = \sqrt{2n+1} \cos \theta$$

Here  $k = 1, 2, \dots, m$  where  $m = [(n+1)/2]$ , and  $k = 1$  is the largest root. The negative roots follow from symmetry. The root at  $x = 0$  for odd  $n$  is included in this approximation.

```

SUBROUTINE gaujac(x,w,alf,bet)
USE nrtype; USE nrutil, ONLY : arth,assert_eq,nrerror
USE nr, ONLY : gammln
IMPLICIT NONE
REAL(SP), INTENT(IN) :: alf,bet
REAL(SP), DIMENSION(:), INTENT(OUT) :: x,w
REAL(DP), PARAMETER :: EPS=3.0e-14_dp
    Given alf and bet, the parameters  $\alpha$  and  $\beta$  of the Jacobi polynomials, this routine returns
    arrays x and w of length  $N$  containing the abscissas and weights of the  $N$ -point Gauss-
    Jacobi quadrature formula. The abscissas are returned in descending order. The parameter
    EPS is the relative precision. Note that internal computations are done in double precision.
INTEGER(I4B) :: its,j,n
INTEGER(I4B), PARAMETER :: MAXIT=10
REAL(DP) :: alfbet,a,c,temp
REAL(DP), DIMENSION(size(x)) :: b,p1,p2,p3,pp,z,z1
LOGICAL(LGT), DIMENSION(size(x)) :: unfinished
n=assert_eq(size(x),size(w),'gaujac')
alfbet=alf+bet          Initial approximations to the roots go into z.
z=cos(PI*(arth(1,1,n)-0.25_dp+0.5_dp*alf)/(n+0.5_dp*(alfbet+1.0_dp)))
unfinished=.true.
do its=1,MAXIT          Newton's method carried out simultaneously on the roots.
    temp=2.0_dp+alfbet
    where (unfinished)  Start the recurrence with  $P_0$  and  $P_1$  to avoid a division
        p1=(alf-bet+temp*z)/2.0_dp          by zero when  $\alpha + \beta = 0$  or  $-1$ .
        p2=1.0
    end where
    do j=2,n            Loop up the recurrence relation to get the Jacobi poly-
        a=2*j*(j+alfbet)*temp              nomials evaluated at z.
        temp=temp+2.0_dp
        c=2.0_dp*(j-1.0_dp+alf)*(j-1.0_dp+bet)*temp
        where (unfinished)
            p3=p2
            p2=p1
            b=(temp-1.0_dp)*(alf*alf-bet*bet+temp*&
                (temp-2.0_dp)*z)
            p1=(b*p2-c*p3)/a
        end where
    end do
    p1 now contains the desired Jacobi polynomials. We next compute pp, the derivatives,
    by a standard relation involving also p2, the polynomials of one lower order.
    where (unfinished)
        pp=(n*(alf-bet-temp*z)*p1+2.0_dp*(n+alf)*&
            (n+bet)*p2)/(temp*(1.0_dp-z*z))
        z1=z
        z=z1-p1/pp          Newton's formula.
        unfinished=(abs(z-z1) > EPS)
    end where
    if (.not. any(unfinished)) exit
end do
if (its == MAXIT+1) call nrerror('too many iterations in gaujac')
x=z          Store the root and the weight.

```

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```
w=exp(gammln(alf+n)+gammln(bet+n)-gammln(n+1.0_sp)-&
      gammln(n+alf+bet+1.0_sp))*temp*2.0_sp**alfbet/(pp*p2)
END SUBROUTINE gaujac
```



Now we need an explicit approximation for the roots of the Jacobi polynomials  $P_n^{(\alpha,\beta)}(x)$ . We start with the asymptotic expansion (10.14.10) of [1]. Setting this to zero gives the formula

$$x = \cos \left[ \frac{k - 1/4 + \alpha/2}{n + (\alpha + \beta + 1)/2} \pi \right] \quad (\text{B4.6})$$

This is better than the formula (22.16.1) in [2], especially at small and moderate  $n$ .

\* \* \*

```
SUBROUTINE gaucof(a,b,amu0,x,w)
USE nrtype; USE nrutil, ONLY : assert_eq,unit_matrix
USE nr, ONLY : eigsrt,tqli
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: a,b
REAL(SP), INTENT(IN) :: amu0
REAL(SP), DIMENSION(:), INTENT(OUT) :: x,w
  Computes the abscissas and weights for a Gaussian quadrature formula from the Jacobi
  matrix. On input, a and b of length N are the coefficients of the recurrence relation for the
  set of monic orthogonal polynomials. The quantity  $\mu_0 \equiv \int_a^b W(x) dx$  is input as amu0. The
  abscissas are returned in descending order in array x of length N, with the corresponding
  weights in w, also of length N. The arrays a and b are modified. Execution can be speeded
  up by modifying tqli and eigsrt to compute only the first component of each eigenvector.
REAL(SP), DIMENSION(size(a),size(a)) :: z
INTEGER(I4B) :: n
n=assert_eq(size(a),size(b),size(x),size(w),'gaucof')
b(2:n)=sqrt(b(2:n))      Set up superdiagonal of Jacobi matrix.
call unit_matrix(z)      Set up identity matrix for tqli to compute eigenvectors.
call tqli(a,b,z)
call eigsrt(a,z)         Sort eigenvalues into descending order.
x=a
w=amu0*z(1,:)**2        Equation (4.5.12).
END SUBROUTINE gaucof
```

\* \* \*

```
SUBROUTINE orthog(anu,alpha,beta,a,b)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: anu,alpha,beta
REAL(SP), DIMENSION(:), INTENT(OUT) :: a,b
  Computes the coefficients  $a_j$  and  $b_j$ ,  $j = 0, \dots, N-1$ , of the recurrence relation for monic orthogonal
  polynomials with weight function  $W(x)$  by Wheeler's algorithm. On input, alpha
  and beta contain the  $2N-1$  coefficients  $\alpha_j$  and  $\beta_j$ ,  $j = 0, \dots, 2N-2$ , of the recurrence
```

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relation for the chosen basis of orthogonal polynomials. The  $2N$  modified moments  $\nu_j$  are input in `anu` for  $j = 0, \dots, 2N - 1$ . The first  $N$  coefficients are returned in `a` and `b`.

```

INTEGER(I4B) :: k,n,ndum
REAL(SP), DIMENSION(2*size(a)+1,2*size(a)+1) :: sig
n=assert_eq(size(a),size(b),'orthog: n')
ndum=assert_eq(2*n,size(alpha)+1,size(anu),size(beta)+1,'orthog: ndum')
sig(1,3:2*n)=0.0           Initialization, Equation (4.5.33).
sig(2,2:2*n+1)=anu(1:2*n)
a(1)=alpha(1)+anu(2)/anu(1)
b(1)=0.0
do k=3,n+1
    Equation (4.5.34).
    sig(k,k:2*n-k+3)=sig(k-1,k+1:2*n-k+4)+(alpha(k-1:2*n-k+2) &
        -a(k-2))*sig(k-1,k:2*n-k+3)-b(k-2)*sig(k-2,k:2*n-k+3) &
        +beta(k-1:2*n-k+2)*sig(k-1,k-1:2*n-k+2)
    a(k-1)=alpha(k-1)+sig(k,k+1)/sig(k,k)-sig(k-1,k)/sig(k-1,k-1)
    b(k-1)=sig(k,k)/sig(k-1,k-1)
end do
END SUBROUTINE orthog

```

\* \* \*

**f90**

As discussed in Volume 1, multidimensional quadrature can be performed by calling a one-dimensional quadrature routine along each dimension.

If the same routine is used for all such calls, then the calls are recursive. The file `quad3d.f90` contains two modules, `quad3d_qgaus_mod` and `quad3d_qromb_mod`. In the first, the basic one-dimensional quadrature routine is a 10-point Gaussian quadrature routine called `qgaus` and three-dimensional quadrature is performed by calling `quad3d_qgaus`. In the second, the basic one-dimensional routine is `qromb` of §4.3 and the three-dimensional routine is `quad3d_qromb`. The Gaussian quadrature is simpler but its accuracy is not controllable. The Romberg integration lets you specify an accuracy, but is apt to be very slow if you try for too much accuracy. The only difference between the stand-alone version of `trapzd` and the version included here is that we have to add the keyword `RECURSIVE`. The only changes from the stand-alone version of `qromb` are: We have to add `RECURSIVE`; we remove `trapzd` from the list of routines in `USE nr`; we increase `EPS` to  $3 \times 10^{-6}$ . Even this value could be too ambitious for difficult functions. You may want to set `JMAX` to a smaller value than 20 to avoid burning up a lot of computer time. Some people advocate using a smaller `EPS` on the inner quadrature (over  $z$  in our routine) than on the outer quadratures (over  $x$  or  $y$ ). That strategy would require separate copies of `qromb`.

```

MODULE quad3d_qgaus_mod
USE nrtype
PRIVATE
PUBLIC quad3d_qgaus
REAL(SP) :: xsav,ysav
INTERFACE
    FUNCTION func(x,y,z)
        The three-dimensional function to be integrated.
        USE nrtype
        REAL(SP), INTENT(IN) :: x,y
        REAL(SP), DIMENSION(:), INTENT(IN) :: z
        REAL(SP), DIMENSION(size(z)) :: func
    END FUNCTION func
    FUNCTION y1(x)
        USE nrtype

```

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```

REAL(SP), INTENT(IN) :: x
REAL(SP) :: y1
END FUNCTION y1

FUNCTION y2(x)
USE nrtype
REAL(SP), INTENT(IN) :: x
REAL(SP) :: y2
END FUNCTION y2

FUNCTION z1(x,y)
USE nrtype
REAL(SP), INTENT(IN) :: x,y
REAL(SP) :: z1
END FUNCTION z1

FUNCTION z2(x,y)
USE nrtype
REAL(SP), INTENT(IN) :: x,y
REAL(SP) :: z2
END FUNCTION z2
END INTERFACE

The routine quad3d_qgaus returns as ss the integral of a user-supplied function func
over a three-dimensional region specified by the limits x1, x2, and by the user-supplied
functions y1, y2, z1, and z2, as defined in (4.6.2). Integration is performed by calling
qgaus recursively.

CONTAINS

FUNCTION h(x) This is H of eq. (4.6.5).
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: h
INTEGER(I4B) :: i
do i=1,size(x)
  xsav=x(i)
  h(i)=qgaus(g,y1(xsav),y2(xsav))
end do
END FUNCTION h

FUNCTION g(y) This is G of eq. (4.6.4).
REAL(SP), DIMENSION(:), INTENT(IN) :: y
REAL(SP), DIMENSION(size(y)) :: g
INTEGER(I4B) :: j
do j=1,size(y)
  ysav=y(j)
  g(j)=qgaus(f,z1(xsav,ysav),z2(xsav,ysav))
end do
END FUNCTION g

FUNCTION f(z) The integrand f(x,y,z) evaluated at fixed x and y.
REAL(SP), DIMENSION(:), INTENT(IN) :: z
REAL(SP), DIMENSION(size(z)) :: f
f=func(xsav,ysav,z)
END FUNCTION f

RECURSIVE FUNCTION qgaus(func,a,b)
REAL(SP), INTENT(IN) :: a,b
REAL(SP) :: qgaus
INTERFACE
  FUNCTION func(x)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: x
  REAL(SP), DIMENSION(size(x)) :: func
  END FUNCTION func
END INTERFACE
REAL(SP) :: xm,xr
REAL(SP), DIMENSION(5) :: dx, w = (/ 0.2955242247_sp,0.2692667193_sp,&
0.2190863625_sp,0.1494513491_sp,0.0666713443_sp /),&
x = (/ 0.1488743389_sp,0.4333953941_sp,0.6794095682_sp,&

```

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```

    0.8650633666_sp,0.9739065285_sp /)
xm=0.5_sp*(b+a)
xr=0.5_sp*(b-a)
dx(:)=xr*x(:)
qgaus=xr*sum(w(:)*(func(xm+dx)+func(xm-dx)))
END FUNCTION qgaus

SUBROUTINE quad3d_qgaus(x1,x2,ss)
REAL(SP), INTENT(IN) :: x1,x2
REAL(SP), INTENT(OUT) :: ss
ss=qgaus(h,x1,x2)
END SUBROUTINE quad3d_qgaus
END MODULE quad3d_qgaus_mod

```

**f90** PRIVATE...PUBLIC quad3d\_qgaus By default, all module entities are accessible by a routine that uses the module (unless we restrict the USE statement with ONLY). In this module, the user needs access only to the routine quad3d\_qgaus; the variables xsav, ysav and the procedures f, g, h, and qgaus are purely internal. It is good programming practice to prevent duplicate name conflicts or data overwriting by limiting access to only the desired entities. Here the PRIVATE statement with no variable names resets the default from PUBLIC. Then we include in the PUBLIC statement only the function name we want to be accessible.

REAL(SP) :: xsav,ysav In Fortran 90, we generally avoid declaring global variables in COMMON blocks. Instead, we give them complete specifications in a module. A deficiency of Fortran 90 is that it does not allow pointers to functions. So here we have to use the fixed-name function func for the function to be integrated over. If we could have a pointer to a function as a global variable, then we would just set the pointer to point to the user function (of any name) in the calling program. Similarly the functions y1, y2, z1, and z2 could also have any name.

CONTAINS Here follow the internal subprograms f, g, h, qgaus, and quad3d\_qgaus. Note that such internal subprograms are all “visible” to each other, i.e., their interfaces are mutually explicit, and do not require INTERFACE statements.

RECURSIVE SUBROUTINE qgaus(func,a,b,ss) The RECURSIVE keyword is required for the compiler to process correctly any procedure that is invoked again in its body before the return from the first call has been completed. While some compilers may let you get away without explicitly informing them that a routine is recursive, don’t count on it!

```

MODULE quad3d_qromb_mod
  Alternative to quad3d_qgaus_mod that uses qromb to perform each one-dimensional
  integration.
  USE nrtype
  PRIVATE
  PUBLIC quad3d_qromb
  REAL(SP) :: xsav,ysav
  INTERFACE
    FUNCTION func(x,y,z)
      USE nrtype
      REAL(SP), INTENT(IN) :: x,y
      REAL(SP), DIMENSION(:), INTENT(IN) :: z
      REAL(SP), DIMENSION(size(z)) :: func
    END FUNCTION func
  END INTERFACE
  FUNCTION y1(x)

```

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```

USE nrtype
REAL(SP), INTENT(IN) :: x
REAL(SP) :: y1
END FUNCTION y1

FUNCTION y2(x)
USE nrtype
REAL(SP), INTENT(IN) :: x
REAL(SP) :: y2
END FUNCTION y2

FUNCTION z1(x,y)
USE nrtype
REAL(SP), INTENT(IN) :: x,y
REAL(SP) :: z1
END FUNCTION z1

FUNCTION z2(x,y)
USE nrtype
REAL(SP), INTENT(IN) :: x,y
REAL(SP) :: z2
END FUNCTION z2
END INTERFACE
CONTAINS

FUNCTION h(x)
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: h
INTEGER(I4B) :: i
do i=1,size(x)
  xsav=x(i)
  h(i)=qromb(g,y1(xsav),y2(xsav))
end do
END FUNCTION h

FUNCTION g(y)
REAL(SP), DIMENSION(:), INTENT(IN) :: y
REAL(SP), DIMENSION(size(y)) :: g
INTEGER(I4B) :: j
do j=1,size(y)
  ysav=y(j)
  g(j)=qromb(f,z1(xsav,ysav),z2(xsav,ysav))
end do
END FUNCTION g

FUNCTION f(z)
REAL(SP), DIMENSION(:), INTENT(IN) :: z
REAL(SP), DIMENSION(size(z)) :: f
f=func(xsav,ysav,z)
END FUNCTION f

RECURSIVE FUNCTION qromb(func,a,b)
USE nrtype; USE nrutil, ONLY : nrerror
USE nr, ONLY : polint
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP) :: qromb
INTERFACE
  FUNCTION func(x)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: x
  REAL(SP), DIMENSION(size(x)) :: func
  END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: JMAX=20,JMAXP=JMAX+1,K=5,KM=K-1
REAL(SP), PARAMETER :: EPS=3.0e-6_sp
REAL(SP), DIMENSION(JMAXP) :: h,s
REAL(SP) :: dqromb

```

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```

INTEGER(I4B) :: j
h(1)=1.0
do j=1,JMAX
  call trapzd(func,a,b,s(j),j)
  if (j >= K) then
    call polint(h(j-KM:j),s(j-KM:j),0.0_sp,qromb,dqromb)
    if (abs(dqromb) <= EPS*abs(qromb)) RETURN
  end if
  s(j+1)=s(j)
  h(j+1)=0.25_sp*h(j)
end do
call nrerror('qromb: too many steps')
END FUNCTION qromb

RECURSIVE SUBROUTINE trapzd(func,a,b,s,n)
USE nrtype; USE nrutil, ONLY : arth
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP), INTENT(INOUT) :: s
INTEGER(I4B), INTENT(IN) :: n
INTERFACE
  FUNCTION func(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: func
  END FUNCTION func
END INTERFACE
REAL(SP) :: del,fsum
INTEGER(I4B) :: it
if (n == 1) then
  s=0.5_sp*(b-a)*sum(func( (/ a,b /) ))
else
  it=2**(n-2)
  del=(b-a)/it
  fsum=sum(func(arth(a+0.5_sp*del,del,it)))
  s=0.5_sp*(s+del*fsum)
end if
END SUBROUTINE trapzd

SUBROUTINE quad3d_qromb(x1,x2,ss)
REAL(SP), INTENT(IN) :: x1,x2
REAL(SP), INTENT(OUT) :: ss
ss=qromb(h,x1,x2)
END SUBROUTINE quad3d_qromb
END MODULE quad3d_qromb_mod

```

MODULE `quad3d_qromb_mod` The only difference between this module and the previous one is that all calls to `qgaus` are replaced by calls to `qromb` and that the routine `qgaus` is replaced by `qromb` and `trapzd`.

#### CITED REFERENCES AND FURTHER READING:

- Erdélyi, A., Magnus, W., Oberhettinger, F., and Tricomi, F.G. 1953, *Higher Transcendental Functions*, Volume II (New York: McGraw-Hill). [1]
- Abramowitz, M., and Stegun, I.A. 1964, *Handbook of Mathematical Functions*, Applied Mathematics Series, Volume 55 (Washington: National Bureau of Standards; reprinted 1968 by Dover Publications, New York). [2]

## Chapter B5. Evaluation of Functions

```

SUBROUTINE eulsum(sum,term,jterm)
USE nrtype; USE nrutil, ONLY : poly_term,reallocate
IMPLICIT NONE
REAL(SP), INTENT(INOUT) :: sum
REAL(SP), INTENT(IN) :: term
INTEGER(I4B), INTENT(IN) :: jterm
    Incorporates into sum the jterm'th term, with value term, of an alternating series. sum
    is input as the previous partial sum, and is output as the new partial sum. The first call
    to this routine, with the first term in the series, should be with jterm=1. On the second
    call, term should be set to the second term of the series, with sign opposite to that of the
    first call, and jterm should be 2. And so on.
REAL(SP), DIMENSION(:), POINTER, SAVE :: wksp
INTEGER(I4B), SAVE :: nterm                Number of saved differences in wksp.
LOGICAL(LGT), SAVE :: init=.true.
if (init) then                             Initialize.
    init=.false.
    nullify(wksp)
end if
if (jterm == 1) then
    nterm=1
    wksp=>reallocate(wksp,100)
    wksp(1)=term
    sum=0.5_sp*term                          Return first estimate.
else
    if (nterm+1 > size(wksp)) wksp=>reallocate(wksp,2*size(wksp))
    wksp(2:nterm+1)=0.5_sp*wksp(1:nterm)      Update saved quantities by van Wijn-
    wksp(1)=term                             gaarden's algorithm.
    wksp(1:nterm+1)=poly_term(wksp(1:nterm+1),0.5_sp)
    if (abs(wksp(nterm+1)) <= abs(wksp(nterm))) then    Favorable to increase p,
        sum=sum+0.5_sp*wksp(nterm+1)
        nterm=nterm+1                                and the table becomes longer.
    else                                           Favorable to increase n,
        sum=sum+wksp(nterm+1)                        the table doesn't become longer.
    end if
end if
END SUBROUTINE eulsum

```

**f90** This routine uses the function `reallocate` in `nrutil` to define a temporary workspace and then, if necessary, enlarge the workspace without destroying the earlier contents. The pointer `wksp` is declared with the `SAVE` attribute. Since Fortran 90 pointers are born “in limbo,” we cannot immediately test whether they are associated or not. Hence the code `if (init)...nullify(wksp)`. Then the line `wksp=>reallocate(wksp,100)` allocates an array of length 100 and points `wksp` to it. On subsequent calls to `eulsum`, if `nterm` ever gets bigger than the size of `wksp`, the call to `reallocate` doubles the size of `wksp` and copies the old contents into the new storage.

You could achieve the same effect as the code `if (init)...nullify(wksp)...wksp=>reallocate(wksp,100)` with a simple `allocate(wksp,100)`. You would then use


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reallocate only for increasing the storage if necessary. Don't! The advantage of the above scheme becomes clear if you consider what happens if `eulsum` is invoked *twice* by the calling program to evaluate two different sums. On the second invocation, when `jterm = 1` again, you would be allocating an already allocated pointer. This does not generate an error — it simply leaves the original target inaccessible. Using `reallocate` instead not only allocates a new array of length 100, but also detects that `wksp` had already been associated. It dutifully (and wastefully) copies the first 100 elements of the old `wksp` into the new storage, and, more importantly, deallocates the old `wksp`, reclaiming its storage. While only two invocations of `eulsum` without intervening deallocation of memory would not cause a problem, many such invocations might well. We believe that, as a general rule, the potential for catastrophe from reckless use of `allocate` is great enough that you should *always* deallocate whenever storage is no longer required.

The unnecessary copying of 100 elements when `eulsum` is invoked a second time could be avoided by making `init` an argument. It hardly seems worth it to us.

For Fortran 90 neophytes, note that unlike in C you have to do nothing special to get the contents of the storage a pointer is addressing. The compiler figures out from the context whether you mean the contents, such as `wksp(1:nterm)`, or the address, such as both occurrences of `wksp` in `wksp=>reallocate(wksp,100)`.

`wksp(1:nterm+1)=poly_term(wksp(1:nterm+1),0.5_sp)` The `poly_term` function in `nrutil` tabulates the partial sums of a polynomial, or, equivalently, performs the synthetic division of a polynomial by a monomial.

 Small-scale parallelism in `eulsum` is achieved straightforwardly by the use of vector constructions and `poly_term` (which parallelizes recursively). The routine is not written to take advantage of data parallelism in the (infrequent) case of wanting to sum many different series simultaneously; nor, since `wksp` is a `SAVED` variable, can it be used in many simultaneous instances on a MIMD machine. (You can easily recode these generalizations if you need them.)

\* \* \*

```

SUBROUTINE ddpoly(c,x,pd)
USE nrtype; USE nrutil, ONLY : arth,cumprod,poly_term
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(IN) :: c
REAL(SP), DIMENSION(:), INTENT(OUT) :: pd
    Given the coefficients of a polynomial of degree  $N_c - 1$  as an array  $c(1:N_c)$  with  $c(1)$ 
    being the constant term, and given a value  $x$ , this routine returns the polynomial evaluated
    at  $x$  as  $pd(1)$  and  $N_d - 1$  derivatives as  $pd(2:N_d)$ .
INTEGER(I4B) :: i,nc,nd
REAL(SP), DIMENSION(size(pd)) :: fac
REAL(SP), DIMENSION(size(c)) :: d
nc=size(c)
nd=size(pd)
d(nc:1:-1)=poly_term(c(nc:1:-1),x)
do i=2,min(nd,nc)
    d(nc:i:-1)=poly_term(d(nc:i:-1),x)
end do
pd=d(1:nd)
fac=cumprod(arth(1.0_sp,1.0_sp,nd))
pd(3:nd)=fac(2:nd-1)*pd(3:nd)
END SUBROUTINE ddpoly

```

After the first derivative, factorial constants  
come in.

**f90** `d(nc:1:-1)=poly_term(c(nc:1:-1),x)` The `poly_term` function in `nrutil` tabulates the partial sums of a polynomial, or, equivalently, performs synthetic division. See §22.3 for a discussion of why `ddpoly` is coded this way.

`fac=cumprod(arth(1.0_sp,1.0_sp,nd))` Here the function `arth` from `nrutil` generates the sequence 1, 2, 3, ... The function `cumprod` then tabulates the cumulative products, thus making a table of factorials.

Notice that `ddpoly` doesn't need an argument to pass  $N_d$ , the number of output terms desired by the user: It gets that information from the length of the array `pd` that the user provides for it to fill. It is a minor curiosity that `pd`, declared as `INTENT(OUT)`, can thus be used, on the sly, to pass some `INTENT(IN)` information. (A Fortran 90 brain teaser could be: A subroutine with only `INTENT(OUT)` arguments can be called to print any specified integer. How is this done?)

```
SUBROUTINE poldiv(u,v,q,r)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: u,v
REAL(SP), DIMENSION(:), INTENT(OUT) :: q,r
  Given the  $N$  coefficients of a polynomial in  $u$ , and the  $N_v$  coefficients of another polynomial in  $v$ , divide the polynomial  $u$  by the polynomial  $v$  ("u"/"v") giving a quotient polynomial whose coefficients are returned in  $q$ , and a remainder polynomial whose coefficients are returned in  $r$ . The arrays  $q$  and  $r$  are of length  $N$ , but only the first  $N - N_v + 1$  elements of  $q$  and the first  $N_v - 1$  elements of  $r$  are used. The remaining elements are returned as zero.
INTEGER(I4B) :: i,n,nv
n=assert_eq(size(u),size(q),size(r),'poldiv')
nv=size(v)
r(:)=u(:)
q(:)=0.0
do i=n-nv,0,-1
  q(i+1)=r(nv+i)/v(nv)
  r(i+1:nv+i-1)=r(i+1:nv+i-1)-q(i+1)*v(1:nv-1)
end do
r(nv:n)=0.0
END SUBROUTINE poldiv
```

\* \* \*

```
FUNCTION ratval_s(x,cof,mm,kk)
USE nrtype; USE nrutil, ONLY : poly
IMPLICIT NONE
REAL(DP), INTENT(IN) :: x          Note precision! Change to REAL(SP) if desired.
INTEGER(I4B), INTENT(IN) :: mm,kk
REAL(DP), DIMENSION(mm+kk+1), INTENT(IN) :: cof
REAL(DP) :: ratval_s
  Given mm, kk, and cof(1:mm+kk+1), evaluate and return the rational function  $(\text{cof}(1) + \text{cof}(2)x + \dots + \text{cof}(mm+1)x^{mm}) / (1 + \text{cof}(mm+2)x + \dots + \text{cof}(mm+kk+1)x^{kk})$ .
  ratval_s=poly(x,cof(1:mm+1))/(1.0_dp+x*poly(x,cof(mm+2:mm+kk+1)))
END FUNCTION ratval_s
```

**f90** This simple routine uses the function `poly` from `nrutil` to evaluate the numerator and denominator polynomials. Single- and double-precision versions, `ratval_s` and `ratval_v`, are overloaded onto the name `ratval` when the module `nr` is used.

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```

FUNCTION ratval_v(x,cof,mm,kk)
USE nrtype; USE nrutil, ONLY : poly
IMPLICIT NONE
REAL(DP), DIMENSION(:), INTENT(IN) :: x
INTEGER(I4B), INTENT(IN) :: mm,kk
REAL(DP), DIMENSION(mm+kk+1), INTENT(IN) :: cof
REAL(DP), DIMENSION(size(x)) :: ratval_v
ratval_v=poly(x,cof(1:mm+1))/(1.0_dp+x*poly(x,cof(mm+2:mm+kk+1)))
END FUNCTION ratval_v

```

\* \* \*

The routines `recur1` and `recur2` are new in this volume, and do not have Fortran 77 counterparts. First- and second-order linear recurrences are implemented as trivial do-loops on strictly serial machines. On parallel machines, however, they pose different, and quite interesting, programming challenges. Since many calculations can be decomposed into recurrences, it is useful to have general, parallelizable routines available. The algorithms behind `recur1` and `recur2` are discussed in §22.2.

```

RECURSIVE FUNCTION recur1(a,b) RESULT(u)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: a,b
REAL(SP), DIMENSION(size(a)) :: u
INTEGER(I4B), PARAMETER :: NPAR_RECUR1=8
    Given vectors a of size n and b of size n - 1, returns a vector u that satisfies the first
    order linear recurrence  $u_1 = a_1$ ,  $u_j = a_j + b_{j-1}u_{j-1}$ , for  $j = 2, \dots, n$ . Parallelization is
    via a recursive evaluation.
INTEGER(I4B) :: n,j
n=assert_eq(size(a),size(b)+1,'recur1')
u(1)=a(1)
if (n < NPAR_RECUR1) then          Do short vectors as a loop.
    do j=2,n
        u(j)=a(j)+b(j-1)*u(j-1)
    end do
else
    Otherwise, combine coefficients and recurse on the even components, then evaluate all
    the odd components in parallel.
    u(2:n:2)=recur1(a(2:n:2)+a(1:n-1:2)*b(1:n-1:2), &
        b(3:n-1:2)*b(2:n-2:2))
    u(3:n:2)=a(3:n:2)+b(2:n-1:2)*u(2:n-1:2)
end if
END FUNCTION recur1

```

**f90** RECURSIVE FUNCTION `recur1(a,b) RESULT(u)` When a recursive function invokes itself only indirectly through a sequence of function calls, then the function name can be used for the result just as in a nonrecursive function. When the function invokes itself directly, however, as in `recur1`, then another name must be used for the result. If you are hazy on the syntax for `RESULT`, see the discussion of recursion in §21.5.

\* \* \*

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```

FUNCTION recur2(a,b,c)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: a,b,c
REAL(SP), DIMENSION(size(a)) :: recur2
  Given vectors a of size n and b and c of size n-2, returns a vector u that satisfies the second
  order linear recurrence  $u_1 = a_1, u_2 = a_2, u_j = a_j + b_{j-2}u_{j-1} + c_{j-2}u_{j-2}$ , for  $j = 3, \dots, n$ .
  Parallelization is via conversion to a first order recurrence for a two-dimensional vector.
INTEGER(I4B) :: n
REAL(SP), DIMENSION(size(a)-1) :: a1,a2,u1,u2
REAL(SP), DIMENSION(size(a)-2) :: b11,b12,b21,b22
n=assert_eq(size(a),size(b)+2,size(c)+2,'recur2')
a1(1)=a(1)           Set up vector a.
a2(1)=a(2)
a1(2:n-1)=0.0
a2(2:n-1)=a(3:n)
b11(1:n-2)=0.0           Set up matrix b.
b12(1:n-2)=1.0
b21(1:n-2)=c(1:n-2)
b22(1:n-2)=b(1:n-2)
call recur1_v(a1,a2,b11,b12,b21,b22,u1,u2)
recur2(1:n-1)=u1(1:n-1)
recur2(n)=u2(n-1)
CONTAINS
RECURSIVE SUBROUTINE recur1_v(a1,a2,b11,b12,b21,b22,u1,u2)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: a1,a2,b11,b12,b21,b22
REAL(SP), DIMENSION(:), INTENT(OUT) :: u1,u2
INTEGER(I4B), PARAMETER :: NPAR_RECUR2=8
  Used by recur2 to evaluate first order vector recurrence. Routine is a two-dimensional
  vector version of recur1, with matrix multiplication replacing scalar multiplication.
INTEGER(I4B) :: n,j,nn,nn1
REAL(SP), DIMENSION(size(a1)/2) :: aa1,aa2
REAL(SP), DIMENSION(size(a1)/2-1) :: bb11,bb12,bb21,bb22
n=assert_eq((/size(a1),size(a2),size(b11)+1,size(b12)+1,size(b21)+1,&
size(b22)+1,size(u1),size(u2)/),'recur1_v')
u1(1)=a1(1)
u2(1)=a2(1)
if (n < NPAR_RECUR2) then           Do short vectors as a loop.
  do j=2,n
    u1(j)=a1(j)+b11(j-1)*u1(j-1)+b12(j-1)*u2(j-1)
    u2(j)=a2(j)+b21(j-1)*u1(j-1)+b22(j-1)*u2(j-1)
  end do
else
  Otherwise, combine coefficients and recurse on the even components, then evaluate all
  the odd components in parallel.
  nn=n/2
  nn1=nn-1
  aa1(1:nn)=a1(2:n:2)+b11(1:n-1:2)*a1(1:n-1:2)+&
    b12(1:n-1:2)*a2(1:n-1:2)
  aa2(1:nn)=a2(2:n:2)+b21(1:n-1:2)*a1(1:n-1:2)+&
    b22(1:n-1:2)*a2(1:n-1:2)
  bb11(1:nn1)=b11(3:n-1:2)*b11(2:n-2:2)+&
    b12(3:n-1:2)*b21(2:n-2:2)
  bb12(1:nn1)=b11(3:n-1:2)*b12(2:n-2:2)+&
    b12(3:n-1:2)*b22(2:n-2:2)
  bb21(1:nn1)=b21(3:n-1:2)*b11(2:n-2:2)+&
    b22(3:n-1:2)*b21(2:n-2:2)
  bb22(1:nn1)=b21(3:n-1:2)*b12(2:n-2:2)+&
    b22(3:n-1:2)*b22(2:n-2:2)
  call recur1_v(aa1,aa2,bb11,bb12,bb21,bb22,u1(2:n:2),u2(2:n:2))
  u1(3:n:2)=aa1(3:n:2)+bb11(2:n-1:2)*u1(2:n-1:2)+&

```

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```

        b12(2:n-1:2)*u2(2:n-1:2)
    u2(3:n:2)=a2(3:n:2)+b21(2:n-1:2)*u1(2:n-1:2)+&
        b22(2:n-1:2)*u2(2:n-1:2)
end if
END SUBROUTINE recur1_v
END FUNCTION recur2

```

\* \* \*

```

FUNCTION dfridr(func,x,h,err)
USE nrtype; USE nrutil, ONLY : assert,geop,iminloc
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x,h
REAL(SP), INTENT(OUT) :: err
REAL(SP) :: dfridr
INTERFACE
    FUNCTION func(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: func
    END FUNCTION func
END INTERFACE
INTEGER(I4B),PARAMETER :: NTAB=10
REAL(SP), PARAMETER :: CON=1.4_sp,CON2=CON*CON,BIG=huge(x),SAFE=2.0
    Returns the derivative of a function func at a point x by Ridders' method of polynomial
    extrapolation. The value h is input as an estimated initial stepsize; it need not be small,
    but rather should be an increment in x over which func changes substantially. An estimate
    of the error in the derivative is returned as err.
    Parameters: Stepsize is decreased by CON at each iteration. Max size of tableau is set by
    NTAB. Return when error is SAFE worse than the best so far.
INTEGER(I4B) :: ierrmin,i,j
REAL(SP) :: hh
REAL(SP), DIMENSION(NTAB-1) :: errt,fac
REAL(SP), DIMENSION(NTAB,NTAB) :: a
call assert(h /= 0.0, 'dfridr arg')
hh=h
a(1,1)=(func(x+hh)-func(x-hh))/(2.0_sp*hh)
err=BIG
fac(1:NTAB-1)=geop(CON2,CON2,NTAB-1)
do i=2,NTAB
    Successive columns in the Neville tableau will go to smaller
    hh=hh/CON
    stepsizes and higher orders of extrapolation.
    a(1,i)=(func(x+hh)-func(x-hh))/(2.0_sp*hh)
    Try new, smaller stepsize.
    do j=2,i
        Compute extrapolations of various orders, requiring no new function evaluations.
        a(j,i)=(a(j-1,i)*fac(j-1)-a(j-1,i-1))/(fac(j-1)-1.0_sp)
    end do
    errt(1:i-1)=max(abs(a(2:i,i)-a(1:i-1,i)),abs(a(2:i,i)-a(1:i-1,i-1)))
    The error strategy is to compare each new extrapolation to one order lower, both at the
    present stepsize and the previous one.
    ierrmin=iminloc(errt(1:i-1))
    if (errt(ierrmin) <= err) then
        If error is decreased, save the improved an-
        err=errt(ierrmin)
        swer.
        dfridr=a(1+ierrmin,i)
    end if
    if (abs(a(i,i)-a(i-1,i-1)) >= SAFE*err) RETURN
    If higher order is worse by a significant factor SAFE, then quit early.
end do
END FUNCTION dfridr

```

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`ierrmin=iminloc(errt(1:i-1))` The function `iminloc` in `nrutil` is useful when you need to know the index of the smallest element in an array.

\* \* \*

```
FUNCTION chebft(a,b,n,func)
USE nrtype; USE nrutil, ONLY : arth,outerprod
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), DIMENSION(n) :: chebft
INTERFACE
  FUNCTION func(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: func
  END FUNCTION func
END INTERFACE
```

Chebyshev fit: Given a function `func`, lower and upper limits of the interval  $[a,b]$ , and a maximum degree  $n$ , this routine computes the  $n$  coefficients  $c_k$  such that  $\text{func}(x) \approx [\sum_{k=1}^n c_k T_{k-1}(y)] - c_1/2$ , where  $y$  and  $x$  are related by (5.8.10). This routine is to be used with moderately large  $n$  (e.g., 30 or 50), the array of  $c$ 's subsequently to be truncated at the smaller value  $m$  such that  $c_{m+1}$  and subsequent elements are negligible.

```
REAL(DP) :: bma,bpa
REAL(DP), DIMENSION(n) :: theta
bma=0.5_dp*(b-a)
bpa=0.5_dp*(b+a)
theta(:)=PI_D*arth(0.5_dp,1.0_dp,n)/n
chebft(:)=matmul(cos(outerprod(arth(0.0_dp,1.0_dp,n),theta)), &
  func(real(cos(theta)*bma+bpa,sp)))*2.0_dp/n
```

We evaluate the function at the  $n$  points required by (5.8.7). We accumulate the sum in double precision for safety.

```
END FUNCTION chebft
```



`chebft(:)=matmul(...)` Here again Fortran 90 produces a very concise parallelizable formulation that requires some effort to decode. Equation (5.8.7) is a product of the matrix of cosines, where the rows are indexed by  $j$  and the columns by  $k$ , with the vector of function values indexed by  $k$ . We use the `outerprod` function in `nrutil` to form the matrix of arguments for the cosine, and rely on the element-by-element application of `cos` to produce the matrix of cosines. `matmul` then takes care of the matrix product. A subtlety is that, while the calculation is being done in double precision to minimize roundoff, the function is assumed to be supplied in single precision. Thus `real(...,sp)` is used to convert the double precision argument to single precision.

```
FUNCTION chebev_s(a,b,c,x)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b,x
REAL(SP), DIMENSION(:), INTENT(IN) :: c
REAL(SP) :: chebev_s
```

Chebyshev evaluation: All arguments are input.  $c$  is an array of length  $M$  of Chebyshev coefficients, the first  $M$  elements of  $c$  output from `chebft` (which must have been called

with the same  $a$  and  $b$ ). The Chebyshev polynomial  $\sum_{k=1}^M c_k T_{k-1}(y) - c_1/2$  is evaluated at a point  $y = [x - (b + a)/2]/[(b - a)/2]$ , and the result is returned as the function value.

```

INTEGER(I4B) :: j,m
REAL(SP) :: d,dd,sv,y,y2
if ((x-a)*(x-b) > 0.0) call nrerror('x not in range in chebev_s')
m=size(c)
d=0.0
dd=0.0
y=(2.0_sp*x-a-b)/(b-a)           Change of variable.
y2=2.0_sp*y
do j=m,2,-1                       Clenshaw's recurrence.
  sv=d
  d=y2*d-dd+c(j)
  dd=sv
end do
chebev_s=y*d-dd+0.5_sp*c(1)       Last step is different.
END FUNCTION chebev_s

```

```

FUNCTION chebev_v(a,b,c,x)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP), DIMENSION(:), INTENT(IN) :: c,x
REAL(SP), DIMENSION(size(x)) :: chebev_v
INTEGER(I4B) :: j,m
REAL(SP), DIMENSION(size(x)) :: d,dd,sv,y,y2
if (any((x-a)*(x-b) > 0.0)) call nrerror('x not in range in chebev_v')
m=size(c)
d=0.0
dd=0.0
y=(2.0_sp*x-a-b)/(b-a)
y2=2.0_sp*y
do j=m,2,-1
  sv=d
  d=y2*d-dd+c(j)
  dd=sv
end do
chebev_v=y*d-dd+0.5_sp*c(1)
END FUNCTION chebev_v

```

**f90** The name `chebev` is overloaded with scalar and vector versions. `chebev_v` is essentially identical to `chebev_s` except for the declarations of the variables. Fortran 90 does the appropriate scalar or vector arithmetic in the body of the routine, depending on the type of the variables.

\* \* \*

```

FUNCTION chder(a,b,c)
USE nrtype; USE nrutil, ONLY : arth,cumsum
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP), DIMENSION(:), INTENT(IN) :: c
REAL(SP), DIMENSION(size(c)) :: chder

```

This routine returns an array of length  $N$  containing the Chebyshev coefficients of the derivative of the function whose coefficients are in the array  $c$ . Input are  $a, b, c$ , as output

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from routine `chebft` §5.8. The desired degree of approximation  $N$  is equal to the length of `c` supplied.

```
INTEGER(I4B) :: n
REAL(SP) :: con
REAL(SP), DIMENSION(size(c)) :: temp
n=size(c)
temp(1)=0.0
temp(2:n)=2.0_sp*arth(n-1,-1,n-1)*c(n:2:-1)
chder(n:1:-2)=cumsum(temp(1:n:2))      Equation (5.9.2).
chder(n-1:1:-2)=cumsum(temp(2:n:2))
con=2.0_sp/(b-a)
chder=chder*con                          Normalize to the interval b-a.
END FUNCTION chder
```

```
FUNCTION chint(a,b,c)
USE nrtype; USE nrutil, ONLY : arth
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP), DIMENSION(:), INTENT(IN) :: c
REAL(SP), DIMENSION(size(c)) :: chint
  This routine returns an array of length  $N$  containing the Chebyshev coefficients of the
  integral of the function whose coefficients are in the array c. Input are a,b,c, as output
  from routine chebft §5.8. The desired degree of approximation  $N$  is equal to the length
  of c supplied. The constant of integration is set so that the integral vanishes at a.
INTEGER(I4B) :: n
REAL(SP) :: con
n=size(c)
con=0.25_sp*(b-a)                          Factor that normalizes to the interval b-a.
chint(2:n-1)=con*(c(1:n-2)-c(3:n))/arth(1,1,n-2)  Equation (5.9.1).
chint(n)=con*c(n-1)/(n-1)                  Special case of (5.9.1) for  $n$ .
chint(1)=2.0_sp*(sum(chint(2:n:2))-sum(chint(3:n:2)))  Set the constant of inte-
  gration.
END FUNCTION chint
```

**f90** If you look at equation (5.9.1) for the Chebyshev coefficients of the integral of a function, you will see  $c_{i-1}$  and  $c_{i+1}$  and be tempted to use `eoshift`. We think it is almost always better to use array sections instead, as in the code above, especially if your code will ever run on a serial machine.

\* \* \*

```
FUNCTION chebpc(c)
USE nrtype
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: c
REAL(SP), DIMENSION(size(c)) :: chebpc
  Chebyshev polynomial coefficients. Given a coefficient array c of length  $N$ , this routine
  returns a coefficient array d of length  $N$  such that  $\sum_{k=1}^N d_k y^{k-1} = \sum_{k=1}^N c_k T_{k-1}(y) - c_1/2$ .
  The method is Clenshaw's recurrence (5.8.11), but now applied algebraically rather
  than arithmetically.
INTEGER(I4B) :: j,n
REAL(SP), DIMENSION(size(c)) :: dd,sv
n=size(c)
chebpc=0.0
dd=0.0
chebpc(1)=c(n)
do j=n-1,2,-1
  sv(2:n-j+1)=chebpc(2:n-j+1)
  chebpc(2:n-j+1)=2.0_sp*chebpc(1:n-j)-dd(2:n-j+1)
  dd(2:n-j+1)=sv(2:n-j+1)
```

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```

    sv(1)=chebpc(1)
    chebpc(1)=-dd(1)+c(j)
    dd(1)=sv(1)
end do
chebpc(2:n)=chebpc(1:n-1)-dd(2:n)
chebpc(1)=-dd(1)+0.5_sp*c(1)
END FUNCTION chebpc

```

\* \* \*

```

SUBROUTINE pcsfft(a,b,d)
USE nrtype; USE nrutil, ONLY : geop
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP), DIMENSION(:), INTENT(INOUT) :: d
    Polynomial coefficient shift. Given a coefficient array d of length N, this routine generates
    a coefficient array g of the same length such that  $\sum_{k=1}^N d_k y^{k-1} = \sum_{k=1}^N g_k x^{k-1}$ , where
    x and y are related by (5.8.10), i.e., the interval  $-1 < y < 1$  is mapped to the interval
     $a < x < b$ . The array g is returned in d.
INTEGER(I4B) :: j,n
REAL(SP), DIMENSION(size(d)) :: dd
REAL(SP) :: x
n=size(d)
dd=d*geop(1.0_sp,2.0_sp/(b-a),n)
x=-0.5_sp*(a+b)
d(1)=dd(n)
d(2:n)=0.0
do j=n-1,1,-1
    We accomplish the shift by synthetic division, that miracle of
    d(2:n+1-j)=d(2:n+1-j)*x+d(1:n-j)      high-school algebra.
    d(1)=d(1)*x+dd(j)
end do
END SUBROUTINE pcsfft

```



There is a subtle, but major, distinction between the synthetic division algorithm used in the Fortran 77 version of `pcsfft` and that used above. In the Fortran 77 version, the synthetic division (translated to Fortran 90 notation) is

```

d(1:n)=dd(1:n)
do j=1,n-1
    do k=n-1,j,-1
        d(k)=x*d(k+1)+d(k)
    end do
end do

```

while, in Fortran 90, it is

```

d(1)=dd(n)
d(2:n)=0.0
do j=n-1,1,-1
    d(2:n+1-j)=d(2:n+1-j)*x+d(1:n-j)
    d(1)=d(1)*x+dd(j)
end do

```

As explained in §22.3, these are algebraically — but not algorithmically — equivalent. The inner loop in the Fortran 77 version does not parallelize, because each  $k$  value uses the result of the previous one. In fact, the  $k$  loop is a synthetic division, which can be parallelized *recursively* (as in the `nrutil` routine `poly_term`), but not simply

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vectorized. In the Fortran 90 version, since not one but  $n-1$  successive synthetic divisions are to be performed (by the outer loop), it is possible to reorganize the calculation to allow vectorization.

```

                *   *   *

FUNCTION pccheb(d)
USE nrtype; USE nrutil, ONLY : arth,cumprod,geop
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: d
REAL(SP), DIMENSION(size(d)) :: pccheb
    Inverse of routine chebpc: given an array of polynomial coefficients d, returns an equivalent
    array of Chebyshev coefficients of the same length.
INTEGER(I4B) :: k,n
REAL(SP), DIMENSION(size(d)) :: denom,numer,pow
n=size(d)
pccheb(1)=2.0_sp*d(1)
pow=geop(1.0_sp,2.0_sp,n)           Powers of 2.
numer(1)=1.0                       Combinatorial coefficients computed as numer/denom.
denom(1)=1.0
denom(2:(n+3)/2)=cumprod(arth(1.0_sp,1.0_sp,(n+1)/2))
pccheb(2:n)=0.0
do k=2,n                            Loop over orders of x in the polynomial.
    numer(2:(k+3)/2)=cumprod(arth(k-1.0_sp,-1.0_sp,(k+1)/2))
    pccheb(k:1:-2)=pccheb(k:1:-2)+&
        d(k)/pow(k-1)*numer(1:(k+1)/2)/denom(1:(k+1)/2)
end do
END FUNCTION pccheb

                *   *   *

SUBROUTINE pade(cof,resid)
USE nrtype
USE nr, ONLY : lubksb,ludcmp,mprove
IMPLICIT NONE
REAL(DP), DIMENSION(:), INTENT(INOUT) :: cof    DP for consistency with ratval.
REAL(SP), INTENT(OUT) :: resid
    Given cof(1:2N+1), the leading terms in the power series expansion of a function, solve
    the linear Padé equations to return the coefficients of a diagonal rational function approxi-
    mation to the same function, namely (cof(1) + cof(2)x + ... + cof(N+1)xN)/(1 +
    cof(N+2)x + ... + cof(2N+1)xN). The value resid is the norm of the residual
    vector; a small value indicates a well-converged solution.
INTEGER(I4B) :: k,n
INTEGER(I4B), DIMENSION((size(cof)-1)/2) :: indx
REAL(SP), PARAMETER :: BIG=1.0e30_sp          A big number.
REAL(SP) :: d,rr,rrold
REAL(SP), DIMENSION((size(cof)-1)/2) :: x,y,z
REAL(SP), DIMENSION((size(cof)-1)/2,(size(cof)-1)/2) :: q,qlu
n=(size(cof)-1)/2
x=cof(n+2:2*n+1)                          Set up matrix for solving.
y=x
do k=1,n
    q(:,k)=cof(n+2-k:2*n+1-k)
end do
qlu=q
call ludcmp(qlu,indx,d)                    Solve by LU decomposition and backsubsti-
call lubksb(qlu,indx,x)                    tution.
rr=BIG
do
    rrold=rr
    Important to use iterative improvement, since
    the Padé equations tend to be ill-conditioned.

```

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```

z=x
call mprove(q,qlu,indx,y,x)
rr=sum((z-x)**2)
if (rr >= rrold) exit
end do
resid=sqrt(rrold)
do k=1,n
y(k)=cof(k+1)-dot_product(z(1:k),cof(k:1:-1))
end do
cof(2:n+1)=y
cof(n+2:2*n+1)=-z
END SUBROUTINE pade

```

Calculate residual.

If it is no longer improving, call it quits.

Calculate the remaining coefficients.

Copy answers to output.

\* \* \*

```

SUBROUTINE ratlsq(func,a,b,mm,kk,cof,dev)
USE nrtype; USE nrutil, ONLY : arth,geop
USE nr, ONLY : ratval,svbksb,svdcmp
IMPLICIT NONE
REAL(DP), INTENT(IN) :: a,b
INTEGER(I4B), INTENT(IN) :: mm,kk
REAL(DP), DIMENSION(:), INTENT(OUT) :: cof
REAL(DP), INTENT(OUT) :: dev
INTERFACE
FUNCTION func(x)
USE nrtype
REAL(DP), DIMENSION(:), INTENT(IN) :: x
REAL(DP), DIMENSION(size(x)) :: func
END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: NPFAC=8,MAXIT=5
REAL(DP), PARAMETER :: BIG=1.0e30_dp
Returns in cof(1:mm+kk+1) the coefficients of a rational function approximation to the
function func in the interval (a,b). Input quantities mm and kk specify the order of the
numerator and denominator, respectively. The maximum absolute deviation of the approx-
imation (insofar as is known) is returned as dev. Note that double-precision versions of
svdcmp and svbksb are called.
INTEGER(I4B) :: it,ncof,npt,npth
REAL(DP) :: devmax,e,theta
REAL(DP), DIMENSION((mm+kk+1)*NPFAC) :: bb,ee,fs,wt,xs
REAL(DP), DIMENSION(mm+kk+1) :: coff,w
REAL(DP), DIMENSION(mm+kk+1,mm+kk+1) :: v
REAL(DP), DIMENSION((mm+kk+1)*NPFAC,mm+kk+1) :: u,temp
ncof=mm+kk+1
npt=NPFAC*ncof
npth=npt/2
dev=BIG
theta=PI02_D/(npt-1)
xs(1:npth-1)=a+(b-a)*sin(theta*arth(0,1,npth-1))**2
Now fill arrays with mesh abscissas and function values. At each end, use formula that mini-
mizes roundoff sensitivity in xs.
xs(npth:npt)=b-(b-a)*sin(theta*arth(npth-npth,-1,npth-npth+1))**2
fs=func(xs)
wt=1.0
ee=1.0
e=0.0
do it=1,MAXIT
bb=wt*(fs+sign(e,ee))
Key idea here: Fit to  $f_n(x) + e$  where the deviation is positive, to  $f_n(x) - e$  where it is
negative. Then  $e$  is supposed to become an approximation to the equal-ripple deviation.
temp=geop(spread(1.0_dp,1,npt),xs,ncof)

```

Number of points where function is evaluated,  
i.e., fineness of the mesh.In later iterations we will adjust these weights to  
combat the largest deviations.

Loop over iterations.

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```

    Note that vector form of geop (returning matrix) is being used.
    u(:,1:mm+1)=temp(:,1:mm+1)*spread(wt,2,mm+1)
    Set up the "design matrix" for the least squares fit.
    u(:,mm+2:ncof)=-temp(:,2:ncof-mm)*spread(bb,2,ncof-mm-1)
    call svdcmp(u,w,v)
    Singular Value Decomposition. In especially singular or difficult cases, one might here
    edit the singular values w(1:ncof), replacing small values by zero.
    call svbksb(u,w,v,bb,coff)
    ee=ratval(xs,coff,mm,kk)-fs      Tabulate the deviations and revise the weights.
    wt=abs(ee)                       Use weighting to emphasize most deviant points.
    devmax=maxval(wt)
    e=sum(wt)/npt                    Update e to be the mean absolute deviation.
    if (devmax <= dev) then         Save only the best coefficient set found.
        coff=coff
        dev=devmax
    end if
    write(*,10) it,devmax
end do
10 format (' ratlsq iteration=',i2,' max error=',1p,e10.3)
END SUBROUTINE ratlsq

```

**f90**

temp=geop(spread(1.0\_dp,1,npt),xs,ncof) The design matrix  $u_{ij}$  is defined for  $i = 1, \dots, npts$  by

$$u_{ij} = \begin{cases} w_i x_i^{j-1}, & j = 1, \dots, m+1 \\ -b_i x_i^{j-m-2}, & j = m+2, \dots, n \end{cases} \quad (\text{B5.12})$$

The first case in equation (B5.12) is computed in parallel by constructing the matrix temp equal to

$$\begin{bmatrix} 1 & x_1 & x_1^2 & \cdots \\ 1 & x_2 & x_2^2 & \cdots \\ 1 & x_3 & x_3^2 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

and then multiplying by the matrix spread(wt,2,mm+1), which is just

$$\begin{bmatrix} w_1 & w_1 & w_1 & \cdots \\ w_2 & w_2 & w_2 & \cdots \\ w_3 & w_3 & w_3 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

(Remember that multiplication using \* means element-by-element multiplication, not matrix multiplication.) A similar construction is used for the second part of the design matrix.



## Chapter B6. Special Functions

**f90** A Fortran 90 intrinsic function such as `sin(x)` is both *generic* and *elemental*. Generic means that the argument `x` can be any of multiple intrinsic data types and kind values (in the case of `sin`, any real or complex kind). Elemental means that `x` need not be a scalar, but can be an array of any rank and shape, in which case the calculation of `sin` is performed independently for each element.

Ideally, when we implement more complicated special functions in Fortran 90, as we do in this chapter, we would make them, too, both generic and elemental. Unfortunately, the language standard does not completely allow this. User-defined elemental functions are prohibited in Fortran 90, though they will be allowed in Fortran 95. And, there is no fully automatic way of providing for a single routine to allow arguments of multiple data types or kinds — nothing like C++’s “class templates,” for example.

However, don’t give up hope! Fortran 90 does provide a powerful mechanism for overloading, which can be used (perhaps not always with a maximum of convenience) to *simulate* both generic and elemental function features. In most cases, when we implement a special function with a scalar argument, `gammln(x)` say, we will also implement a corresponding vector-valued function of vector argument that evaluates the special function for each component of the vector argument. We will then overload the scalar and vector version of the function onto the same function name. For example, within the `nr` module are the lines

```
INTERFACE gammln
  FUNCTION gammln_s(xx)
    USE nrtype
    REAL(SP), INTENT(IN) :: xx
    REAL(SP) :: gammln_s
  END FUNCTION gammln_s

  FUNCTION gammln_v(xx)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: xx
    REAL(SP), DIMENSION(size(xx)) :: gammln_v
  END FUNCTION gammln_v
END INTERFACE
```


which can be included by a statement like “`USE nr, ONLY: gammln,`” and then allow you to write `gammln(x)` without caring (or even thinking about) whether `x` is a scalar or a vector. If you want arguments of even higher rank (matrices, and so forth), you can provide these yourself, based on our models, and overload them, too.

That takes care of “elemental”; what about “generic”? Here, too, overloading provides an acceptable, if not perfect, solution. Where double-precision versions of special functions are needed, you can in many cases easily construct them from our provided routines by changing the variable kinds (and any necessary convergence

parameters), and then additionally overload them onto the same generic function names. (In general, in the interest of brevity, we will not ourselves do this for the functions in this chapter.)

At first meeting, Fortran 90's overloading capability may seem trivial, or merely cosmetic, to the Fortran 77 programmer; but one soon comes to rely on it as an important conceptual simplification. Programming at a "higher level of abstraction" is usually more productive than spending time "bogged down in the mud." Furthermore, the use of overloading is generally fail-safe: If you invoke a generic name with arguments of shapes or types for which a specific routine has not been defined, the compiler tells you about it.

We won't reprint the module `nr`'s interface blocks for all the routines in this chapter. When you see routines named `something_s` and `something_v`, below, you can safely assume that the generic name `something` is defined in the module `nr` and overloaded with the two specific routine names. A full alphabetical listing of all the interface blocks in `nr` is given in Appendix C2.



Given our heavy investment, in this chapter, in overloadable vector-valued special function routines, it is worth discussing whether this effort is simply a stopgap measure for Fortran 90, soon to be made obsolete by Fortran 95's provision of user-definable ELEMENTAL procedures. The answer is "not necessarily," and takes us into some speculation about the future of SIMD, versus MIMD, computing.

Elemental procedures, while applying the same executable code to each element, do not insist that it be feasible to perform all the parallel calculations in lockstep. That is, elemental procedures can have tests and branches (`if-then-else` constructions) that result in different elements being calculated by totally different pieces of code, in a fashion that can only be determined at run time. For true 100% MIMD (multiple instruction, multiple data) machines, this is not a problem: individual processors do the individual element calculations asynchronously.

However, virtually none of today's (and likely tomorrow's) largest-scale parallel supercomputers are 100% MIMD in this way. While modern parallel supercomputers increasingly have MIMD features, they continue to reward the use of SIMD (single instruction, multiple data) code with greater computational speed, often because of hardware pipelining or vector processing features within the individual processors. The use of Fortran 90 (or, for that matter Fortran 95) in a data-parallel or SIMD mode is thus by no means superfluous, or obviated by Fortran 95's ELEMENTAL construction.

The problem we face is that parallel calculation of special function values often doesn't fit well into the SIMD mold: Since the calculation of the value of a special function typically requires the convergence of an iterative process, as well as possible branches for different values of arguments, it cannot *in general* be done efficiently with "lockstep" SIMD programming.

Luckily, in particular cases, including most (but not all) of the functions in this chapter, one can in fact make reasonably good parallel implementations with the SIMD tools provided by the language. We will in fact see a number of different tricks for accomplishing this in the code that follows.

We are interested in demonstrating SIMD techniques, but we are not completely impractical. None of the data-parallel implementations given below are too inefficient on a scalar machine, and some may in fact be faster than Fortran 95's ELEMENTAL

alternative, or than do-loops over calls to the scalar version of the function. On a scalar machine, how can this be? We have already, above, hinted at the answer: (i) most modern scalar processors can overlap instructions to some degree, and data-parallel coding often provides compilers with the ability to accomplish this more efficiently; and (ii) data-parallel code can sometimes give better cache utilization.

\* \* \*

```

FUNCTION gammln_s(xx)
USE nrtype; USE nrutil, ONLY : arth,assert
IMPLICIT NONE
REAL(SP), INTENT(IN) :: xx
REAL(SP) :: gammln_s
  Returns the value  $\ln[\Gamma(xx)]$  for  $xx > 0$ .
REAL(DP) :: tmp,x
  Internal arithmetic will be done in double precision, a nicety that you can omit if five-figure
  accuracy is good enough.
REAL(DP) :: stp = 2.5066282746310005_dp
REAL(DP), DIMENSION(6) :: coef = (/76.18009172947146_dp,&
  -86.50532032941677_dp,24.01409824083091_dp,&
  -1.231739572450155_dp,0.1208650973866179e-2_dp,&
  -0.5395239384953e-5_dp/)
call assert(xx > 0.0, 'gammln_s arg')
x=xx
tmp=x+5.5_dp
tmp=(x+0.5_dp)*log(tmp)-tmp
gammln_s=tmp+log(stp*(1.000000000190015_dp+&
  sum(coef(:)/arth(x+1.0_dp,1.0_dp,size(coef))))/x)
END FUNCTION gammln_s

```


```

FUNCTION gammln_v(xx)
USE nrtype; USE nrutil, ONLY: assert
IMPLICIT NONE
INTEGER(I4B) :: i
REAL(SP), DIMENSION(:), INTENT(IN) :: xx
REAL(SP), DIMENSION(size(xx)) :: gammln_v
REAL(DP), DIMENSION(size(xx)) :: ser,tmp,x,y
REAL(DP) :: stp = 2.5066282746310005_dp
REAL(DP), DIMENSION(6) :: coef = (/76.18009172947146_dp,&
  -86.50532032941677_dp,24.01409824083091_dp,&
  -1.231739572450155_dp,0.1208650973866179e-2_dp,&
  -0.5395239384953e-5_dp/)
if (size(xx) == 0) RETURN
call assert(all(xx > 0.0), 'gammln_v arg')
x=xx
tmp=x+5.5_dp
tmp=(x+0.5_dp)*log(tmp)-tmp
ser=1.000000000190015_dp
y=x
do i=1,size(coef)
  y=y+1.0_dp
  ser=ser+coef(i)/y
end do
gammln_v=tmp+log(stp*ser/x)
END FUNCTION gammln_v

```

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**f90** call assert(xx > 0.0, 'gammln\_s arg') We use the `nrutil` routine `assert` for functions that have restrictions on the allowed range of arguments. One could instead have used an `if` statement with a call to `nrerror`; but we think that the uniformity of using `assert`, and the fact that its logical arguments read the “desired” way, not the “erroneous” way, make for a clearer programming style. In the vector version, the `assert` line is: `call assert(all(xx > 0.0), 'gammln_v arg')`

 Notice that the scalar and vector versions achieve parallelism in quite different ways, something that we will see many times in this chapter. In the scalar case, parallelism (at least small-scale) is achieved through constructions like

```
sum(coef(:)/arth(x+1.0_dp,1.0_dp,size(coef)))
```

Here vector utilities construct the series  $x + 1, x + 2, \dots$  and then sum a series with these terms in the denominators and a vector of coefficients in the numerators. (This code may seem terse to Fortran 90 novices, but once you get used to it, it is quite clear to read.)

In the vector version, by contrast, parallelism is achieved across the components of the vector argument, and the above series is evaluated sequentially as a `do-loop`. Obviously the assumption is that the length of the vector argument is much longer than the very modest number (here, 6) of terms in the sum.

\* \* \*

```
FUNCTION factrl_s(n)
USE nrtype; USE nrutil, ONLY : arth,assert,cumprod
USE nr, ONLY : gammln
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP) :: factrl_s
  Returns the value n! as a floating-point number.
INTEGER(I4B), SAVE :: ntop=0
INTEGER(I4B), PARAMETER :: NMAX=32
REAL(SP), DIMENSION(NMAX), SAVE :: a      Table of stored values.
call assert(n >= 0, 'factrl_s arg')
if (n < ntop) then                          Already in table.
  factrl_s=a(n+1)
else if (n < NMAX) then                      Fill in table up to NMAX.
  ntop=NMAX
  a(1)=1.0
  a(2:NMAX)=cumprod(arth(1.0_sp,1.0_sp,NMAX-1))
  factrl_s=a(n+1)
else                                         Larger value than size of table is required.
  factrl_s=exp(gammln(n+1.0_sp))             Actually, this big a value is going to over-
end if                                       flow on many computers, but no harm in
END FUNCTION factrl_s                       trying.
```

**f90** `cumprod(arth(1.0_sp,1.0_sp,NMAX-1))` By now you should recognize this as an idiom for generating a vector of consecutive factorials. The routines `cumprod` and `arth`, both in `nrutil`, are both capable of being parallelized, e.g., by recursion, so this idiom is potentially faster than an in-line `do-loop`.

```

FUNCTION factrl_v(n)
USE nrtype; USE nrutil, ONLY : arth,assert,cumprod
USE nr, ONLY : gammln
IMPLICIT NONE
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: n
REAL(SP), DIMENSION(size(n)) :: factrl_v
LOGICAL(LGT), DIMENSION(size(n)) :: mask
INTEGER(I4B), SAVE :: ntop=0
INTEGER(I4B), PARAMETER :: NMAX=32
REAL(SP), DIMENSION(NMAX), SAVE :: a
call assert(all(n >= 0), 'factrl_v arg')
if (ntop == 0) then
  ntop=NMAX
  a(1)=1.0
  a(2:NMAX)=cumprod(arth(1.0_sp,1.0_sp,NMAX-1))
end if
mask = (n >= NMAX)
factrl_v=unpack(exp(gammln(pack(n,mask)+1.0_sp)),mask,0.0_sp)
where (.not. mask) factrl_v=a(n+1)
END FUNCTION factrl_v

```



`unpack(exp(gammln(pack(n,mask)+1.0_sp)),mask,0.0_sp)` Here we meet the first of several solutions to a common problem: How shall we get answers, from an external vector-valued function, for just a *subset* of vector arguments, those defined by a mask? Here we use what we call the “pack-unpack” solution: Pack up all the arguments using the mask, send them to the function, and unpack the answers that come back. This packing and unpacking is not without cost (highly dependent on machine architecture, to be sure), but we hope to “earn it back” in the parallelism of the external function.

`where (.not. mask) factrl_v=a(n+1)` In some cases we might take care of the `.not. mask` case directly within the unpack construction, using its third (“FIELD=”) argument to provide the not-unpacked values. However, there is no guarantee that the compiler won’t evaluate all components of the “FIELD=” array, if it finds it efficient to do so. Here, since the index of `a(n+1)` would be out of range, we can’t do it this way. Thus the separate `where` statement.

\* \* \*

```

FUNCTION bico_s(n,k)
USE nrtype
USE nr, ONLY : factln
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n,k
REAL(SP) :: bico_s
  Returns the binomial coefficient  $\binom{n}{k}$  as a floating-point number.
bico_s=nint(exp(factln(n)-factln(k)-factln(n-k)))
  The nearest-integer function cleans up roundoff error for smaller values of n and k.
END FUNCTION bico_s

```

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```

FUNCTION bico_v(n,k)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : factln
IMPLICIT NONE
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: n,k
REAL(SP), DIMENSION(size(n)) :: bico_v
INTEGER(I4B) :: ndum
ndum=assert_eq(size(n),size(k),'bico_v')
bico_v=nint(exp(factln(n)-factln(k)-factln(n-k)))
END FUNCTION bico_v

```

\* \* \*

```

FUNCTION factln_s(n)
USE nrtype; USE nrutil, ONLY : arth,assert
USE nr, ONLY : gammln
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP) :: factln_s
  Returns ln(n!).
INTEGER(I4B), PARAMETER :: TMAX=100
REAL(SP), DIMENSION(TMAX), SAVE :: a
LOGICAL(LGT), SAVE :: init=.true.
if (init) then      Initialize the table.
  a(1:TMAX)=gammln(arth(1.0_sp,1.0_sp,TMAX))
  init=.false.
end if
call assert(n >= 0, 'factln_s arg')
if (n < TMAX) then  In range of the table.
  factln_s=a(n+1)
else                Out of range of the table.
  factln_s=gammln(n+1.0_sp)
end if
END FUNCTION factln_s

```

```

FUNCTION factln_v(n)
USE nrtype; USE nrutil, ONLY : arth,assert
USE nr, ONLY : gammln
IMPLICIT NONE
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: n
REAL(SP), DIMENSION(size(n)) :: factln_v
LOGICAL(LGT), DIMENSION(size(n)) :: mask
INTEGER(I4B), PARAMETER :: TMAX=100
REAL(SP), DIMENSION(TMAX), SAVE :: a
LOGICAL(LGT), SAVE :: init=.true.
if (init) then
  a(1:TMAX)=gammln(arth(1.0_sp,1.0_sp,TMAX))
  init=.false.
end if
call assert(all(n >= 0), 'factln_v arg')
mask = (n >= TMAX)
factln_v=unpack(gammln(pack(n,mask)+1.0_sp),mask,0.0_sp)
where (.not. mask) factln_v=a(n+1)
END FUNCTION factln_v

```

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**f90** `gammln(arth(1.0_sp,1.0_sp,TMAX))` Another example of the programming convenience of combining a function returning a vector (here, `arth`) with a special function whose generic name (here, `gammln`) has an overloaded vector version.

\* \* \*

```
FUNCTION beta_s(z,w)
USE nrtype
USE nr, ONLY : gammln
IMPLICIT NONE
REAL(SP), INTENT(IN) :: z,w
REAL(SP) :: beta_s
    Returns the value of the beta function  $B(z,w)$ .
beta_s=exp(gammln(z)+gammln(w)-gammln(z+w))
END FUNCTION beta_s
```

```
FUNCTION beta_v(z,w)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : gammln
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: z,w
REAL(SP), DIMENSION(size(z)) :: beta_v
INTEGER(I4B) :: ndum
ndum=assert_eq(size(z),size(w),'beta_v')
beta_v=exp(gammln(z)+gammln(w)-gammln(z+w))
END FUNCTION beta_v
```

\* \* \*

```
FUNCTION gammp_s(a,x)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : gcf,gser
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,x
REAL(SP) :: gammp_s
    Returns the incomplete gamma function  $P(a,x)$ .
call assert( x >= 0.0, a > 0.0, 'gammp_s args')
if (x<a+1.0_sp) then
    gammp_s=gser(a,x)
    Use the series representation.
else
    gammp_s=1.0_sp-gcf(a,x)
    Use the continued fraction representation
    and take its complement.
end if
END FUNCTION gammp_s
```

```
FUNCTION gammp_v(a,x)
USE nrtype; USE nrutil, ONLY : assert,assert_eq
USE nr, ONLY : gcf,gser
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: a,x
REAL(SP), DIMENSION(size(x)) :: gammp_v
LOGICAL(LGT), DIMENSION(size(x)) :: mask
INTEGER(I4B) :: ndum
ndum=assert_eq(size(a),size(x),'gammp_v')
call assert( all(x >= 0.0), all(a > 0.0), 'gammp_v args')
mask = (x<a+1.0_sp)
gammp_v=merge(gser(a,merge(x,0.0_sp,mask)), &
    1.0_sp-gcf(a,merge(x,0.0_sp,.not. mask)),mask)
END FUNCTION gammp_v
```

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call `assert( x >= 0.0, a > 0.0, 'gammq_s args')` The generic routine `assert` in `nrutil` is overloaded with variants for more than one logical assertion, so you can make more than one assertion about argument ranges.



```
gammq_v=merge(gser(a,merge(x,0.0_sp,mask)), &
              1.0_sp-gcf(a,merge(x,0.0_sp,.not. mask)),mask)
```

Here we meet the *second* solution to the problem of getting masked values from an external vector function. (For the first solution, see note to `factrl`, above.)

We call this one “merge with dummy values”: Inappropriate values of the argument `x` (as determined by `mask`) are set to zero before `gser`, and later `gcf`, are called, and the supernumerary answers returned are discarded by a final merge. The assumption here is that the dummy value sent to the function (here, zero) is a special value that computes extremely fast, so that the overhead of computing and returning the supernumerary function values is outweighed by the parallelism achieved on the nontrivial components of `x`. Look at `gser_v` and `gcf_v` below to judge whether this assumption is realistic in this case.

```
FUNCTION gammq_s(a,x)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : gcf,gser
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,x
REAL(SP) :: gammq_s
    Returns the incomplete gamma function  $Q(a,x) \equiv 1 - P(a,x)$ .
call assert( x >= 0.0, a > 0.0, 'gammq_s args')
if (x<a+1.0_sp) then
    gammq_s=1.0_sp-gser(a,x)      Use the series representation
                                and take its complement.
else
    gammq_s=gcf(a,x)            Use the continued fraction representation.
end if
END FUNCTION gammq_s
```

```
FUNCTION gammq_v(a,x)
USE nrtype; USE nrutil, ONLY : assert,assert_eq
USE nr, ONLY : gcf,gser
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: a,x
REAL(SP), DIMENSION(size(a)) :: gammq_v
LOGICAL(LGT), DIMENSION(size(x)) :: mask
INTEGER(I4B) :: ndum
ndum=assert_eq(size(a),size(x),'gammq_v')
call assert( all(x >= 0.0), all(a > 0.0), 'gammq_v args')
mask = (x<a+1.0_sp)
gammq_v=merge(1.0_sp-gser(a,merge(x,0.0_sp,mask)), &
              gcf(a,merge(x,0.0_sp,.not. mask)),mask)
END FUNCTION gammq_v
```

```
FUNCTION gser_s(a,x,gln)
USE nrtype; USE nrutil, ONLY : nrerror
USE nr, ONLY : gammln
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,x
REAL(SP), OPTIONAL, INTENT(OUT) :: gln
REAL(SP) :: gser_s
INTEGER(I4B), PARAMETER :: ITMAX=100
REAL(SP), PARAMETER :: EPS=epsilon(x)
```



Returns the incomplete gamma function  $P(a, x)$  evaluated by its series representation as `gser`. Also optionally returns  $\ln \Gamma(a)$  as `gln`.

```

INTEGER(I4B) :: n
REAL(SP) :: ap, del, summ
if (x == 0.0) then
  gser_s=0.0
  RETURN
end if
ap=a
summ=1.0_sp/a
del=summ
do n=1, ITMAX
  ap=ap+1.0_sp
  del=del*x/ap
  summ=summ+del
  if (abs(del) < abs(summ)*EPS) exit
end do
if (n > ITMAX) call nrerror('a too large, ITMAX too small in gser_s')
if (present(gln)) then
  gln=gammln(a)
  gser_s=summ*exp(-x+a*log(x)-gln)
else
  gser_s=summ*exp(-x+a*log(x)-gammln(a))
end if
END FUNCTION gser_s

```

```

FUNCTION gser_v(a,x,gln)
USE nrtype; USE nrutil, ONLY : assert_eq, nrerror
USE nr, ONLY : gammln
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: a,x
REAL(SP), DIMENSION(:), OPTIONAL, INTENT(OUT) :: gln
REAL(SP), DIMENSION(size(a)) :: gser_v
INTEGER(I4B), PARAMETER :: ITMAX=100
REAL(SP), PARAMETER :: EPS=epsilon(x)
INTEGER(I4B) :: n
REAL(SP), DIMENSION(size(a)) :: ap, del, summ
LOGICAL(LGT), DIMENSION(size(a)) :: converged, zero
n=assert_eq(size(a), size(x), 'gser_v')
zero=(x == 0.0)
where (zero) gser_v=0.0
ap=a
summ=1.0_sp/a
del=summ
converged=zero
do n=1, ITMAX
  where (.not. converged)
    ap=ap+1.0_sp
    del=del*x/ap
    summ=summ+del
    converged = (abs(del) < abs(summ)*EPS)
  end where
  if (all(converged)) exit
end do
if (n > ITMAX) call nrerror('a too large, ITMAX too small in gser_v')
if (present(gln)) then
  if (size(gln) < size(a)) call &
    nrerror('gser: Not enough space for gln')
  gln=gammln(a)
  where (.not. zero) gser_v=summ*exp(-x+a*log(x)-gln)
else
  where (.not. zero) gser_v=summ*exp(-x+a*log(x)-gammln(a))

```


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```
end if
END FUNCTION gser_v
```

**f90** REAL(SP), OPTIONAL, INTENT(OUT) :: gln Normally, an OPTIONAL argument will be INTENT(IN) and be used to provide a less-often-used extra input argument to a function. Here, the OPTIONAL argument is INTENT(OUT), used to provide a useful value that is a byproduct of the main calculation.

Also note that although  $x \geq 0$  is required, we omit our usual call `assert` check for this, because `gser` is supposed to be called only by `gammp` or `gammq` — and these routines supply the argument checking themselves.

`do n=1,ITMAX...end do...if (n > ITMAX)...` This is typical code in Fortran 90 for a loop with a maximum number of iterations, relying on Fortran 90's guarantee that the index of the do-loop will be available after normal completion of the loop with a predictable value, greater by one than the upper limit of the loop. If the exit statement within the loop is ever taken, the `if` statement is guaranteed to fail; if the loop goes all the way through `ITMAX` cycles, the `if` statement is guaranteed to succeed.

 `zero=(x == 0.0)...where (zero) gser_v=0.0...converged=zero` This is the code that provides for very low overhead calculation of zero arguments, as is assumed by the merge-with-dummy-values strategy in `gammp` and `gammq`. Zero arguments are “pre-converged” and are never the holdouts in the convergence test.

```
FUNCTION gcf_s(a,x,gln)
USE nrtype; USE nrutil, ONLY : nrerror
USE nr, ONLY : gammln
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,x
REAL(SP), OPTIONAL, INTENT(OUT) :: gln
REAL(SP) :: gcf_s
INTEGER(I4B), PARAMETER :: ITMAX=100
REAL(SP), PARAMETER :: EPS=epsilon(x),FPMIN=tiny(x)/EPS
```

Returns the incomplete gamma function  $Q(a, x)$  evaluated by its continued fraction representation as `gammcf`. Also optionally returns  $\ln \Gamma(a)$  as `gln`.

Parameters: `ITMAX` is the maximum allowed number of iterations; `EPS` is the relative accuracy; `FPMIN` is a number near the smallest representable floating-point number.

```
INTEGER(I4B) :: i
REAL(SP) :: an,b,c,d,del,h
if (x == 0.0) then
  gcf_s=1.0
  RETURN
end if
b=x+1.0_sp-a
c=1.0_sp/FPMIN
d=1.0_sp/b
h=d
do i=1,ITMAX
  an=-i*(i-a)
  b=b+2.0_sp
  d=an*d+b
  if (abs(d) < FPMIN) d=FPMIN
  c=b+an/c
  if (abs(c) < FPMIN) c=FPMIN
```

Set up for evaluating continued fraction by modified Lentz's method (§5.2) with  $b_0 = 0$ .

Iterate to convergence.

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```

    d=1.0_sp/d
    del=d*c
    h=h*del
    if (abs(del-1.0_sp) <= EPS) exit
end do
if (i > ITMAX) call nrerror('a too large, ITMAX too small in gcf_s')
if (present(gln)) then
    gln=gammln(a)
    gcf_s=exp(-x+a*log(x)-gln)*h      Put factors in front.
else
    gcf_s=exp(-x+a*log(x)-gammln(a))*h
end if
END FUNCTION gcf_s

FUNCTION gcf_v(a,x,gln)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
USE nr, ONLY : gammln
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: a,x
REAL(SP), DIMENSION(:), OPTIONAL, INTENT(OUT) :: gln
REAL(SP), DIMENSION(size(a)) :: gcf_v
INTEGER(I4B), PARAMETER :: ITMAX=100
REAL(SP), PARAMETER :: EPS=epsilon(x),FPMIN=tiny(x)/EPS
INTEGER(I4B) :: i
REAL(SP), DIMENSION(size(a)) :: an,b,c,d,del,h
LOGICAL(LGT), DIMENSION(size(a)) :: converged,zero
i=assert_eq(size(a),size(x),'gcf_v')
zero=(x == 0.0)
where (zero)
    gcf_v=1.0
elsewhere
    b=x+1.0_sp-a
    c=1.0_sp/FPMIN
    d=1.0_sp/b
    h=d
end where
converged=zero
do i=1,ITMAX
    where (.not. converged)
        an=-i*(i-a)
        b=b+2.0_sp
        d=an*d+b
        d=merge(FPMIN,d, abs(d)<FPMIN )
        c=b+an/c
        c=merge(FPMIN,c, abs(c)<FPMIN )
        d=1.0_sp/d
        del=d*c
        h=h*del
        converged = (abs(del-1.0_sp)<=EPS)
    end where
    if (all(converged)) exit
end do
if (i > ITMAX) call nrerror('a too large, ITMAX too small in gcf_v')
if (present(gln)) then
    if (size(gln) < size(a)) call &
        nrerror('gser: Not enough space for gln')
    gln=gammln(a)
    where (.not. zero) gcf_v=exp(-x+a*log(x)-gln)*h
else
    where (.not. zero) gcf_v=exp(-x+a*log(x)-gammln(a))*h
end if
END FUNCTION gcf_v

```

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zero=(x == 0.0)...where (zero) gcf\_v=1.0...converged=zero See note on  
gser. Here, too, we pre-converge the special value of zero.

\* \* \*

```
FUNCTION erf_s(x)
USE nrtype
USE nr, ONLY : gammp
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: erf_s
  Returns the error function erf(x).
erf_s=gammp(0.5_sp,x**2)
if (x < 0.0) erf_s=-erf_s
END FUNCTION erf_s
```

```
FUNCTION erf_v(x)
USE nrtype
USE nr, ONLY : gammp
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: erf_v
erf_v=gammp(spread(0.5_sp,1,size(x)),x**2)
where (x < 0.0) erf_v=-erf_v
END FUNCTION erf_v
```

**f90** erf\_v=gammp(spread(0.5\_sp,1,size(x)),x\*\*2) Yes, we do have an overloaded vector version of gammp, but it is vectorized on *both* its arguments. Thus, in a case where we want to vectorize on only *one* argument, we need a spread construction. In many contexts, Fortran 90 automatically makes scalars conformable with arrays (i.e., it automatically spreads them to the shape of the array); but the language does *not* do so when trying to match a generic function or subroutine call to a specific overloaded name. Perhaps this is wise; it is safer to prevent “accidental” invocations of vector-specific functions. Or, perhaps it is an area where the language could be improved.

```
FUNCTION erfc_s(x)
USE nrtype
USE nr, ONLY : gammp,gammq
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: erfc_s
  Returns the complementary error function erfc(x).
erfc_s=merge(1.0_sp+gammp(0.5_sp,x**2),gammq(0.5_sp,x**2), x < 0.0)
END FUNCTION erfc_s
```

**f90** erfc\_s=merge(1.0\_sp+gammp(0.5\_sp,x\*\*2),gammq(0.5\_sp,x\*\*2), x < 0.0)  
An example of our use of merge as an idiom for a conditional expression. Once you get used to these, you’ll find them just as clear as the multiline if...then...else alternative.

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```

FUNCTION erfc_v(x)
USE nrtype
USE nr, ONLY : gammq,gammq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: erfc_v
LOGICAL(LGT), DIMENSION(size(x)) :: mask
mask = (x < 0.0)
erfc_v=merge(1.0_sp+gammq(spread(0.5_sp,1,size(x)), &
    merge(x,0.0_sp,mask)**2),gammq(spread(0.5_sp,1,size(x)), &
    merge(x,0.0_sp,.not. mask)**2),mask)
END FUNCTION erfc_v

```

**f90** `erfc_v=merge(1.0_sp+...)` Another example of the “merge with dummy values” idiom described on p. 1090. Here positive values of  $x$  in the call to `gammq`, and negative values in the call to `gammq`, are first set to the dummy value zero. The value zero is a special argument that computes very fast. The unwanted dummy function values are then discarded by the final outer merge.

\* \* \*

```

FUNCTION erfcc_s(x)
USE nrtype; USE nrutil, ONLY : poly
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: erfcc_s
    Returns the complementary error function erfc(x) with fractional error everywhere less than
     $1.2 \times 10^{-7}$ .
REAL(SP) :: t,z
REAL(SP), DIMENSION(10) :: coef = (/ -1.26551223_sp, 1.00002368_sp, &
    0.37409196_sp, 0.09678418_sp, -0.18628806_sp, 0.27886807_sp, &
    -1.13520398_sp, 1.48851587_sp, -0.82215223_sp, 0.17087277_sp /)
z=abs(x)
t=1.0_sp/(1.0_sp+0.5_sp*z)
erfcc_s=t*exp(-z*z+poly(t,coef))
if (x < 0.0) erfcc_s=2.0_sp-erfcc_s
END FUNCTION erfcc_s

```

```

FUNCTION erfcc_v(x)
USE nrtype; USE nrutil, ONLY : poly
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: erfcc_v,t,z
REAL(SP), DIMENSION(10) :: coef = (/ -1.26551223_sp, 1.00002368_sp, &
    0.37409196_sp, 0.09678418_sp, -0.18628806_sp, 0.27886807_sp, &
    -1.13520398_sp, 1.48851587_sp, -0.82215223_sp, 0.17087277_sp /)
z=abs(x)
t=1.0_sp/(1.0_sp+0.5_sp*z)
erfcc_v=t*exp(-z*z+poly(t,coef))
where (x < 0.0) erfcc_v=2.0_sp-erfcc_v
END FUNCTION erfcc_v

```

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**f90** `erfcc_v=t*exp(-z*z+poly(t,coef))` The vector code is identical to the scalar, because the `nrutil` routine `poly` has overloaded cases for the evaluation of a polynomial at a single value of the independent variable, and at multiple values. One *could* also overload a version with a matrix of coefficients whose columns could be used for the simultaneous evaluation of different polynomials at different values of independent variable. The point is that as long as there are differences in the shapes of at least one argument, the intended version of `poly` can be discerned by the compiler.

\* \* \*

```

FUNCTION expint(n,x)
USE nrtype; USE nrutil, ONLY : arth,assert,nrerror
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), INTENT(IN) :: x
REAL(SP) :: expint
INTEGER(I4B), PARAMETER :: MAXIT=100
REAL(SP), PARAMETER :: EPS=epsilon(x),BIG=huge(x)*EPS
  Evaluates the exponential integral  $E_n(x)$ .
  Parameters: MAXIT is the maximum allowed number of iterations; EPS is the desired relative
  error, not smaller than the machine precision; BIG is a number near the largest representable
  floating-point number; EULER (in nrtype) is Euler's constant  $\gamma$ .
INTEGER(I4B) :: i,nm1
REAL(SP) :: a,b,c,d,del,fact,h
call assert(n >= 0, x >= 0.0, (x > 0.0 .or. n > 1), &
'expint args')
if (n == 0) then
  expint=exp(-x)/x
  RETURN
end if
nm1=n-1
if (x == 0.0) then
  expint=1.0_sp/nm1
else if (x > 1.0) then
  b=x+n
  c=BIG
  d=1.0_sp/b
  h=d
  do i=1,MAXIT
    a=-i*(nm1+i)
    b=b+2.0_sp
    d=1.0_sp/(a*d+b)
    c=b+a/c
    del=c*d
    h=h*del
    if (abs(del-1.0_sp) <= EPS) exit
  end do
  if (i > MAXIT) call nrerror('expint: continued fraction failed')
  expint=h*exp(-x)
else
  if (nm1 /= 0) then
    expint=1.0_sp/nm1
  else
    expint=-log(x)-EULER
  end if
  fact=1.0
  do i=1,MAXIT
    fact=-fact*x/i
    if (i /= nm1) then
      del=-fact/(i-nm1)

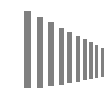
```

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```

else
     $\psi(n)$  appears here.
    del=fact*(-log(x)-EULER+sum(1.0_sp/arth(1,1,nm1)))
end if
expint=expint+del
if (abs(del) < abs(expint)*EPS) exit
end do
if (i > MAXIT) call nrerror('expint: series failed')
end if
END FUNCTION expint

```



expint does not readily parallelize, and we thus don't provide a vector version. For syntactic convenience you could make a vector version with a do-loop over calls to this scalar version; or, in Fortran 95, you can of course make the function ELEMENTAL.

\* \* \*

```

FUNCTION ei(x)
USE nrtype; USE nrutil, ONLY : assert,nrerror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: ei
INTEGER(I4B), PARAMETER :: MAXIT=100
REAL(SP), PARAMETER :: EPS=epsilon(x),FPMIN=tiny(x)/EPS
    Computes the exponential integral  $Ei(x)$  for  $x > 0$ .
    Parameters: MAXIT is the maximum number of iterations allowed; EPS is the relative error,
    or absolute error near the zero of  $Ei$  at  $x = 0.3725$ ; FPMIN is a number near the smallest
    representable floating-point number; EULER (in nrtype) is Euler's constant  $\gamma$ .
INTEGER(I4B) :: k
REAL(SP) :: fact,prev,sm,term
call assert(x > 0.0, 'ei arg')
if (x < FPMIN) then
    ei=log(x)+EULER
else if (x <= -log(EPS)) then
    sm=0.0
    fact=1.0
    do k=1,MAXIT
        fact=fact*x/k
        term=fact/k
        sm=sm+term
        if (term < EPS*sm) exit
    end do
    if (k > MAXIT) call nrerror('series failed in ei')
    ei=sm+log(x)+EULER
else
    sm=0.0
    term=1.0
    do k=1,MAXIT
        prev=term
        term=term*k/x
        if (term < EPS) exit
        if (term < prev) then
            sm=sm+term
        else
            sm=sm-prev
            exit
        end if
    end do
    if (k > MAXIT) call nrerror('asymptotic failed in ei')
    ei=exp(x)*(1.0_sp+sm)/x
end if
END FUNCTION ei

```

Special case: avoid failure of convergence test  
because of underflow.

Use power series.

Use asymptotic series.  
Start with second term.

Since final sum is greater than one, term itself  
approximates the relative error.  
Still converging: add new term.  
Diverging: subtract previous term and exit.

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ei does not readily parallelize, and we thus don't provide a vector version. For syntactic convenience you could make a vector version with a do-loop over calls to this scalar version; or, in Fortran 95, you can of course make the function ELEMENTAL.

\* \* \*

```

FUNCTION betai_s(a,b,x)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : betacf,gammln
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b,x
REAL(SP) :: betai_s
    Returns the incomplete beta function  $I_x(a,b)$ .
REAL(SP) :: bt
call assert(x >= 0.0, x <= 1.0, 'betai_s arg')
if (x == 0.0 .or. x == 1.0) then
    bt=0.0
else
    bt=exp(gammln(a+b)-gammln(a)-gammln(b)&
           +a*log(x)+b*log(1.0_sp-x))
    Factors in front of the continued frac-
    tion.
end if
if (x < (a+1.0_sp)/(a+b+2.0_sp)) then
    betai_s=bt*betacf(a,b,x)/a
    Use continued fraction directly.
else
    betai_s=1.0_sp-bt*betacf(b,a,1.0_sp-x)/b
    Use continued fraction after making the
    symmetry transformation.
end if
END FUNCTION betai_s

```

```

FUNCTION betai_v(a,b,x)
USE nrtype; USE nrutil, ONLY : assert,assert_eq
USE nr, ONLY : betacf,gammln
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: a,b,x
REAL(SP), DIMENSION(size(a)) :: betai_v
REAL(SP), DIMENSION(size(a)) :: bt
LOGICAL(LGT), DIMENSION(size(a)) :: mask
INTEGER(I4B) :: ndum
ndum=assert_eq(size(a),size(b),size(x),'betai_v')
call assert(all(x >= 0.0), all(x <= 1.0), 'betai_v arg')
where (x == 0.0 .or. x == 1.0)
    bt=0.0
elsewhere
    bt=exp(gammln(a+b)-gammln(a)-gammln(b)&
           +a*log(x)+b*log(1.0_sp-x))
end where
mask=(x < (a+1.0_sp)/(a+b+2.0_sp))
betai_v=bt*betacf(merge(a,b,mask),merge(b,a,mask),&
                merge(x,1.0_sp-x,mask))/merge(a,b,mask)
where (.not. mask) betai_v=1.0_sp-betai_v
END FUNCTION betai_v

```

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Compare the scalar

```
if (x < (a+1.0_sp)/(a+b+2.0_sp)) then
  betai_s=bt*betacf(a,b,x)/a
else
  betai_s=1.0_sp-bt*betacf(b,a,1.0_sp-x)/b
end if
```

with the vector

```
mask=(x < (a+1.0_sp)/(a+b+2.0_sp))
betai_v=bt*betacf(merge(a,b,mask),merge(b,a,mask), &
  merge(x,1.0_sp-x,mask))/merge(a,b,mask)
where (.not. mask) betai_v=1.0_sp-betai_v
```

Here `merge` is used (several times) to evaluate all the required components in a single call to the vectorized `betacf`, notwithstanding that some components require one pattern of arguments, some a different pattern.

```
FUNCTION betacf_s(a,b,x)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b,x
REAL(SP) :: betacf_s
INTEGER(I4B), PARAMETER :: MAXIT=100
REAL(SP), PARAMETER :: EPS=epsilon(x), FPMIN=tiny(x)/EPS
  Used by betai: Evaluates continued fraction for incomplete beta function by modified
  Lentz's method (§5.2).
REAL(SP) :: aa,c,d,del,h,qab,qam,qap
INTEGER(I4B) :: m,m2
qab=a+b
qap=a+1.0_sp
qam=a-1.0_sp
c=1.0
d=1.0_sp-qab*x/qap
if (abs(d) < FPMIN) d=FPMIN
d=1.0_sp/d
h=d
do m=1,MAXIT
  m2=2*m
  aa=m*(b-m)*x/((qam+m2)*(a+m2))
  d=1.0_sp+aa*d
  if (abs(d) < FPMIN) d=FPMIN
  c=1.0_sp+aa/c
  if (abs(c) < FPMIN) c=FPMIN
  d=1.0_sp/d
  h=h*d*c
  aa=-(a+m)*(qab+m)*x/((a+m2)*(qap+m2))
  d=1.0_sp+aa*d
  if (abs(d) < FPMIN) d=FPMIN
  c=1.0_sp+aa/c
  if (abs(c) < FPMIN) c=FPMIN
  d=1.0_sp/d
  del=d*c
  h=h*del
  if (abs(del-1.0_sp) <= EPS) exit
end do
if (m > MAXIT)&
  call nrerror('a or b too big, or MAXIT too small in betacf_s')
betacf_s=h
END FUNCTION betacf_s
```

These  $q$ 's will be used in factors that occur in the coefficients (6.4.6).

First step of Lentz's method.

One step (the even one) of the recurrence.

Next step of the recurrence (the odd one).

Are we done?

```

FUNCTION betacf_v(a,b,x)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: a,b,x
REAL(SP), DIMENSION(size(x)) :: betacf_v
INTEGER(I4B), PARAMETER :: MAXIT=100
REAL(SP), PARAMETER :: EPS=epsilon(x), FPMIN=tiny(x)/EPS
REAL(SP), DIMENSION(size(x)) :: aa,c,d,del,h,qab,qam,qap
LOGICAL(LGT), DIMENSION(size(x)) :: converged
INTEGER(I4B) :: m
INTEGER(I4B), DIMENSION(size(x)) :: m2
m=assert_eq(size(a),size(b),size(x),'betacf_v')
qab=a+b
qap=a+1.0_sp
qam=a-1.0_sp
c=1.0
d=1.0_sp-qab*x/qap
where (abs(d) < FPMIN) d=FPMIN
d=1.0_sp/d
h=d
converged=.false.
do m=1,MAXIT
  where (.not. converged)
    m2=2*m
    aa=m*(b-m)*x/((qam+m2)*(a+m2))
    d=1.0_sp+aa*d
    d=merge(FPMIN,d, abs(d)<FPMIN )
    c=1.0_sp+aa/c
    c=merge(FPMIN,c, abs(c)<FPMIN )
    d=1.0_sp/d
    h=h*d*c
    aa=-(a+m)*(qab+m)*x/((a+m2)*(qap+m2))
    d=1.0_sp+aa*d
    d=merge(FPMIN,d, abs(d)<FPMIN )
    c=1.0_sp+aa/c
    c=merge(FPMIN,c, abs(c)<FPMIN )
    d=1.0_sp/d
    del=d*c
    h=h*del
    converged = (abs(del-1.0_sp) <= EPS)
  end where
  if (all(converged)) exit
end do
if (m > MAXIT)&
  call nrerror('a or b too big, or MAXIT too small in betacf_v')
betacf_v=h
END FUNCTION betacf_v

```

**f90** `d=merge(FPMIN,d, abs(d)<FPMIN )` The scalar version does this with an `if`. Why does it become a `merge` here in the vector version, rather than a `where`? Because we are already inside a “`where (.not. converged)`” block, and Fortran 90 doesn’t allow nested `where`’s! (Fortran 95 *will* allow nested `where`’s.)

\* \* \*

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```

FUNCTION bessj0_s(x)
USE nrtype; USE nrutil, ONLY : poly
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: bessj0_s
  Returns the Bessel function  $J_0(x)$  for any real x.
REAL(SP) :: ax,xx,z
REAL(DP) :: y
  We'll accumulate polynomials in double precision.
REAL(DP), DIMENSION(5) :: p = (/1.0_dp,-0.1098628627e-2_dp,&
  0.2734510407e-4_dp,-0.2073370639e-5_dp,0.2093887211e-6_dp/)
REAL(DP), DIMENSION(5) :: q = (/ -0.1562499995e-1_dp,&
  0.1430488765e-3_dp,-0.6911147651e-5_dp,0.7621095161e-6_dp,&
  -0.934945152e-7_dp/)
REAL(DP), DIMENSION(6) :: r = (/57568490574.0_dp,-13362590354.0_dp,&
  651619640.7_dp,-11214424.18_dp,77392.33017_dp,&
  -184.9052456_dp/)
REAL(DP), DIMENSION(6) :: s = (/57568490411.0_dp,1029532985.0_dp,&
  9494680.718_dp,59272.64853_dp,267.8532712_dp,1.0_dp/)
if (abs(x) < 8.0) then
  Direct rational function fit.
  y=x**2
  bessj0_s=poly(y,r)/poly(y,s)
else
  Fitting function (6.5.9).
  ax=abs(x)
  z=8.0_sp/ax
  y=z**2
  xx=ax-0.785398164_sp
  bessj0_s=sqrt(0.636619772_sp/ax)*(cos(xx)*&
    poly(y,p)-z*sin(xx)*poly(y,q))
end if
END FUNCTION bessj0_s


```

```

FUNCTION bessj0_v(x)
USE nrtype; USE nrutil, ONLY : poly
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: bessj0_v
REAL(SP), DIMENSION(size(x)) :: ax,xx,z
REAL(DP), DIMENSION(size(x)) :: y
LOGICAL(LGT), DIMENSION(size(x)) :: mask
REAL(DP), DIMENSION(5) :: p = (/1.0_dp,-0.1098628627e-2_dp,&
  0.2734510407e-4_dp,-0.2073370639e-5_dp,0.2093887211e-6_dp/)
REAL(DP), DIMENSION(5) :: q = (/ -0.1562499995e-1_dp,&
  0.1430488765e-3_dp,-0.6911147651e-5_dp,0.7621095161e-6_dp,&
  -0.934945152e-7_dp/)
REAL(DP), DIMENSION(6) :: r = (/57568490574.0_dp,-13362590354.0_dp,&
  651619640.7_dp,-11214424.18_dp,77392.33017_dp,&
  -184.9052456_dp/)
REAL(DP), DIMENSION(6) :: s = (/57568490411.0_dp,1029532985.0_dp,&
  9494680.718_dp,59272.64853_dp,267.8532712_dp,1.0_dp/)
mask = (abs(x) < 8.0)
where (mask)
  y=x**2
  bessj0_v=poly(y,r,mask)/poly(y,s,mask)
elsewhere
  ax=abs(x)
  z=8.0_sp/ax
  y=z**2
  xx=ax-0.785398164_sp
  bessj0_v=sqrt(0.636619772_sp/ax)*(cos(xx)*&
    poly(y,p,.not. mask)-z*sin(xx)*poly(y,q,.not. mask))
end where
END FUNCTION bessj0_v

```

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where  $(\text{mask}) \dots \text{bessj0\_v} = \text{poly}(y, r, \text{mask}) / \text{poly}(y, s, \text{mask})$ . Here we meet the *third* solution to the problem of getting masked values from an external vector function. (For the other two solutions, see notes to `factr1`, p. 1087, and `gammp`, p. 1090.) Here we simply evade all responsibility and pass the mask into every routine that is supposed to be masked. Let it be somebody else's problem! That works here because your hardworking authors have overloaded the `nrutil` routine `poly` with a masked vector version. More typically, of course, it becomes *your* problem, and you have to remember to write masked versions of all the vector routines that you call in this way. (We'll meet examples of this later.)

\* \* \*

```

FUNCTION bessy0_s(x)
USE nrtype; USE nrutil, ONLY : assert,poly
USE nr, ONLY : bessj0
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: bessy0_s
    Returns the Bessel function  $Y_0(x)$  for positive x.
REAL(SP) :: xx,z
REAL(DP) :: y
    We'll accumulate polynomials in double precision.
REAL(DP), DIMENSION(5) :: p = (/1.0_dp,-0.1098628627e-2_dp,&
    0.2734510407e-4_dp,-0.2073370639e-5_dp,0.2093887211e-6_dp/)
REAL(DP), DIMENSION(5) :: q = (/ -0.1562499995e-1_dp,&
    0.1430488765e-3_dp,-0.6911147651e-5_dp,0.7621095161e-6_dp,&
    -0.934945152e-7_dp/)
REAL(DP), DIMENSION(6) :: r = (/ -2957821389.0_dp,7062834065.0_dp,&
    -512359803.6_dp,10879881.29_dp,-86327.92757_dp,&
    228.4622733_dp/)
REAL(DP), DIMENSION(6) :: s = (/40076544269.0_dp,745249964.8_dp,&
    7189466.438_dp,47447.26470_dp,226.1030244_dp,1.0_dp/)
call assert(x > 0.0, 'bessy0_s arg')
if (abs(x) < 8.0) then
    Rational function approximation of (6.5.8).
    y=x**2
    bessy0_s=(poly(y,r)/poly(y,s))+&
        0.636619772_sp*bessj0(x)*log(x)
else
    Fitting function (6.5.10).
    z=8.0_sp/x
    y=z**2
    xx=x-0.785398164_sp
    bessy0_s=sqrt(0.636619772_sp/x)*(sin(xx)*&
        poly(y,p)+z*cos(xx)*poly(y,q))
end if
END FUNCTION bessy0_s

```

```

FUNCTION bessy0_v(x)
USE nrtype; USE nrutil, ONLY : assert,poly
USE nr, ONLY : bessj0
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: bessy0_v
REAL(SP), DIMENSION(size(x)) :: xx,z
REAL(DP), DIMENSION(size(x)) :: y
LOGICAL(LGT), DIMENSION(size(x)) :: mask
REAL(DP), DIMENSION(5) :: p = (/1.0_dp,-0.1098628627e-2_dp,&
    0.2734510407e-4_dp,-0.2073370639e-5_dp,0.2093887211e-6_dp/)
REAL(DP), DIMENSION(5) :: q = (/ -0.1562499995e-1_dp,&
    0.1430488765e-3_dp,-0.6911147651e-5_dp,0.7621095161e-6_dp,&

```

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```

-0.934945152e-7_dp/)
REAL(DP), DIMENSION(6) :: r = (/ -2957821389.0_dp, 7062834065.0_dp, &
-512359803.6_dp, 10879881.29_dp, -86327.92757_dp, &
228.4622733_dp/)
REAL(DP), DIMENSION(6) :: s = (/ 40076544269.0_dp, 745249964.8_dp, &
7189466.438_dp, 47447.26470_dp, 226.1030244_dp, 1.0_dp/)
call assert(all(x > 0.0), 'bessy0_v arg')
mask = (abs(x) < 8.0)
where (mask)
  y=x**2
  bessy0_v=(poly(y,r,mask)/poly(y,s,mask))+&
0.636619772_sp*bessj0(x)*log(x)
elsewhere
  z=8.0_sp/x
  y=z**2
  xx=x-0.785398164_sp
  bessy0_v=sqrt(0.636619772_sp/x)*(sin(xx)*&
poly(y,p,.not. mask)+z*cos(xx)*poly(y,q,.not. mask))
end where
END FUNCTION bessy0_v

```

\* \* \*

```

FUNCTION bessj1_s(x)
USE nrtype; USE nrutil, ONLY : poly
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: bessj1_s
  Returns the Bessel function  $J_1(x)$  for any real x.
REAL(SP) :: ax,xx,z
REAL(DP) :: y
  We'll accumulate polynomials in double precision.
REAL(DP), DIMENSION(6) :: r = (/ 72362614232.0_dp, &
-7895059235.0_dp, 242396853.1_dp, -2972611.439_dp, &
15704.48260_dp, -30.16036606_dp/)
REAL(DP), DIMENSION(6) :: s = (/ 144725228442.0_dp, 2300535178.0_dp, &
18583304.74_dp, 99447.43394_dp, 376.9991397_dp, 1.0_dp/)
REAL(DP), DIMENSION(5) :: p = (/ 1.0_dp, 0.183105e-2_dp, &
-0.3516396496e-4_dp, 0.2457520174e-5_dp, -0.240337019e-6_dp/)
REAL(DP), DIMENSION(5) :: q = (/ 0.04687499995_dp, &
-0.2002690873e-3_dp, 0.8449199096e-5_dp, -0.88228987e-6_dp, &
0.105787412e-6_dp/)
if (abs(x) < 8.0) then
  Direct rational approximation.
  y=x**2
  bessj1_s=x*(poly(y,r)/poly(y,s))
else
  Fitting function (6.5.9).
  ax=abs(x)
  z=8.0_sp/ax
  y=z**2
  xx=ax-2.356194491_sp
  bessj1_s=sqrt(0.636619772_sp/ax)*(cos(xx)*&
poly(y,p)-z*sin(xx)*poly(y,q))*sign(1.0_sp,x)
end if
END FUNCTION bessj1_s

```

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```

FUNCTION bessj1_v(x)
USE nrtype; USE nrutil, ONLY : poly
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: bessj1_v
REAL(SP), DIMENSION(size(x)) :: ax,xx,z
REAL(DP), DIMENSION(size(x)) :: y
LOGICAL(LGT), DIMENSION(size(x)) :: mask
REAL(DP), DIMENSION(6) :: r = (/72362614232.0_dp,&
-7895059235.0_dp,242396853.1_dp,-2972611.439_dp,&
15704.48260_dp,-30.16036606_dp/)
REAL(DP), DIMENSION(6) :: s = (/144725228442.0_dp,2300535178.0_dp,&
18583304.74_dp,99447.43394_dp,376.9991397_dp,1.0_dp/)
REAL(DP), DIMENSION(5) :: p = (/1.0_dp,0.183105e-2_dp,&
-0.3516396496e-4_dp,0.2457520174e-5_dp,-0.240337019e-6_dp/)
REAL(DP), DIMENSION(5) :: q = (/0.04687499995_dp,&
-0.2002690873e-3_dp,0.8449199096e-5_dp,-0.88228987e-6_dp,&
0.105787412e-6_dp/)
mask = (abs(x) < 8.0)
where (mask)
  y=x**2
  bessj1_v=x*(poly(y,r,mask)/poly(y,s,mask))
elsewhere
  ax=abs(x)
  z=8.0_sp/ax
  y=z**2
  xx=ax-2.356194491_sp
  bessj1_v=sqrt(0.636619772_sp/ax)*(cos(xx)*&
    poly(y,p,.not. mask)-z*sin(xx)*poly(y,q,.not. mask))*&
    sign(1.0_sp,x)
end where
END FUNCTION bessj1_v

```

\* \* \*

```

FUNCTION bessy1_s(x)
USE nrtype; USE nrutil, ONLY : assert,poly
USE nr, ONLY : bessj1
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: bessy1_s
Returns the Bessel function  $Y_1(x)$  for positive x.
REAL(SP) :: xx,z
REAL(DP) :: y
REAL(DP), DIMENSION(5) :: p = (/1.0_dp,0.183105e-2_dp,&
-0.3516396496e-4_dp,0.2457520174e-5_dp,-0.240337019e-6_dp/)
REAL(DP), DIMENSION(5) :: q = (/0.04687499995_dp,&
-0.2002690873e-3_dp,0.8449199096e-5_dp,-0.88228987e-6_dp,&
0.105787412e-6_dp/)
REAL(DP), DIMENSION(6) :: r = (/ -0.4900604943e13_dp,&
0.1275274390e13_dp,-0.5153438139e11_dp,0.7349264551e9_dp,&
-0.4237922726e7_dp,0.8511937935e4_dp/)
REAL(DP), DIMENSION(7) :: s = (/0.2499580570e14_dp,&
0.4244419664e12_dp,0.3733650367e10_dp,0.2245904002e8_dp,&
0.1020426050e6_dp,0.3549632885e3_dp,1.0_dp/)
call assert(x > 0.0, 'bessy1_s arg')
if (abs(x) < 8.0) then
  Rational function approximation of (6.5.8).
  y=x**2
  bessy1_s=x*(poly(y,r)/poly(y,s))+&
    0.636619772_sp*(bessj1(x)*log(x)-1.0_sp/x)
else
  Fitting function (6.5.10).

```

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```

z=8.0_sp/x
y=z**2
xx=x-2.356194491_sp
bessy1_s=sqrt(0.636619772_sp/x)*(sin(xx)*&
poly(y,p)+z*cos(xx)*poly(y,q))
end if
END FUNCTION bessy1_s

FUNCTION bessy1_v(x)
USE nrtype; USE nrutil, ONLY : assert,poly
USE nr, ONLY : bessj1
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: bessy1_v
REAL(SP), DIMENSION(size(x)) :: xx,z
REAL(DP), DIMENSION(size(x)) :: y
LOGICAL(LGT), DIMENSION(size(x)) :: mask
REAL(DP), DIMENSION(5) :: p = (/1.0_dp,0.183105e-2_dp,&
-0.3516396496e-4_dp,0.2457520174e-5_dp,-0.240337019e-6_dp/)
REAL(DP), DIMENSION(5) :: q = (/0.04687499995_dp,&
-0.2002690873e-3_dp,0.8449199096e-5_dp,-0.88228987e-6_dp,&
0.105787412e-6_dp/)
REAL(DP), DIMENSION(6) :: r = (/ -0.4900604943e13_dp,&
0.1275274390e13_dp,-0.5153438139e11_dp,0.7349264551e9_dp,&
-0.4237922726e7_dp,0.8511937935e4_dp/)
REAL(DP), DIMENSION(7) :: s = (/0.2499580570e14_dp,&
0.4244419664e12_dp,0.3733650367e10_dp,0.2245904002e8_dp,&
0.1020426050e6_dp,0.3549632885e3_dp,1.0_dp/)
call assert(all(x > 0.0), 'bessy1_v arg')
mask = (abs(x) < 8.0)
where (mask)
y=x**2
bessy1_v=x*(poly(y,r,mask)/poly(y,s,mask))+&
0.636619772_sp*(bessj1(x)*log(x)-1.0_sp/x)
elsewhere
z=8.0_sp/x
y=z**2
xx=x-2.356194491_sp
bessy1_v=sqrt(0.636619772_sp/x)*(sin(xx)*&
poly(y,p,.not. mask)+z*cos(xx)*poly(y,q,.not. mask))
end where
END FUNCTION bessy1_v

```

\* \* \*

```

FUNCTION bessy_s(n,x)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : bessy0,bessy1
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), INTENT(IN) :: x
REAL(SP) :: bessy_s
Returns the Bessel function  $Y_n(x)$  for positive  $x$  and  $n \geq 2$ .
INTEGER(I4B) :: j
REAL(SP) :: by,bym,byp,tox
call assert(n >= 2, x > 0.0, 'bessy_s args')
tox=2.0_sp/x
by=bessy1(x) Starting values for the recurrence.
bym=bessy0(x)
do j=1,n-1 Recurrence (6.5.7).

```

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```

    byp=j*tox*by-bym
    bym=by
    by=byp
end do
bessy_s=by
END FUNCTION bessy_s

```

```

FUNCTION bessy_v(n,x)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : bessy0,bessy1
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: bessy_v
INTEGER(I4B) :: j
REAL(SP), DIMENSION(size(x)) :: by,bym,byp,tox
call assert(n >= 2, all(x > 0.0), 'bessy_v args')
tox=2.0_sp/x
by=bessy1(x)
bym=bessy0(x)
do j=1,n-1
    byp=j*tox*by-bym
    bym=by
    by=byp
end do
bessy_v=by
END FUNCTION bessy_v

```

**f<sub>90</sub>** Notice that the vector routine is *exactly* the same as the scalar routine, but operates only on vectors, and that nothing in the routine is specific to any level of precision or kind type of real variable. Cases like this make us wish that Fortran 90 provided for “template” types that could automatically take the type and shape of the actual arguments. (Such facilities are available in other, more object-oriented languages such as C++.)

\* \* \*

```

FUNCTION bessj_s(n,x)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : bessj0,bessj1
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), INTENT(IN) :: x
REAL(SP) :: bessj_s
INTEGER(I4B), PARAMETER :: IACC=40,IEXP=maxexponent(x)/2
    Returns the Bessel function  $J_n(x)$  for any real  $x$  and  $n \geq 2$ . Make the parameter IACC
    larger to increase accuracy.
INTEGER(I4B) :: j,jsum,m
REAL(SP) :: ax,bj,bjm,bjp,summ,tox
call assert(n >= 2, 'bessj_s args')
ax=abs(x)
if (ax*ax <= 8.0_sp*tiny(x)) then
    bessj_s=0.0
    Underflow limit.
else if (ax > real(n,sp)) then
    Upwards recurrence from  $J_0$  and  $J_1$ .
    tox=2.0_sp/ax
    bj=bessj0(ax)
    bjm=bessj1(ax)
    do j=1,n-1

```

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```

        bjp=j*tox*bj-bjm
        bjm=bj
        bj=bjp
    end do
    bessj_s=bj
else
    tox=2.0_sp/ax
    m=2*(n+int(sqrt(real(IACC*n,sp))))/2)
    bessj_s=0.0
    jsum=0
    summ=0.0
    bjp=0.0
    bj=1.0
    do j=m,1,-1
        bjm=j*tox*bj-bjp
        bjp=bj
        bj=bjm
        if (exponent(bj) > IEXP) then
            bj=scale(bj,-IEXP)
            bjp=scale(bjp,-IEXP)
            bessj_s=scale(bessj_s,-IEXP)
            summ=scale(summ,-IEXP)
        end if
        if (jsum /= 0) summ=summ+bj
        jsum=1-jsum
        if (j == n) bessj_s=bjp
    end do
    summ=2.0_sp*summ-bj
    bessj_s=bessj_s/summ
end if
if (x < 0.0 .and. mod(n,2) == 1) bessj_s=-bessj_s
END FUNCTION bessj_s

```

Downwards recurrence from an even  $m$  here computed.

$j$ sum will alternate between 0 and 1; when it is 1, we accumulate in sum the even terms in (5.5.16).

The downward recurrence.

Renormalize to prevent overflows.

Accumulate the sum.  
Change 0 to 1 or vice versa.  
Save the unnormalized answer.

Compute (5.5.16)  
and use it to normalize the answer.



The `bessj` routine does not conveniently parallelize with Fortran 90's language constructions, but Bessel functions are of sufficient importance that we feel the need for a parallel version nevertheless. The basic method adopted below is to encapsulate as contained vector functions two separate algorithms, one for the case  $x \leq n$ , the other for  $x > n$ . Both of these have masks as input arguments; within each routine, however, they immediately revert to the pack-unpack method. The choice to pack in the subsidiary routines, rather than in the main routine, is arbitrary; the main routine is supposed to be a little clearer this way.

**f90** if (exponent(bj) > IEXP) then... In the Fortran 77 version of this routine, we scaled the variables by  $10^{-10}$  whenever `bj` was bigger than  $10^{10}$ . On a machine with a large exponent range, we could improve efficiency by scaling less often. In order to remain portable, however, we used the conservative value of  $10^{10}$ . An elegant way of handling renormalization is provided by the Fortran 90 intrinsic functions that manipulate real numbers. We test with `if (exponent(bj) > IEXP)` and then if necessary renormalize with `bj=scale(bj,-IEXP)` and similarly for the other variables. Our conservative choice is to set `IEXP=maxexponent(x)/2`. Note that an added benefit of scaling this way is that only the exponent of each variable is modified; no roundoff error is introduced as it can be if we do a floating-point division instead.

```

FUNCTION bessj_v(n,xx)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : bessj0,bessj1
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), DIMENSION(:), INTENT(IN) :: xx
REAL(SP), DIMENSION(size(xx)) :: bessj_v
INTEGER(I4B), PARAMETER :: IACC=40,IEXP=maxexponent(xx)/2
REAL(SP), DIMENSION(size(xx)) :: ax
LOGICAL(LGT), DIMENSION(size(xx)) :: mask,mask0
REAL(SP), DIMENSION(:), ALLOCATABLE :: x,bj,bjm,bjp,summ,tox,bessjle
LOGICAL(LGT), DIMENSION(:), ALLOCATABLE :: renorm
INTEGER(I4B) :: j,jsum,m,npak
call assert(n >= 2, 'bessj_v args')
ax=abs(xx)
mask = (ax <= real(n,sp))
mask0 = (ax*ax <= 8.0_sp*tiny(xx))
bessj_v=bessjle_v(n,ax,logical(mask .and. .not.mask0, kind=lgd))
bessj_v=merge(bessjgt_v(n,ax,.not. mask),bessj_v,.not. mask)
where (mask0) bessj_v=0.0
where (xx < 0.0 .and. mod(n,2) == 1) bessj_v=-bessj_v
CONTAINS

FUNCTION bessjgt_v(n,xx,mask)
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), DIMENSION(:), INTENT(IN) :: xx
LOGICAL(LGT), DIMENSION(size(xx)), INTENT(IN) :: mask
REAL(SP), DIMENSION(size(xx)) :: bessjgt_v
npak=count(mask)
if (npak == 0) RETURN
allocate(x(npak),bj(npak),bjm(npak),bjp(npak),tox(npak))
x=pack(xx,mask)
tox=2.0_sp/x
bjm=bessj0(x)
bj=bessj1(x)
do j=1,n-1
    bjp=j*tox*bj-bjm
    bjm=bj
    bj=bjp
end do
bessjgt_v=unpack(bj,mask,0.0_sp)
deallocate(x,bj,bjm,bjp,tox)
END FUNCTION bessjgt_v

FUNCTION bessjle_v(n,xx,mask)
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), DIMENSION(:), INTENT(IN) :: xx
LOGICAL(LGT), DIMENSION(size(xx)), INTENT(IN) :: mask
REAL(SP), DIMENSION(size(xx)) :: bessjle_v
npak=count(mask)
if (npak == 0) RETURN
allocate(x(npak),bj(npak),bjm(npak),bjp(npak),summ(npak), &
    bessjle(npak),tox(npak),renorm(npak))
x=pack(xx,mask)
tox=2.0_sp/x
m=2*((n+int(sqrt(real(IACC*n,sp)))))/2)
bessjle=0.0
jsum=0
summ=0.0
bjp=0.0
bj=1.0
do j=m,1,-1
    bjm=j*tox*bj-bjp

```

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```

bjp=bj
bj=bjm
renorm = (exponent(bj)>IEXP)
bj=merge(scale(bj,-IEXP),bj,renorm)
bjp=merge(scale(bjp,-IEXP),bjp,renorm)
bessjle=merge(scale(bessjle,-IEXP),bessjle,renorm)
summ=merge(scale(summ,-IEXP),summ,renorm)
if (jsum /= 0) summ=summ+bj
jsum=1-jsum
if (j == n) bessjle=bjp
end do
summ=2.0_sp*summ-bj
bessjle=bessjle/summ
bessjle_v=unpack(bessjle,mask,0.0_sp)
deallocate(x,bj,bjm,bjp,summ,bessjle,tox,renorm)
END FUNCTION bessjle_v
END FUNCTION bessj_v

```

**f90** `bessj_v=...` `bessj_v=merge(bessjgt_v(...),bessj_v,...)` The vector `bessj_v` is set once (with a mask) and then merged with *itself*, along with the vector result of the `bessjgt_v` call. Thus are the two evaluation methods combined. (A third case, where an argument is zero, is then handled by an immediately following where.)

\* \* \*

```

FUNCTION bessj0_s(x)
USE nrtype; USE nrutil, ONLY : poly
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: bessj0_s
Returns the modified Bessel function  $I_0(x)$  for any real x.
REAL(SP) :: ax
REAL(DP), DIMENSION(7) :: p = (/1.0_dp,3.5156229_dp,&
3.0899424_dp,1.2067492_dp,0.2659732_dp,0.360768e-1_dp,&
0.45813e-2_dp/) Accumulate polynomials in double precision.
REAL(DP), DIMENSION(9) :: q = (/0.39894228_dp,0.1328592e-1_dp,&
0.225319e-2_dp,-0.157565e-2_dp,0.916281e-2_dp,&
-0.2057706e-1_dp,0.2635537e-1_dp,-0.1647633e-1_dp,&
0.392377e-2_dp/)
ax=abs(x)
if (ax < 3.75) then Polynomial fit.
bessj0_s=poly(real((x/3.75_sp)**2,dp),p)
else
bessj0_s=(exp(ax)/sqrt(ax))*poly(real(3.75_sp/ax,dp),q)
end if
END FUNCTION bessj0_s

```

```

FUNCTION bessj0_v(x)
USE nrtype; USE nrutil, ONLY : poly
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: bessj0_v
REAL(SP), DIMENSION(size(x)) :: ax
REAL(DP), DIMENSION(size(x)) :: y
LOGICAL(LGT), DIMENSION(size(x)) :: mask
REAL(DP), DIMENSION(7) :: p = (/1.0_dp,3.5156229_dp,&
3.0899424_dp,1.2067492_dp,0.2659732_dp,0.360768e-1_dp,&

```

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```

    0.45813e-2_dp/)
REAL(DP), DIMENSION(9) :: q = (/0.39894228_dp,0.1328592e-1_dp,&
    0.225319e-2_dp,-0.157565e-2_dp,0.916281e-2_dp,&
    -0.2057706e-1_dp,0.2635537e-1_dp,-0.1647633e-1_dp,&
    0.392377e-2_dp/)
ax=abs(x)
mask = (ax < 3.75)
where (mask)
    bessio_v=poly(real((x/3.75_sp)**2,dp),p,mask)
elsewhere
    y=3.75_sp/ax
    bessio_v=(exp(ax)/sqrt(ax))*poly(real(y,dp),q,.not. mask)
end where
END FUNCTION bessio_v

```

\* \* \*

```

FUNCTION bessk0_s(x)
USE nrtype; USE nrutil, ONLY : assert,poly
USE nr, ONLY : bessio
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: bessk0_s
    Returns the modified Bessel function  $K_0(x)$  for positive real x.
REAL(DP) :: y
    Accumulate polynomials in double precision.
REAL(DP), DIMENSION(7) :: p = (/ -0.57721566_dp, 0.42278420_dp, &
    0.23069756_dp, 0.3488590e-1_dp, 0.262698e-2_dp, 0.10750e-3_dp, &
    0.74e-5_dp/)
REAL(DP), DIMENSION(7) :: q = (/ 1.25331414_dp, -0.7832358e-1_dp, &
    0.2189568e-1_dp, -0.1062446e-1_dp, 0.587872e-2_dp, &
    -0.251540e-2_dp, 0.53208e-3_dp/)
call assert(x > 0.0, 'bessk0_s arg')
if (x <= 2.0) then
    Polynomial fit.
    y=x*x/4.0_sp
    bessk0_s=(-log(x/2.0_sp)*bessio(x))+poly(y,p)
else
    y=(2.0_sp/x)
    bessk0_s=(exp(-x)/sqrt(x))*poly(y,q)
end if
END FUNCTION bessk0_s

```

```

FUNCTION bessk0_v(x)
USE nrtype; USE nrutil, ONLY : assert,poly
USE nr, ONLY : bessio
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: bessk0_v
REAL(DP), DIMENSION(size(x)) :: y
LOGICAL(LGT), DIMENSION(size(x)) :: mask
REAL(DP), DIMENSION(7) :: p = (/ -0.57721566_dp, 0.42278420_dp, &
    0.23069756_dp, 0.3488590e-1_dp, 0.262698e-2_dp, 0.10750e-3_dp, &
    0.74e-5_dp/)
REAL(DP), DIMENSION(7) :: q = (/ 1.25331414_dp, -0.7832358e-1_dp, &
    0.2189568e-1_dp, -0.1062446e-1_dp, 0.587872e-2_dp, &
    -0.251540e-2_dp, 0.53208e-3_dp/)
call assert(all(x > 0.0), 'bessk0_v arg')
mask = (x <= 2.0)
where (mask)
    y=x*x/4.0_sp
    bessk0_v=(-log(x/2.0_sp)*bessio(x))+poly(y,p,mask)

```

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```

elsewhere
  y=(2.0_sp/x)
  bessk0_v=(exp(-x)/sqrt(x))*poly(y,q,.not. mask)
end where
END FUNCTION bessk0_v

```

\* \* \*

```

FUNCTION bess1_s(x)
USE nrtype; USE nrutil, ONLY : poly
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: bess1_s
  Returns the modified Bessel function  $I_1(x)$  for any real x.
REAL(SP) :: ax
REAL(DP), DIMENSION(7) :: p = (/0.5_dp,0.87890594_dp,&
  0.51498869_dp,0.15084934_dp,0.2658733e-1_dp,&
  0.301532e-2_dp,0.32411e-3_dp/)
  Accumulate polynomials in double precision.
REAL(DP), DIMENSION(9) :: q = (/0.39894228_dp,-0.3988024e-1_dp,&
  -0.362018e-2_dp,0.163801e-2_dp,-0.1031555e-1_dp,&
  0.2282967e-1_dp,-0.2895312e-1_dp,0.1787654e-1_dp,&
  -0.420059e-2_dp/)
ax=abs(x)
if (ax < 3.75) then      Polynomial fit.
  bess1_s=ax*poly(real((x/3.75_sp)**2,dp),p)
else
  bess1_s=(exp(ax)/sqrt(ax))*poly(real(3.75_sp/ax,dp),q)
end if
if (x < 0.0) bess1_s=-bess1_s
END FUNCTION bess1_s

```

```

FUNCTION bess1_v(x)
USE nrtype; USE nrutil, ONLY : poly
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: bess1_v
REAL(SP), DIMENSION(size(x)) :: ax
REAL(DP), DIMENSION(size(x)) :: y
LOGICAL(LGT), DIMENSION(size(x)) :: mask
REAL(DP), DIMENSION(7) :: p = (/0.5_dp,0.87890594_dp,&
  0.51498869_dp,0.15084934_dp,0.2658733e-1_dp,&
  0.301532e-2_dp,0.32411e-3_dp/)
REAL(DP), DIMENSION(9) :: q = (/0.39894228_dp,-0.3988024e-1_dp,&
  -0.362018e-2_dp,0.163801e-2_dp,-0.1031555e-1_dp,&
  0.2282967e-1_dp,-0.2895312e-1_dp,0.1787654e-1_dp,&
  -0.420059e-2_dp/)
ax=abs(x)
mask = (ax < 3.75)
where (mask)
  bess1_v=ax*poly(real((x/3.75_sp)**2,dp),p,mask)
elsewhere
  y=3.75_sp/ax
  bess1_v=(exp(ax)/sqrt(ax))*poly(real(y,dp),q,.not. mask)
end where
where (x < 0.0) bess1_v=-bess1_v
END FUNCTION bess1_v

```

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\* \* \*

```

FUNCTION bessk1_s(x)
USE nrtype; USE nrutil, ONLY : assert,poly
USE nr, ONLY : bess1
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: bessk1_s
  Returns the modified Bessel function  $K_1(x)$  for positive real x.
REAL(DP) :: y
  Accumulate polynomials in double precision.
REAL(DP), DIMENSION(7) :: p = (/1.0_dp,0.15443144_dp,&
-0.67278579_dp,-0.18156897_dp,-0.1919402e-1_dp,&
-0.110404e-2_dp,-0.4686e-4_dp/)
REAL(DP), DIMENSION(7) :: q = (/1.25331414_dp,0.23498619_dp,&
-0.3655620e-1_dp,0.1504268e-1_dp,-0.780353e-2_dp,&
0.325614e-2_dp,-0.68245e-3_dp/)
call assert(x > 0.0, 'bessk1_s arg')
if (x <= 2.0) then
  Polynomial fit.
  y=x*x/4.0_sp
  bessk1_s=(log(x/2.0_sp)*bess1(x)+(1.0_sp/x)*poly(y,p)
else
  y=2.0_sp/x
  bessk1_s=(exp(-x)/sqrt(x))*poly(y,q)
end if
END FUNCTION bessk1_s

```

```

FUNCTION bessk1_v(x)
USE nrtype; USE nrutil, ONLY : assert,poly
USE nr, ONLY : bess1
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: bessk1_v
REAL(DP), DIMENSION(size(x)) :: y
LOGICAL(LGT), DIMENSION(size(x)) :: mask
REAL(DP), DIMENSION(7) :: p = (/1.0_dp,0.15443144_dp,&
-0.67278579_dp,-0.18156897_dp,-0.1919402e-1_dp,&
-0.110404e-2_dp,-0.4686e-4_dp/)
REAL(DP), DIMENSION(7) :: q = (/1.25331414_dp,0.23498619_dp,&
-0.3655620e-1_dp,0.1504268e-1_dp,-0.780353e-2_dp,&
0.325614e-2_dp,-0.68245e-3_dp/)
call assert(all(x > 0.0), 'bessk1_v arg')
mask = (x <= 2.0)
where (mask)
  y=x*x/4.0_sp
  bessk1_v=(log(x/2.0_sp)*bess1(x)+(1.0_sp/x)*poly(y,p,mask)
elsewhere
  y=2.0_sp/x
  bessk1_v=(exp(-x)/sqrt(x))*poly(y,q,.not. mask)
end where
END FUNCTION bessk1_v

```

\* \* \*

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```

FUNCTION bessk_s(n,x)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : bessk0,bessk1
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), INTENT(IN) :: x
REAL(SP) :: bessk_s
  Returns the modified Bessel function  $K_n(x)$  for positive  $x$  and  $n \geq 2$ .
INTEGER(I4B) :: j
REAL(SP) :: bk,bkm,bkp,tox
call assert(n >= 2, x > 0.0, 'bessk_s args')
tox=2.0_sp/x
bkm=bessk0(x)           Upward recurrence for all x...
bk=bessk1(x)           ...and here it is.
do j=1,n-1
  bkp=bkm+j*tox*bk
  bkm=bk
  bk=bkp
end do
bessk_s=bk
END FUNCTION bessk_s

```

```

FUNCTION bessk_v(n,x)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : bessk0,bessk1
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: bessk_v
INTEGER(I4B) :: j
REAL(SP), DIMENSION(size(x)) :: bk,bkm,bkp,tox
call assert(n >= 2, all(x > 0.0), 'bessk_v args')
tox=2.0_sp/x
bkm=bessk0(x)
bk=bessk1(x)
do j=1,n-1
  bkp=bkm+j*tox*bk
  bkm=bk
  bk=bkp
end do
bessk_v=bk
END FUNCTION bessk_v

```



The scalar and vector versions of `bessk` are identical, and have no precision-specific constants, another example of where we would like to define a generic “template” function if the language had this facility.

\* \* \*

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```

FUNCTION bessj_s(n,x)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : bessj0
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), INTENT(IN) :: x
REAL(SP) :: bessj_s
INTEGER(I4B), PARAMETER :: IACC=40, IEXP=maxexponent(x)/2
  Returns the modified Bessel function  $I_n(x)$  for any real  $x$  and  $n \geq 2$ . Make the parameter
  IACC larger to increase accuracy.
INTEGER(I4B) :: j,m
REAL(SP) :: bi,bim,bip,tox
call assert(n >= 2, 'bessj_s args')
bessj_s=0.0
if (x*x <= 8.0_sp*tiny(x)) RETURN          Underflow limit.
tox=2.0_sp/abs(x)
bip=0.0
bi=1.0
m=2*((n+int(sqrt(real(IACC*n,sp))))))      Downward recurrence from even m.
do j=m,1,-1
  bim=bip+j*tox*bi                          The downward recurrence.
  bip=bi
  bi=bim
  if (exponent(bi) > IEXP) then              Renormalize to prevent overflows.
    bessj_s=scale(bessj_s,-IEXP)
    bi=scale(bi,-IEXP)
    bip=scale(bip,-IEXP)
  end if
  if (j == n) bessj_s=bip
end do
bessj_s=bessj_s*bessj0(x)/bi                 Normalize with bessj0.
if (x < 0.0 .and. mod(n,2) == 1) bessj_s=-bessj_s
END FUNCTION bessj_s

```



if (exponent(bi) > IEXP) then See discussion of scaling for bessj on p. 1107.

```

FUNCTION bessj_v(n,x)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : bessj0
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: bessj_v
INTEGER(I4B), PARAMETER :: IACC=40, IEXP=maxexponent(x)/2
INTEGER(I4B) :: j,m
REAL(SP), DIMENSION(size(x)) :: bi,bim,bip,tox
LOGICAL(LGT), DIMENSION(size(x)) :: mask
call assert(n >= 2, 'bessj_v args')
bessj_v=0.0
mask = (x <= 8.0_sp*tiny(x))
tox=2.0_sp/merge(2.0_sp,abs(x),mask)
bip=0.0
bi=1.0_sp
m=2*((n+int(sqrt(real(IACC*n,sp))))))
do j=m,1,-1
  bim=bip+j*tox*bi
  bip=bi
  bi=bim
  where (exponent(bi) > IEXP)
    bessj_v=scale(bessj_v,-IEXP)

```



```

        bi=scale(bi,-IEXP)
        bip=scale(bip,-IEXP)
    end where
    if (j == n) bessj_v=bip
end do
bessj_v=bessj_v*bessj0(x)/bi
where (mask) bessj_v=0.0_sp
where (x < 0.0 .and. mod(n,2) == 1) bessj_v=-bessj_v
END FUNCTION bessj_v

```



```

mask = (x == 0.0)
tox=2.0_sp/merge(2.0_sp,abs(x),mask)

```

For the special case  $x = 0$ , the value of the returned function should be zero; however, the evaluation of `tox` will give a divide check. We substitute an innocuous value for the zero cases, then fix up their answers at the end.

\* \* \*

```

SUBROUTINE bessjy_s(x,xnu,rj,ry,rjp,ryp)
USE nrtype; USE nrutil, ONLY : assert,nrerror
USE nr, ONLY : beschb
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x,xnu
REAL(SP), INTENT(OUT) :: rj,ry,rjp,ryp
INTEGER(I4B), PARAMETER :: MAXIT=10000
REAL(DP), PARAMETER :: XMIN=2.0_dp, EPS=1.0e-10_dp, FPMIN=1.0e-30_dp
    Returns the Bessel functions  $rj = J_\nu$ ,  $ry = Y_\nu$  and their derivatives  $rjp = J'_\nu$ ,  $ryp = Y'_\nu$ ,
    for positive  $x$  and for  $xnu = \nu \geq 0$ . The relative accuracy is within one or two significant
    digits of EPS, except near a zero of one of the functions, where EPS controls its absolute
    accuracy. FPMIN is a number close to the machine's smallest floating-point number. All
    internal arithmetic is in double precision. To convert the entire routine to double precision,
    change the SP declaration above and decrease EPS to  $10^{-16}$ . Also convert the subroutine
    beschb.
INTEGER(I4B) :: i, isign, l, nl
REAL(DP) :: a, b, c, d, del, del1, e, f, fact, fact2, fact3, ff, gam, gam1, gam2, &
    gammi, gampl, h, p, pimu, pimu2, q, r, rj1, rj11, rjmu, rjpl, rjpl, rjtemp, &
    ry1, rymu, rymup, rytemp, sum, sum1, w, x2, xi, xi2, xmu, xmu2
COMPLEX(DPC) :: aa, bb, cc, dd, dl, pq
call assert(x > 0.0, xnu >= 0.0, 'bessjy args')
nl=merge(int(xnu+0.5_dp), max(0,int(xnu-x+1.5_dp)), x < XMIN)
    nl is the number of downward recurrences of the  $J$ 's and upward recurrences of  $Y$ 's. xmu
    lies between  $-1/2$  and  $1/2$  for  $x < XMIN$ , while it is chosen so that  $x$  is greater than the
    turning point for  $x \geq XMIN$ .
xmu=xnu-nl
xmu2=xmu*xmu
xi=1.0_dp/x
xi2=2.0_dp*xi
w=xi2/PI_D
isign=1
h=xnu*xi
if (h < FPMIN) h=FPMIN
b=xi2*xnu
d=0.0
c=h
do i=1,MAXIT
    b=b+xi2
    d=b-d
    if (abs(d) < FPMIN) d=FPMIN
    c=b-1.0_dp/c

```

The Wronskian.  
Evaluate CF1 by modified Lentz's method (§5.2). `isign` keeps track of sign changes in the denominator.

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```

    if (abs(c) < FPMIN) c=FPMIN
    d=1.0_dp/d
    del=c*d
    h=del*h
    if (d < 0.0) isign=-isign
    if (abs(del-1.0_dp) < EPS) exit
end do
if (i > MAXIT) call nrerror('x too large in bessjy; try asymptotic expansion')
rjl=isign*FPMIN           Initialize  $J_\nu$  and  $J'_\nu$  for downward recurrence.
rjpl=h*rjl
rjl1=rjl                 Store values for later rescaling.
rjp1=rjpl
fact=xnu*xi
do l=nl,1,-1
    rjtemp=fact*rjl+rjpl
    fact=fact-xi
    rjpl=fact*rjtemp-rjl
    rjl=rjtemp
end do
if (rjl == 0.0) rjl=EPS
f=rjpl/rjl               Now have unnormalized  $J_\mu$  and  $J'_\mu$ .
if (x < XMIN) then      Use series.
    x2=0.5_dp*x
    pimu=PI_D*xmu
    if (abs(pimu) < EPS) then
        fact=1.0
    else
        fact=pimu/sin(pimu)
    end if
    d=-log(x2)
    e=xmu*d
    if (abs(e) < EPS) then
        fact2=1.0
    else
        fact2=sinh(e)/e
    end if
    call beschb(xmu,gam1,gam2,gampl,gammi)   Chebyshev evaluation of  $\Gamma_1$  and  $\Gamma_2$ .
    ff=2.0_dp/PI_D*fact*(gam1*cosh(e)+gam2*fact2*d)    $f_0$ .
    e=exp(e)
    p=e/(gampl*PI_D)    $p_0$ .
    q=1.0_dp/(e*PI_D*gammi)    $q_0$ .
    pimu2=0.5_dp*pimu
    if (abs(pimu2) < EPS) then
        fact3=1.0
    else
        fact3=sin(pimu2)/pimu2
    end if
    r=PI_D*pimu2*fact3*fact3
    c=1.0
    d=-x2*x2
    sum=ff+r*q
    sum1=p
    do i=1,MAXIT
        ff=(i*ff+p*q)/(i*xmu2)
        c=c*d/i
        p=p/(i-xmu)
        q=q/(i+xmu)
        del=c*(ff+r*q)
        sum=sum+del
        del1=c*p-i*del
        sum1=sum1+del1
        if (abs(del) < (1.0_dp+abs(sum))*EPS) exit
    end do
if (i > MAXIT) call nrerror('bessy series failed to converge')

```

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```

rymu=-sum
ry1=-sum1*xi2
rymup=xmu*xi*rymu-ry1
rjmu=w/(rymup-f*rymu)
else
a=0.25_dp-xmu2
pq=cplx(-0.5_dp*xi,1.0_dp,kind=dpc)
aa=cplx(0.0_dp,xi*a,kind=dpc)
bb=cplx(2.0_dp*x,2.0_dp,kind=dpc)
cc=bb+aa/pq
dd=1.0_dp/bb
pq=cc*dd*pq
do i=2,MAXIT
  a=a+2*(i-1)
  bb=bb+cplx(0.0_dp,2.0_dp,kind=dpc)
  dd=a*dd+bb
  if (absc(dd) < FPMIN) dd=FPMIN
  cc=bb+a/cc
  if (absc(cc) < FPMIN) cc=FPMIN
  dd=1.0_dp/dd
  dl=cc*dd
  pq=pq*dl
  if (absc(dl-1.0_dp) < EPS) exit
end do
if (i > MAXIT) call nrerror('cf2 failed in bessjy')
p=real(pq)
q=aimag(pq)
gam=(p-f)/q
rjmu=sqrt(w/((p-f)*gam+q))
rjmu=sign(rjmu,rj1)
rymu=rjmu*gam
rymup=rymu*(p+q/gam)
ry1=xmu*xi*rymu-rymup
end if
fact=rjmu/rj1
rj=rj1*fact
rjp=rjp1*fact
do i=1,nl
  rytemp=(xmu+i)*xi2*ry1-rymu
  rymu=ry1
  ry1=rytemp
end do
ry=rymu
ryp=xnu*xi*rymu-ry1
CONTAINS

FUNCTION absc(z)
IMPLICIT NONE
COMPLEX(DPC), INTENT(IN) :: z
REAL(DP) :: absc
absc=abs(real(z))+abs(aimag(z))
END FUNCTION absc
END SUBROUTINE bessjy_s

```

Equation (6.7.13).  
Evaluate CF2 by modified Lentz's method (§5.2).

Equations (6.7.6) – (6.7.10).

Scale original  $J_\nu$  and  $J'_\nu$ .

Upward recurrence of  $Y_\nu$ .



Yes there is a vector version `bessjy_v`. Its general scheme is to have a bunch of contained functions for various cases, and then combine their outputs (somewhat like `bessj_v`, above, but much more complicated). A listing runs to about four printed pages, and we judge it to be of not much interest, so we will not include it here. (It is included on the machine-readable media.)

\* \* \*

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```

SUBROUTINE beschb_s(x,gam1,gam2,gampl,gammi)
USE nrtype
USE nr, ONLY : chebev
IMPLICIT NONE
REAL(DP), INTENT(IN) :: x
REAL(DP), INTENT(OUT) :: gam1,gam2,gampl,gammi
INTEGER(I4B), PARAMETER :: NUSE1=5,NUSE2=5
  Evaluates  $\Gamma_1$  and  $\Gamma_2$  by Chebyshev expansion for  $|x| \leq 1/2$ . Also returns  $1/\Gamma(1+x)$  and
   $1/\Gamma(1-x)$ . If converting to double precision, set NUSE1 = 7, NUSE2 = 8.
REAL(SP) :: xx
REAL(SP), DIMENSION(7) :: c1=(-1.142022680371168_sp,&
  6.5165112670737e-3_sp,3.087090173086e-4_sp,-3.4706269649e-6_sp,&
  6.9437664e-9_sp,3.67795e-11_sp,-1.356e-13_sp/)
REAL(SP), DIMENSION(8) :: c2=(/1.843740587300905_sp,&
  -7.68528408447867e-2_sp,1.2719271366546e-3_sp,&
  -4.9717367042e-6_sp,-3.31261198e-8_sp,2.423096e-10_sp,&
  -1.702e-13_sp,-1.49e-15_sp/)
xx=8.0_dp*x*x-1.0_dp      Multiply x by 2 to make range be -1 to 1, and then apply
gam1=chebev(-1.0_sp,1.0_sp,c1(1:NUSE1),xx)      transformation for evaluating even Cheby-
gam2=chebev(-1.0_sp,1.0_sp,c2(1:NUSE2),xx)      shev series.
gampl=gam2-x*gam1
gammi=gam2+x*gam1
END SUBROUTINE beschb_s

```

```

SUBROUTINE beschb_v(x,gam1,gam2,gampl,gammi)
USE nrtype
USE nr, ONLY : chebev
IMPLICIT NONE
REAL(DP), DIMENSION(:), INTENT(IN) :: x
REAL(DP), DIMENSION(:), INTENT(OUT) :: gam1,gam2,gampl,gammi
INTEGER(I4B), PARAMETER :: NUSE1=5,NUSE2=5
REAL(SP), DIMENSION(size(x)) :: xx
REAL(SP), DIMENSION(7) :: c1=(-1.142022680371168_sp,&
  6.5165112670737e-3_sp,3.087090173086e-4_sp,-3.4706269649e-6_sp,&
  6.9437664e-9_sp,3.67795e-11_sp,-1.356e-13_sp/)
REAL(SP), DIMENSION(8) :: c2=(/1.843740587300905_sp,&
  -7.68528408447867e-2_sp,1.2719271366546e-3_sp,&
  -4.9717367042e-6_sp,-3.31261198e-8_sp,2.423096e-10_sp,&
  -1.702e-13_sp,-1.49e-15_sp/)
xx=8.0_dp*x*x-1.0_dp
gam1=chebev(-1.0_sp,1.0_sp,c1(1:NUSE1),xx)
gam2=chebev(-1.0_sp,1.0_sp,c2(1:NUSE2),xx)
gampl=gam2-x*gam1
gammi=gam2+x*gam1
END SUBROUTINE beschb_v

```

\* \* \*

```

SUBROUTINE bessik(x,xnu,ri,rk,rip,rkp)
USE nrtype; USE nrutil, ONLY : assert,nrerror
USE nr, ONLY : beschb
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x,xnu
REAL(SP), INTENT(OUT) :: ri,rk,rip,rkp
INTEGER(I4B), PARAMETER :: MAXIT=10000
REAL(SP), PARAMETER :: XMIN=2.0
REAL(DP), PARAMETER :: EPS=1.0e-10_dp,FPMIN=1.0e-30_dp
  Returns the modified Bessel functions  $ri = I_\nu$ ,  $rk = K_\nu$  and their derivatives  $rip = I'_\nu$ ,
   $rkp = K'_\nu$ , for positive x and for  $xnu = \nu \geq 0$ . The relative accuracy is within one or

```

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two significant digits of EPS. FPMIN is a number close to the machine's smallest floating-point number. All internal arithmetic is in double precision. To convert the entire routine to double precision, change the REAL declaration above and decrease EPS to  $10^{-16}$ . Also convert the subroutine beschb.

```

INTEGER(I4B) :: i,l,nl
REAL(DP) :: a,a1,b,c,d,del,del1,delh,dels,e,f,fact,fact2,ff,&
    gam1,gam2,gammi,gampl,h,p,pimu,q,q1,q2,qnew,&
    ril,ril1,rimu,ripl,ripl,ritemp,rk1,rkmu,rkmup,rktemp,&
    s,sum,sum1,x2,xi,xi2,xmu,xmu2
call assert(x > 0.0, xnu >= 0.0, 'bessik args')
nl=int(xnu+0.5_dp)
xmu=xnu-nl
xmu2=xmu*xmu
xi=1.0_dp/x
xi2=2.0_dp*xi
h=xnu*xi
if (h < FPMIN) h=FPMIN
b=xi2*xnu
d=0.0
c=h
do i=1,MAXIT
    b=b+xi2
    d=1.0_dp/(b+d)
    c=b+1.0_dp/c
    del=c*d
    h=del*h
    if (abs(del-1.0_dp) < EPS) exit
end do
if (i > MAXIT) call nrerror('x too large in bessik; try asymptotic expansion')
ril=FPMIN
ripl=h*ril
ril1=ril
ripl1=ripl
fact=xnu*xi
do l=nl,1,-1
    ritemp=fact*ril+ripl
    fact=fact-xi
    ripl=fact*ritemp+ril
    ril=ritemp
end do
f=ripl/ril
if (x < XMIN) then
    x2=0.5_dp*x
    pimiu=PI_D*xmu
    if (abs(pimiu) < EPS) then
        fact=1.0
    else
        fact=pimiu/sin(pimiu)
    end if
    d=-log(x2)
    e=xmu*d
    if (abs(e) < EPS) then
        fact2=1.0
    else
        fact2=sinh(e)/e
    end if
    call beschb(xmu,gam1,gam2,gampl,gammi)
    ff=fact*(gam1*cosh(e)+gam2*fact2*d)
    sum=ff
    e=exp(e)
    p=0.5_dp*e/gampl
    q=0.5_dp/(e*gammi)
    c=1.0
    d=x2*x2

```

nl is the number of downward recurrences of the  $I$ 's and upward recurrences of  $K$ 's.  $xmu$  lies between  $-1/2$  and  $1/2$ .

Evaluate CF1 by modified Lentz's method (§5.2).

Denominators cannot be zero here, so no need for special precautions.

Initialize  $I_\nu$  and  $I'_\nu$  for downward recurrence.

Store values for later rescaling.

Now have unnormalized  $I_\mu$  and  $I'_\mu$ . Use series.

Chebyshev evaluation of  $\Gamma_1$  and  $\Gamma_2$ .

$f_0$ .

$p_0$ .

$q_0$ .

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```

sum1=p
do i=1,MAXIT
  ff=(i*ff+p+q)/(i*i-xmu2)
  c=c*d/i
  p=p/(i-xmu)
  q=q/(i+xmu)
  del=c*ff
  sum=sum+del
  del1=c*(p-i*ff)
  sum1=sum1+del1
  if (abs(del) < abs(sum)*EPS) exit
end do
if (i > MAXIT) call nrerror('bessk series failed to converge')
rkmu=sum
rk1=sum1*xi2
else
  Evaluate CF2 by Steed's algorithm (§5.2),
  which is OK because there can be no
  zero denominators.

  b=2.0_dp*(1.0_dp+x)
  d=1.0_dp/b
  delh=d
  h=delh
  q1=0.0
  q2=1.0
  a1=0.25_dp-xmu2
  c=a1
  q=c
  a=-a1
  s=1.0_dp+q*delh
  do i=2,MAXIT
    a=a-2*(i-1)
    c=-a*c/i
    qnew=(q1-b*q2)/a
    q1=q2
    q2=qnew
    q=q+c*qnew
    b=b+2.0_dp
    d=1.0_dp/(b+a*d)
    delh=(b*d-1.0_dp)*delh
    h=h+delh
    dels=q*delh
    s=s+dels
    if (abs(dels/s) < EPS) exit
  end do
  if (i > MAXIT) call nrerror('bessik: failure to converge in cf2')
  h=a1*h
  rkmu=sqrt(PI_D/(2.0_dp*x))*exp(-x)/s
  rk1=rkmu*(xmu+x+0.5_dp-h)*xi
  Omit the factor exp(-x) to scale all the
  returned functions by exp(x) for x ≥
  XMIN.

  end if
  rkmup=xmu*xi*rkmu-rk1
  rimu=xi/(f*rkmu-rkmup)
  Get Iμ from Wronskian.
  Scale original Iν and I'ν.
  ri=(rimu*ril1)/ril
  rip=(rimu*rip1)/ril
  do i=1,nl
    rktemp=(xmu+i)*xi2*rk1+rkmu
    rkmu=rk1
    rk1=rktemp
  end do
  rkp=xmu*xi*rkmu-rk1
  Upward recurrence of Kν.
END SUBROUTINE bessik

```

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bessik does not readily parallelize, and we thus don't provide a vector version. Since airy, immediately following, requires bessik, we don't have a vector version of it, either.

\* \* \*

```

SUBROUTINE airy(x,ai,bi,aip,bip)
USE nrtype
USE nr, ONLY : bessik,bessjy
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP), INTENT(OUT) :: ai,bi,aip,bip
  Returns Airy functions  $Ai(x)$ ,  $Bi(x)$ , and their derivatives  $Ai'(x)$ ,  $Bi'(x)$ .
REAL(SP) :: absx,ri,rip,rj,rjp,rk,rkp,rootx,ry,ryp,z
REAL(SP), PARAMETER :: THIRD=1.0_sp/3.0_sp,TWOTHR=2.0_sp/3.0_sp, &
  ONOVRT=0.5773502691896258_sp
absx=abs(x)
rootx=sqrt(absx)
z=TWOTHR*absx*rootx
if (x > 0.0) then
  call bessik(z,THIRD,ri,rk,rip,rkp)
  ai=rootx*ONOVRT*rk/PI
  bi=rootx*(rk/PI+2.0_sp*ONOVRT*ri)
  call bessik(z,TWOTHR,ri,rk,rip,rkp)
  aip=-x*ONOVRT*rk/PI
  bip=x*(rk/PI+2.0_sp*ONOVRT*ri)
else if (x < 0.0) then
  call bessjy(z,THIRD,rj,ry,rjp,ryp)
  ai=0.5_sp*rootx*(rj-ONOVRT*ry)
  bi=-0.5_sp*rootx*(ry+ONOVRT*rj)
  call bessjy(z,TWOTHR,rj,ry,rjp,ryp)
  aip=0.5_sp*absx*(ONOVRT*ry+rj)
  bip=0.5_sp*absx*(ONOVRT*rj-ry)
else
  Case  $x = 0$ .
  ai=0.3550280538878172_sp
  bi=ai/ONOVRT
  aip=-0.2588194037928068_sp
  bip=-aip/ONOVRT
end if
END SUBROUTINE airy

```

\* \* \*

```

SUBROUTINE sphbes_s(n,x,sj,sy,sjp,syp)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : bessjy
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), INTENT(IN) :: x
REAL(SP), INTENT(OUT) :: sj,sy,sjp,syp
  Returns spherical Bessel functions  $j_n(x)$ ,  $y_n(x)$ , and their derivatives  $j'_n(x)$ ,  $y'_n(x)$  for
  integer  $n \geq 0$  and  $x > 0$ .
REAL(SP), PARAMETER :: RTPIO2=1.253314137315500_sp
REAL(SP) :: factor,order,rj,rjp,ry,ryp
call assert(n >= 0, x > 0.0, 'sphbes_s args')
order=n+0.5_sp
call bessjy(x,order,rj,ry,rjp,ryp)
factor=RTPIO2/sqrt(x)
sj=factor*rj
sy=factor*ry

```

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```

sjp=factor*rjp-sj/(2.0_sp*x)
syp=factor*ryp-sy/(2.0_sp*x)
END SUBROUTINE sphbes_s

```

```

SUBROUTINE sphbes_v(n,x,sj,sy,sjp,syp)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : bessjy
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(OUT) :: sj,sy,sjp,syp
REAL(SP), PARAMETER :: RTPIO2=1.253314137315500_sp
REAL(SP) :: order
REAL(SP), DIMENSION(size(x)) :: factor,rj,rjp,ry,ryp
call assert(n >= 0, all(x > 0.0), 'sphbes_v args')
order=n+0.5_sp
call bessjy(x,order,rj,ry,rjp,ryp)
factor=RTPIO2/sqrt(x)
sj=factor*rj
sy=factor*ry
sjp=factor*rjp-sj/(2.0_sp*x)
syp=factor*ryp-sy/(2.0_sp*x)
END SUBROUTINE sphbes_v

```



Note that `sphbes_v` uses (through overloading) `bessjy_v`. The listing of that routine was omitted above, but it is on the machine-readable media.

\* \* \*

```

FUNCTION plgndr_s(l,m,x)
USE nrtype; USE nrutil, ONLY : arth,assert
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: l,m
REAL(SP), INTENT(IN) :: x
REAL(SP) :: plgndr_s
  Computes the associated Legendre polynomial  $P_l^m(x)$ . Here  $m$  and  $l$  are integers satisfying
   $0 \leq m \leq l$ , while  $x$  lies in the range  $-1 \leq x \leq 1$ .
INTEGER(I4B) :: ll
REAL(SP) :: pll,pmm,pmmp1,somx2
call assert(m >= 0, m <= l, abs(x) <= 1.0, 'plgndr_s args')
pmm=1.0          Compute  $P_m^m$ .
if (m > 0) then
  somx2=sqrt((1.0_sp-x)*(1.0_sp+x))
  pmm=product(arth(1.0_sp,2.0_sp,m))*somx2**m
  if (mod(m,2) == 1) pmm=-pmm
end if
if (l == m) then
  plgndr_s=pmm
else
  pmmp1=x*(2*m+1)*pmm          Compute  $P_{m+1}^m$ .
  if (l == m+1) then
    plgndr_s=pmmp1
  else
    Compute  $P_l^m, l > m + 1$ .
    do ll=m+2,l
      pll=(x*(2*ll-1)*pmmp1-(ll+m-1)*pmm)/(ll-m)
      pmm=pmmp1
      pmmp1=pll
    end do
    plgndr_s=pll

```

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```

    end if
end if
END FUNCTION plgndr_s

```

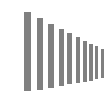


product(arth(1.0\_sp,2.0\_sp,m))  
That is,  $(2m - 1)!!$

```

FUNCTION plgndr_v(l,m,x)
USE nrtype; USE nrutil, ONLY : arth,assert
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: l,m
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: plgndr_v
INTEGER(I4B) :: ll
REAL(SP), DIMENSION(size(x)) :: pll,pmm,pmmp1,somx2
call assert(m >= 0, m <= 1, all(abs(x) <= 1.0), 'plgndr_v args')
pmm=1.0
if (m > 0) then
    somx2=sqrt((1.0_sp-x)*(1.0_sp+x))
    pmm=product(arth(1.0_sp,2.0_sp,m))*somx2**m
    if (mod(m,2) == 1) pmm=-pmm
end if
if (l == m) then
    plgndr_v=pmm
else
    pmmp1=x*(2*m+1)*pmm
    if (l == m+1) then
        plgndr_v=pmmp1
    else
        do ll=m+2,l
            pll=(x*(2*ll-1)*pmmp1-(ll+m-1)*pmm)/(ll-m)
            pmm=pmmp1
            pmmp1=pll
        end do
        plgndr_v=pll
    end if
end if
END FUNCTION plgndr_v

```



All those if's (not where's) may strike you as odd in a vector routine, but it is vectorized only on  $x$ , the dependent variable, not on the scalar indices  $l$  and  $m$ . Much harder to write a routine that is parallel for a vector of arbitrary triplets  $(l, m, x)$ . Try it!

\* \* \*

```

SUBROUTINE frenel(x,s,c)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP), INTENT(OUT) :: s,c
INTEGER(I4B), PARAMETER :: MAXIT=100
REAL(SP), PARAMETER :: EPS=epsilon(x),FPMIN=tiny(x),BIG=huge(x)*EPS,&
    XMIN=1.5

```

Computes the Fresnel integrals  $S(x)$  and  $C(x)$  for all real  $x$ .

Parameters: MAXIT is the maximum number of iterations allowed; EPS is the relative error; FPMIN is a number near the smallest representable floating-point number; BIG is a number

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```

near the machine overflow limit; XMIN is the dividing line between using the series and
continued fraction.
INTEGER(I4B) :: k,n
REAL(SP) :: a,ax,fact,pix2,sign,sum,sumc,sums,term,test
COMPLEX(SPC) :: b,cc,d,h,del,cs
LOGICAL(LGT) :: odd
ax=abs(x)
if (ax < sqrt(FPMIN)) then           Special case: avoid failure of convergence test be-
    s=0.0                             cause of underflow.
    c=ax
else if (ax <= XMIN) then           Evaluate both series simultaneously.
    sum=0.0
    sums=0.0
    sumc=ax
    sign=1.0
    fact=PI02*ax*ax
    odd=.true.
    term=ax
    n=3
    do k=1,MAXIT
        term=term*fact/k
        sum=sum+sign*term/n
        test=abs(sum)*EPS
        if (odd) then
            sign=-sign
            sums=sum
            sum=sumc
        else
            sumc=sum
            sum=sums
        end if
        if (term < test) exit
        odd=.not. odd
        n=n+2
    end do
    if (k > MAXIT) call nrerror('frenel: series failed')
    s=sums
    c=sumc
else                                 Evaluate continued fraction by modified Lentz's method
    pix2=PI*ax*ax                    (§5.2).
    b=cplx(1.0_sp,-pix2,kind=spc)
    cc=BIG
    d=1.0_sp/b
    h=d
    n=-1
    do k=2,MAXIT
        n=n+2
        a=-n*(n+1)
        b=b+4.0_sp
        d=1.0_sp/(a*d+b)             Denominators cannot be zero.
        cc=b+a/cc
        del=cc*d
        h=h*del
        if (absc(del-1.0_sp) <= EPS) exit
    end do
    if (k > MAXIT) call nrerror('cf failed in frenel')
    h=cplx(ax,-ax,kind=spc)
    cs=cplx(0.5_sp,0.5_sp,kind=spc)*(1.0_sp-&
        cplx(cos(0.5_sp*pix2),sin(0.5_sp*pix2),kind=spc)*h)
    c=real(cs)
    s=aimag(cs)
end if
if (x < 0.0) then                   Use antisymmetry.
    c=-c

```

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```

      s=-s
end if
CONTAINS
FUNCTION absc(z)
IMPLICIT NONE
COMPLEX(SPC), INTENT(IN) :: z
REAL(SP) :: absc
absc=abs(real(z))+abs(aimag(z))
END FUNCTION absc
END SUBROUTINE frenel

```

**f90** `b=cplx(1.0_sp,-pix2,kind=spc)` It's a good idea *always* to include the `kind=` parameter when you use the `cplx` intrinsic. The reason is that, perhaps counterintuitively, the result of `cplx` is not determined by the kind of its arguments, but is rather the “default complex kind.” Since that default may not be what you think it is (or what `spc` is defined to be), the desired kind should be specified explicitly.

`c=real(cs)` And why not specify a `kind=` parameter here, where it is also optionally allowed? Our answer is that the `real` intrinsic actually merges two different usages. When its argument is complex, it is the counterpart of `aimag` and returns a value whose kind is determined by the kind of its argument. In fact `aimag` doesn't even allow an optional kind parameter, so we never put one in the corresponding use of `real`. The other usage of `real` is for “casting,” that is, converting one real type to another (e.g., double precision to single precision, or vice versa). Here we *always* include a kind parameter, since otherwise the result is the default real kind, with the same dangers mentioned in the previous paragraph.

\* \* \*

```

SUBROUTINE cisi(x,ci,si)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP), INTENT(OUT) :: ci,si
INTEGER(I4B), PARAMETER :: MAXIT=100
REAL(SP), PARAMETER :: EPS=epsilon(x),FPMIN=4.0_sp*tiny(x),&
  BIG=huge(x)*EPS,TMIN=2.0
  Computes the cosine and sine integrals  $Ci(x)$  and  $Si(x)$ .  $Ci(0)$  is returned as a large negative
  number and no error message is generated. For  $x < 0$  the routine returns  $Ci(-x)$  and you
  must supply the  $-i\pi$  yourself.
  Parameters: MAXIT is the maximum number of iterations allowed; EPS is the relative error,
  or absolute error near a zero of  $Ci(x)$ ; FPMIN is a number near the smallest representable
  floating-point number; BIG is a number near the machine overflow limit; TMIN is the dividing
  line between using the series and continued fraction; EULER =  $\gamma$  (in nrtype).
INTEGER(I4B) :: i,k
REAL(SP) :: a,err,fact,sign,sum,sumc,sums,t,term
COMPLEX(SPC) :: h,b,c,d,del
LOGICAL(LGT) :: odd
t=abs(x)
if (t == 0.0) then
  Special case.
  si=0.0
  ci=-BIG
  RETURN
end if
if (t > TMIN) then
  Evaluate continued fraction by modified Lentz's
  method (§5.2).
  b=cplx(1.0_sp,t,kind=spc)

```

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```

c=BIG
d=1.0_sp/b
h=d
do i=2,MAXIT
  a=-(i-1)**2
  b=b+2.0_sp
  d=1.0_sp/(a*d+b)          Denominators cannot be zero.
  c=b+a/c
  del=c*d
  h=h*del
  if (absc(del-1.0_sp) <= EPS) exit
end do
if (i > MAXIT) call nrerror('continued fraction failed in cisi')
h=cplx(cos(t),-sin(t),kind=spc)*h
ci=-real(h)
si=PI02+aimag(h)
else
  Evaluate both series simultaneously.
  Special case: avoid failure of convergence test
  because of underflow.
  if (t < sqrt(FPMIN)) then
    sumc=0.0
    sums=t
  else
    sum=0.0
    sums=0.0
    sumc=0.0
    sign=1.0
    fact=1.0
    odd=.true.
    do k=1,MAXIT
      fact=fact*t/k
      term=fact/k
      sum=sum+sign*term
      err=term/abs(sum)
      if (odd) then
        sign=-sign
        sums=sum
        sum=sumc
      else
        sumc=sum
        sum=sums
      end if
      if (err < EPS) exit
      odd=.not. odd
    end do
    if (k > MAXIT) call nrerror('MAXIT exceeded in cisi')
  end if
  si=sums
  ci=sumc+log(t)+EULER
end if
if (x < 0.0) si=-si
CONTAINS
FUNCTION absc(z)
IMPLICIT NONE
COMPLEX(SPC), INTENT(IN) :: z
REAL(SP) :: absc
absc=abs(real(z))+abs(aimag(z))
END FUNCTION absc
END SUBROUTINE cisi

```

\* \* \*

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```

FUNCTION dawson_s(x)
USE nrtype; USE nrutil, ONLY : arth,geop
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: dawson_s
  Returns Dawson's integral  $F(x) = \exp(-x^2) \int_0^x \exp(t^2) dt$  for any real  $x$ .
INTEGER(I4B), PARAMETER :: NMAX=6
REAL(SP), PARAMETER :: H=0.4_sp, A1=2.0_sp/3.0_sp, A2=0.4_sp, &
  A3=2.0_sp/7.0_sp
INTEGER(I4B) :: i, n0
REAL(SP) :: ec, x2, xp, xx
REAL(SP), DIMENSION(NMAX) :: d1, d2, e1
REAL(SP), DIMENSION(NMAX), SAVE :: c=(/ (0.0_sp, i=1, NMAX) /)
if (c(1) == 0.0) c(1:NMAX)=exp(-(arth(1,2,NMAX)*H)**2)
  Initialize c on first call.
if (abs(x) < 0.2_sp) then                                Use series expansion.
  x2=x**2
  dawson_s=x*(1.0_sp-A1*x2*(1.0_sp-A2*x2*(1.0_sp-A3*x2)))
else                                                       Use sampling theorem representation.
  xx=abs(x)
  n0=2*nint(0.5_sp*xx/H)
  xp=xx-real(n0,sp)*H
  ec=exp(2.0_sp*xp*H)
  d1=arth(n0+1,2,NMAX)
  d2=arth(n0-1,-2,NMAX)
  e1=geop(ec,ec**2,NMAX)
  dawson_s=0.5641895835477563_sp*sign(exp(-xp**2),x)*&  Constant is  $1/\sqrt{\pi}$ .
    sum(c*(e1/d1+1.0_sp/(d2*e1)))
end if
END FUNCTION dawson_s

```

**f90** REAL(SP), DIMENSION(NMAX), SAVE :: c=(/ (0.0\_sp, i=1, NMAX) /) This is one way to give initial values to an array. Actually, we're somewhat nervous about using the “implied do-loop” form of the array constructor, as above, because our parallel compilers might not always be smart enough to execute the constructor in parallel. In this case, with NMAX=6, the damage potential is quite minimal. An alternative way to initialize the array would be with a data statement, “DATA c /NMAX\*0.0\_sp/”; however, this is not considered good Fortran 90 style, and there is no reason to think that it would be faster.

c(1:NMAX)=exp(-(arth(1,2,NMAX)\*H)\*\*2) Another example where the arth function of nrutil comes in handy. Otherwise, this would be

```

do i=1,NMAX
  c(i)=exp(-((2.0_sp*i-1.0_sp)*H)**2)
end do

```

arth(n0+1,2,NMAX) . . . arth(n0-1,-2,NMAX) . . . geop(ec,ec\*\*2,NMAX) These are not just notationally convenient for generating the sequences  $(n_0 + 1, n_0 + 3, n_0 + 5, \dots)$ ,  $(n_0 - 1, n_0 - 3, n_0 - 5, \dots)$ , and  $(ec, ec^3, ec^5, \dots)$ . They also may allow parallelization with parallel versions of arth and geop, such as those in nrutil.

```

FUNCTION dawson_v(x)
USE nrtype; USE nrutil, ONLY : arth
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: dawson_v
INTEGER(I4B), PARAMETER :: NMAX=6


```

```

REAL(SP), PARAMETER :: H=0.4_sp,A1=2.0_sp/3.0_sp,A2=0.4_sp,&
    A3=2.0_sp/7.0_sp
INTEGER(I4B) :: i,n
REAL(SP), DIMENSION(size(x)) :: x2
REAL(SP), DIMENSION(NMAX), SAVE :: c=(/ (0.0_sp,i=1,NMAX) /)
LOGICAL(LGT), DIMENSION(size(x)) :: mask
if (c(1) == 0.0) c(1:NMAX)=exp(-(arth(1,2,NMAX)*H)**2)
mask = (abs(x) >= 0.2_sp)
dawson_v=dawsonseries_v(x,mask)
where (.not. mask)
    x2=x**2
    dawson_v=x*(1.0_sp-A1*x2*(1.0_sp-A2*x2*(1.0_sp-A3*x2)))
end where
CONTAINS

FUNCTION dawsonseries_v(xin,mask)
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: xin
LOGICAL(LGT), DIMENSION(size(xin)), INTENT(IN) :: mask
REAL(SP), DIMENSION(size(xin)) :: dawsonseries_v
INTEGER(I4B), DIMENSION(:), ALLOCATABLE :: n0
REAL(SP), DIMENSION(:), ALLOCATABLE :: d1,d2,e1,e2,sm,xp,xx,x
n=count(mask)
if (n == 0) RETURN
allocate(n0(n),d1(n),d2(n),e1(n),e2(n),sm(n),xp(n),xx(n),x(n))
x=pack(xin,mask)
xx=abs(x)
n0=2*nint(0.5_sp*xx/H)
xp=xx-real(n0,sp)*H
e1=exp(2.0_sp*xp*H)
e2=e1**2
d1=n0+1.0_sp
d2=d1-2.0_sp
sm=0.0
do i=1,NMAX
    sm=sm+c(i)*(e1/d1+1.0_sp/(d2*e1))
    d1=d1+2.0_sp
    d2=d2-2.0_sp
    e1=e2*e1
end do
sm=0.5641895835477563_sp*sign(exp(-xp**2),x)*sm
dawsonseries_v=unpack(sm,mask,0.0_sp)
deallocate(n0,d1,d2,e1,e2,sm,xp,xx)
END FUNCTION dawsonseries_v
END FUNCTION dawson_v

```

 dawson\_v=dawsonseries\_v(x,mask) Pass-the-buck method for getting masked values, see note to bessj0\_v above, p. 1102. Within the contained dawsonseries, we use the pack-unpack method. Note that, unlike in dawson\_s, the sums are done by do-loops, because the parallelization is already over the components of the vector argument.

\* \* \*

```

FUNCTION rf_s(x,y,z)
USE nrtype; USE nrutil, ONLY : assert
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x,y,z
REAL(SP) :: rf_s
REAL(SP), PARAMETER :: ERRTOL=0.08_sp,TINY=1.5e-38_sp,BIG=3.0e37_sp,&
    THIRD=1.0_sp/3.0_sp,&

```

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```

C1=1.0_sp/24.0_sp,C2=0.1_sp,C3=3.0_sp/44.0_sp,C4=1.0_sp/14.0_sp
Computes Carlson's elliptic integral of the first kind,  $R_F(x,y,z)$ .  $x$ ,  $y$ , and  $z$  must be
nonnegative, and at most one can be zero. TINY must be at least 5 times the machine
underflow limit, BIG at most one-fifth the machine overflow limit.
REAL(SP) :: alamb,ave,delx,dely,delz,e2,e3,sqrtx,sqrty,sqrtz,xt,yt,zt
call assert(min(x,y,z) >= 0.0, min(x+y,x+z,y+z) >= TINY, &
  max(x,y,z) <= BIG, 'rf_s args')
xt=x
yt=y
zt=z
do
  sqrtx=sqrt(xt)
  sqrty=sqrt(yt)
  sqrtz=sqrt(zt)
  alamb=sqrtx*(sqrty+sqrtz)+sqrty*sqrtz
  xt=0.25_sp*(xt+alamb)
  yt=0.25_sp*(yt+alamb)
  zt=0.25_sp*(zt+alamb)
  ave=THIRD*(xt+yt+zt)
  delx=(ave-xt)/ave
  dely=(ave-yt)/ave
  delz=(ave-zt)/ave
  if (max(abs(delx),abs(dely),abs(delz)) <= ERRTOL) exit
end do
e2=delx*dely-delz**2
e3=delx*dely*delz
rf_s=(1.0_sp+(C1*e2-C2-C3*e3)*e2+C4*e3)/sqrt(ave)
END FUNCTION rf_s

```

```

FUNCTION rf_v(x,y,z)
USE nrtype; USE nrutil, ONLY : assert,assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,z
REAL(SP), DIMENSION(size(x)) :: rf_v
REAL(SP), PARAMETER :: ERRTOL=0.08_sp,TINY=1.5e-38_sp,BIG=3.0e37_sp,&
  THIRD=1.0_sp/3.0_sp,&
  C1=1.0_sp/24.0_sp,C2=0.1_sp,C3=3.0_sp/44.0_sp,C4=1.0_sp/14.0_sp
REAL(SP), DIMENSION(size(x)) :: alamb,ave,delx,dely,delz,e2,e3,&
  sqrtx,sqrty,sqrtz,xt,yt,zt
LOGICAL(LGT), DIMENSION(size(x)) :: converged
INTEGER(I4B) :: ndum
ndum=assert_eq(size(x),size(y),size(z),'rf_v')
call assert(all(min(x,y,z) >= 0.0), all(min(x+y,x+z,y+z) >= TINY), &
  all(max(x,y,z) <= BIG), 'rf_v args')
xt=x
yt=y
zt=z
converged=.false.
do
  where (.not. converged)
    sqrtx=sqrt(xt)
    sqrty=sqrt(yt)
    sqrtz=sqrt(zt)
    alamb=sqrtx*(sqrty+sqrtz)+sqrty*sqrtz
    xt=0.25_sp*(xt+alamb)
    yt=0.25_sp*(yt+alamb)
    zt=0.25_sp*(zt+alamb)
    ave=THIRD*(xt+yt+zt)
    delx=(ave-xt)/ave
    dely=(ave-yt)/ave
    delz=(ave-zt)/ave
    converged = (max(abs(delx),abs(dely),abs(delz)) <= ERRTOL)
  end where
end do

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```

        end where
        if (all(converged)) exit
    end do
    e2=delx*dely-delz**2
    e3=delx*dely*delz
    rf_v=(1.0_sp+(C1*e2-C2-C3*e3)*e2+C4*e3)/sqrt(ave)
END FUNCTION rf_v

```

```

FUNCTION rd_s(x,y,z)
USE nrtype; USE nrutil, ONLY : assert
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x,y,z
REAL(SP) :: rd_s
REAL(SP), PARAMETER :: ERRTOL=0.05_sp, TINY=1.0e-25_sp, BIG=4.5e21_sp, &
    C1=3.0_sp/14.0_sp, C2=1.0_sp/6.0_sp, C3=9.0_sp/22.0_sp, &
    C4=3.0_sp/26.0_sp, C5=0.25_sp*C3, C6=1.5_sp*C4
    Computes Carlson's elliptic integral of the second kind,  $R_D(x,y,z)$ .  $x$  and  $y$  must be
    nonnegative, and at most one can be zero.  $z$  must be positive. TINY must be at least twice
    the negative 2/3 power of the machine overflow limit. BIG must be at most  $0.1 \times \text{ERRTOL}$ 
    times the negative 2/3 power of the machine underflow limit.
REAL(SP) :: alamb, ave, delx, dely, delz, ea, eb, ec, ed, &
    ee, fac, sqrtx, sqrtz, sum, xt, yt, zt
call assert(min(x,y) >= 0.0, min(x+y,z) >= TINY, max(x,y,z) <= BIG, &
    'rd_s args')
xt=x
yt=y
zt=z
sum=0.0
fac=1.0
do
    sqrtx=sqrt(xt)
    sqrtz=sqrt(zt)
    alamb=sqrtx*(sqrtz+sqrtz)+sqrtz*sqrtz
    sum=sum+fac/(sqrtz*(zt+alamb))
    fac=0.25_sp*fac
    xt=0.25_sp*(xt+alamb)
    yt=0.25_sp*(yt+alamb)
    zt=0.25_sp*(zt+alamb)
    ave=0.2_sp*(xt+yt+3.0_sp*zt)
    delx=(ave-xt)/ave
    dely=(ave-yt)/ave
    delz=(ave-zt)/ave
    if (max(abs(delx),abs(dely),abs(delz)) <= ERRTOL) exit
end do
ea=delx*dely
eb=delz*delz
ec=ea-eb
ed=ea-6.0_sp*eb
ee=ed+ec+ec
rd_s=3.0_sp*sum+fac*(1.0_sp+ed*(-C1+C5*ed-C6*delz*ee)&
    +delz*(C2*ee+delz*(-C3*ec+delz*C4*ea)))/(ave*sqrt(ave))
END FUNCTION rd_s

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```

FUNCTION rd_v(x,y,z)
USE nrtype; USE nrutil, ONLY : assert,assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,z
REAL(SP), DIMENSION(size(x)) :: rd_v
REAL(SP), PARAMETER :: ERRTOL=0.05_sp,TINY=1.0e-25_sp,BIG=4.5e21_sp,&
  C1=3.0_sp/14.0_sp,C2=1.0_sp/6.0_sp,C3=9.0_sp/22.0_sp,&
  C4=3.0_sp/26.0_sp,C5=0.25_sp*C3,C6=1.5_sp*C4
REAL(SP), DIMENSION(size(x)) :: alamb,ave,delx,dely,delz,ea,eb,ec,ed,&
  ee,fac,sqrtx,sqrty,sqrtz,sum,xt,yt,zt
LOGICAL(LGT), DIMENSION(size(x)) :: converged
INTEGER(I4B) :: ndum
ndum=assert_eq(size(x),size(y),size(z),'rd_v')
call assert(all(min(x,y) >= 0.0), all(min(x+y,z) >= TINY), &
  all(max(x,y,z) <= BIG), 'rd_v args')
xt=x
yt=y
zt=z
sum=0.0
fac=1.0
converged=.false.
do
  where (.not. converged)
    sqrtx=sqrt(xt)
    sqrty=sqrt(yt)
    sqrtz=sqrt(zt)
    alamb=sqrtx*(sqrty+sqrtz)+sqrty*sqrtz
    sum=sum+fac/(sqrtz*(zt+alamb))
    fac=0.25_sp*fac
    xt=0.25_sp*(xt+alamb)
    yt=0.25_sp*(yt+alamb)
    zt=0.25_sp*(zt+alamb)
    ave=0.2_sp*(xt+yt+3.0_sp*zt)
    delx=(ave-xt)/ave
    dely=(ave-yt)/ave
    delz=(ave-zt)/ave
    converged = (all(max(abs(delx),abs(dely),abs(delz)) <= ERRTOL))
  end where
  if (all(converged)) exit
end do
ea=delx*dely
eb=delz*dely
ec=ea-eb
ed=ea-6.0_sp*eb
ee=ed+ec
rd_v=3.0_sp*sum+fac*(1.0_sp+ed*(-C1+C5*ed-C6*delz*ee)&
  +delz*(C2*ee+delz*(-C3*ec+delz*C4*ea)))/(ave*sqrt(ave))
END FUNCTION rd_v

```

```

FUNCTION rj_s(x,y,z,p)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : rc,rf
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x,y,z,p
REAL(SP) :: rj_s
REAL(SP), PARAMETER :: ERRTOL=0.05_sp,TINY=2.5e-13_sp,BIG=9.0e11_sp,&
  C1=3.0_sp/14.0_sp,C2=1.0_sp/3.0_sp,C3=3.0_sp/22.0_sp,&
  C4=3.0_sp/26.0_sp,C5=0.75_sp*C3,C6=1.5_sp*C4,C7=0.5_sp*C2,&
  C8=C3+C3
Computes Carlson's elliptic integral of the third kind,  $R_J(x,y,z,p)$ .  $x$ ,  $y$ , and  $z$  must be
nonnegative, and at most one can be zero.  $p$  must be nonzero. If  $p < 0$ , the Cauchy

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principal value is returned. TINY must be at least twice the cube root of the machine underflow limit, BIG at most one-fifth the cube root of the machine overflow limit.

```

REAL(SP) :: a,alamb,alpha,ave,b,bet,delp,delx,&
  dely,delz,ea,eb,ec,ed,ee,fac,pt,rho,sqrtx,sqrty,sqrtz,&
  sm,tau,xt,yt,zt
call assert(min(x,y,z) >= 0.0, min(x+y,x+z,y+z,abs(p)) >= TINY, &
  max(x,y,z,abs(p)) <= BIG, 'rj_s args')
sm=0.0
fac=1.0
if (p > 0.0) then
  xt=x
  yt=y
  zt=z
  pt=p
else
  xt=min(x,y,z)
  zt=max(x,y,z)
  yt=x+y+z-xt-zt
  a=1.0_sp/(yt-pt)
  b=a*(zt-yt)*(yt-xt)
  pt=yt+b
  rho=xt*zt/yt
  tau=p*pt/yt
end if
do
  sqrtx=sqrt(xt)
  sqrty=sqrt(yt)
  sqrtz=sqrt(zt)
  alamb=sqrtx*(sqrty+sqrtz)+sqrty*sqrtz
  alpha=(pt*(sqrtx+sqrty+sqrtz)+sqrtx*sqrty*sqrtz)**2
  bet=pt*(pt+alamb)**2
  sm=sm+fac*rc(alpha,bet)
  fac=0.25_sp*fac
  xt=0.25_sp*(xt+alamb)
  yt=0.25_sp*(yt+alamb)
  zt=0.25_sp*(zt+alamb)
  pt=0.25_sp*(pt+alamb)
  ave=0.2_sp*(xt+yt+zt+pt+pt)
  delx=(ave-xt)/ave
  dely=(ave-yt)/ave
  delz=(ave-zt)/ave
  delp=(ave-pt)/ave
  if (max(abs(delx),abs(dely),abs(delz),abs(delp)) <= ERRTOL) exit
end do
ea=delx*(dely+delz)+dely*delz
eb=delx*dely*delz
ec=delp**2
ed=ea-3.0_sp*ec
ee=eb+2.0_sp*delp*(ea-ec)
rj_s=3.0_sp*sm+fac*(1.0_sp+ed*(-C1+C5*ed-C6*ee)+eb*(C7+delp*(-C8&
  +delp*C4))+delp*ea*(C2-delp*C3)-C2*delp*ec)/(ave*sqrt(ave))
if (p <= 0.0) rj_s=a*(b*rj_s+3.0_sp*(rc(rho,tau)-rf(xt,yt,zt)))
END FUNCTION rj_s

```

```

FUNCTION rj_v(x,y,z,p)
USE nrtype; USE nrutil, ONLY : assert,assert_eq
USE nr, ONLY : rc,rf
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,z,p
REAL(SP), DIMENSION(size(x)) :: rj_v
REAL(SP), PARAMETER :: ERRTOL=0.05_sp,TINY=2.5e-13_sp,BIG=9.0e11_sp,&
  C1=3.0_sp/14.0_sp,C2=1.0_sp/3.0_sp,C3=3.0_sp/22.0_sp,&

```

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```

C4=3.0_sp/26.0_sp,C5=0.75_sp*C3,C6=1.5_sp*C4,C7=0.5_sp*C2,&
C8=C3+C3
REAL(SP), DIMENSION(size(x)) :: a,alamb,alpha,ave,b,bet,delp,delx,&
dely,delz,ea,eb,ec,ed,ee,fac,pt,rho,sqrtx,sqrty,sqrtz,&
sm,tau,xt,yt,zt
LOGICAL(LGT), DIMENSION(size(x)) :: mask
INTEGER(I4B) :: ndum
ndum=assert_eq(size(x),size(y),size(z),size(p),'rj_v')
call assert(all(min(x,y,z) >= 0.0), all(min(x+y,x+z,y+z,abs(p)) >= TINY), &
all(max(x,y,z,abs(p)) <= BIG), 'rj_v args')
sm=0.0
fac=1.0
where (p > 0.0)
  xt=x
  yt=y
  zt=z
  pt=p
elsewhere
  xt=min(x,y,z)
  zt=max(x,y,z)
  yt=x+y+z-xt-zt
  a=1.0_sp/(yt-pt)
  b=a*(zt-yt)*(yt-xt)
  pt=yt+b
  rho=xt*zt/yt
  tau=p*pt/yt
end where
mask=.false.
do
  where (.not. mask)
    sqrtx=sqrt(xt)
    sqrty=sqrt(yt)
    sqrtz=sqrt(zt)
    alamb=sqrtx*(sqrty+sqrtz)+sqrty*sqrtz
    alpha=(pt*(sqrtx+sqrty+sqrtz)+sqrtx*sqrty*sqrtz)**2
    bet=pt*(pt+alamb)**2
    sm=sm+fac*rc(alpha,bet)
    fac=0.25_sp*fac
    xt=0.25_sp*(xt+alamb)
    yt=0.25_sp*(yt+alamb)
    zt=0.25_sp*(zt+alamb)
    pt=0.25_sp*(pt+alamb)
    ave=0.2_sp*(xt+yt+zt+pt+pt)
    delx=(ave-xt)/ave
    dely=(ave-yt)/ave
    delz=(ave-zt)/ave
    delp=(ave-pt)/ave
    mask = (max(abs(delx),abs(dely),abs(delz),abs(delp)) <= ERRTOL)
  end where
  if (all(mask)) exit
end do
ea=delx*(dely+delz)+dely*delz
eb=delx*dely*delz
ec=delp**2
ed=ea-3.0_sp*ec
ee=eb+2.0_sp*delp*(ea-ec)
rj_v=3.0_sp*sm+fac*(1.0_sp+ed*(-C1+C5*ed-C6*ee)+eb*(C7+delp*(-C8&
+delp*C4))+delp*ea*(C2-delp*C3)-C2*delp*ec)/(ave*sqrt(ave))
mask = (p <= 0.0)
where (mask) rj_v=a*(b*rj_v+&
unpack(3.0_sp*(rc(pack(rho,mask),pack(tau,mask)))-&
rf(pack(xt,mask),pack(yt,mask),pack(zt,mask))),mask,0.0_sp))
END FUNCTION rj_v

```

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unpack(3.0\_sp\*(rc(pack(rho,mask),pack(tau,mask))...),mask,0.0\_sp)

If you're willing to put up with fairly unreadable code, you can use the pack-unpack trick (for getting a masked subset of components out of a vector function) right in-line, as here. Of course the "outer level" that is seen by the enclosing where construction has to contain only objects that have the same shape as the mask that goes with the where. Because it is so hard to read, we don't like to do this very often. An alternative would be to use CONTAINS to incorporate short, masked "wrapper functions" for the functions used in this way.

```

FUNCTION rc_s(x,y)
USE nrtype; USE nrutil, ONLY : assert
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x,y
REAL(SP) :: rc_s
REAL(SP), PARAMETER :: ERRTOL=0.04_sp,TINY=1.69e-38_sp,&
  SQRRTNY=1.3e-19_sp,BIG=3.0e37_sp,TNBG=TINY*BIG,&
  COMP1=2.236_sp/SQRRTNY,COMP2=TNBG*TNBG/25.0_sp,&
  THIRD=1.0_sp/3.0_sp,&
  C1=0.3_sp,C2=1.0_sp/7.0_sp,C3=0.375_sp,C4=9.0_sp/22.0_sp
  Computes Carlson's degenerate elliptic integral,  $R_C(x,y)$ .  $x$  must be nonnegative and  $y$ 
  must be nonzero. If  $y < 0$ , the Cauchy principal value is returned. TINY must be at least
  5 times the machine underflow limit, BIG at most one-fifth the machine maximum overflow
  limit.
REAL(SP) :: alamb,ave,s,w,xt,yt
call assert( (/x >= 0.0,y /= 0.0,x+abs(y) >= TINY,x+abs(y) <= BIG, &
  y >= -COMP1 .or. x <= 0.0 .or. x >= COMP2/), 'rc_s')
if (y > 0.0) then
  xt=x
  yt=y
  w=1.0
else
  xt=x-y
  yt=-y
  w=sqrt(x)/sqrt(xt)
end if
do
  alamb=2.0_sp*sqrt(xt)*sqrt(yt)+yt
  xt=0.25_sp*(xt+alamb)
  yt=0.25_sp*(yt+alamb)
  ave=THIRD*(xt+yt+yt)
  s=(yt-ave)/ave
  if (abs(s) <= ERRTOL) exit
end do
rc_s=w*(1.0_sp+s*s*(C1+s*(C2+s*(C3+s*C4)))/sqrt(ave)
END FUNCTION rc_s

```

```

FUNCTION rc_v(x,y)
USE nrtype; USE nrutil, ONLY : assert,assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
REAL(SP), DIMENSION(size(x)) :: rc_v
REAL(SP), PARAMETER :: ERRTOL=0.04_sp,TINY=1.69e-38_sp,&
  SQRRTNY=1.3e-19_sp,BIG=3.0e37_sp,TNBG=TINY*BIG,&
  COMP1=2.236_sp/SQRRTNY,COMP2=TNBG*TNBG/25.0_sp,&
  THIRD=1.0_sp/3.0_sp,&
  C1=0.3_sp,C2=1.0_sp/7.0_sp,C3=0.375_sp,C4=9.0_sp/22.0_sp
REAL(SP), DIMENSION(size(x)) :: alamb,ave,s,w,xt,yt
LOGICAL(LGT), DIMENSION(size(x)) :: converged
INTEGER(I4B) :: ndum

```

```

ndum=assert_eq(size(x),size(y),'rc_v')
call assert( (/all(x >= 0.0),all(y /= 0.0),all(x+abs(y) >= TINY), &
  all(x+abs(y) <= BIG),all(y >= -COMP1 .or. x <= 0.0 &
  .or. x >= COMP2) /),'rc_v')
where (y > 0.0)
  xt=x
  yt=y
  w=1.0
elsewhere
  xt=x-y
  yt=-y
  w=sqrt(x)/sqrt(xt)
end where
converged=.false.
do
  where (.not. converged)
    alamb=2.0_sp*sqrt(xt)*sqrt(yt)+yt
    xt=0.25_sp*(xt+alamb)
    yt=0.25_sp*(yt+alamb)
    ave=THIRD*(xt+yt+yt)
    s=(yt-ave)/ave
    converged = (abs(s) <= ERRTOL)
  end where
  if (all(converged)) exit
end do
rc_v=w*(1.0_sp+s*s*(C1+s*(C2+s*(C3+s*C4)))/sqrt(ave)
END FUNCTION rc_v

```

\* \* \*

```

FUNCTION ellf_s(phi,ak)
USE nrtype
USE nr, ONLY : rf
IMPLICIT NONE
REAL(SP), INTENT(IN) :: phi,ak
REAL(SP) :: ellf_s
  Legendre elliptic integral of the 1st kind  $F(\phi, k)$ , evaluated using Carlson's function  $R_F$ .
  The argument ranges are  $0 \leq \phi \leq \pi/2$ ,  $0 \leq k \sin \phi \leq 1$ .
REAL(SP) :: s
s=sin(phi)
ellf_s=s*rf(cos(phi)**2,(1.0_sp-s*ak)*(1.0_sp+s*ak),1.0_sp)
END FUNCTION ellf_s

```

```

FUNCTION ellf_v(phi,ak)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : rf
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: phi,ak
REAL(SP), DIMENSION(size(phi)) :: ellf_v
REAL(SP), DIMENSION(size(phi)) :: s
INTEGER(I4B) :: ndum
ndum=assert_eq(size(phi),size(ak),'ellf_v')
s=sin(phi)
ellf_v=s*rf(cos(phi)**2,(1.0_sp-s*ak)*(1.0_sp+s*ak),&
  spread(1.0_sp,1,size(phi)))
END FUNCTION ellf_v

```

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```

FUNCTION elle_s(phi,ak)
USE nrtype
USE nr, ONLY : rd,rf
IMPLICIT NONE
REAL(SP), INTENT(IN) :: phi,ak
REAL(SP) :: elle_s
    Legendre elliptic integral of the 2nd kind  $E(\phi, k)$ , evaluated using Carlson's functions  $R_D$ 
    and  $R_F$ . The argument ranges are  $0 \leq \phi \leq \pi/2$ ,  $0 \leq k \sin \phi \leq 1$ .
REAL(SP) :: cc,q,s
s=sin(phi)
cc=cos(phi)**2
q=(1.0_sp-s*ak)*(1.0_sp+s*ak)
elle_s=s*(rf(cc,q,1.0_sp)-((s*ak)**2)*rd(cc,q,1.0_sp)/3.0_sp)
END FUNCTION elle_s

```

```

FUNCTION elle_v(phi,ak)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : rd,rf
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: phi,ak
REAL(SP), DIMENSION(size(phi)) :: elle_v
REAL(SP), DIMENSION(size(phi)) :: cc,q,s
INTEGER(I4B) :: ndum
ndum=assert_eq(size(phi),size(ak),'elle_v')
s=sin(phi)
cc=cos(phi)**2
q=(1.0_sp-s*ak)*(1.0_sp+s*ak)
elle_v=s*(rf(cc,q,spread(1.0_sp,1,size(phi)))-((s*ak)**2)*&
rd(cc,q,spread(1.0_sp,1,size(phi)))/3.0_sp)
END FUNCTION elle_v

```



rd(cc,q,spread(1.0\_sp,1,size(phi))) See note to erf\_v, p. 1094 above.

```

FUNCTION ellpi_s(phi,en,ak)
USE nrtype
USE nr, ONLY : rf,rj
IMPLICIT NONE
REAL(SP), INTENT(IN) :: phi,en,ak
REAL(SP) :: ellpi_s
    Legendre elliptic integral of the 3rd kind  $\Pi(\phi, n, k)$ , evaluated using Carlson's functions  $R_J$ 
    and  $R_F$ . (Note that the sign convention on  $n$  is opposite that of Abramowitz and Stegun.)
    The ranges of  $\phi$  and  $k$  are  $0 \leq \phi \leq \pi/2$ ,  $0 \leq k \sin \phi \leq 1$ .
REAL(SP) :: cc,enss,q,s
s=sin(phi)
enss=en*s*s
cc=cos(phi)**2
q=(1.0_sp-s*ak)*(1.0_sp+s*ak)
ellpi_s=s*(rf(cc,q,1.0_sp)-enss*rj(cc,q,1.0_sp,1.0_sp+enss)/3.0_sp)
END FUNCTION ellpi_s

```

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```

FUNCTION ellpi_v(phi,en,ak)
USE nrtype
USE nr, ONLY : rf,rj
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: phi,en,ak
REAL(SP), DIMENSION(size(phi)) :: ellpi_v
REAL(SP), DIMENSION(size(phi)) :: cc,enss,q,s
s=sin(phi)
enss=en*s*s
cc=cos(phi)**2
q=(1.0_sp-s*ak)*(1.0_sp+s*ak)
ellpi_v=s*(rf(cc,q,spread(1.0_sp,1,size(phi))))-enss*&
  rj(cc,q,spread(1.0_sp,1,size(phi)),1.0_sp+enss)/3.0_sp)
END FUNCTION ellpi_v

```

\* \* \*

```

SUBROUTINE sncndn(uu,emmc,sn,cn,dn)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: uu,emmc
REAL(SP), INTENT(OUT) :: sn,cn,dn
  Returns the Jacobian elliptic functions  $sn(u, k_c)$ ,  $cn(u, k_c)$ , and  $dn(u, k_c)$ . Here  $uu = u$ ,
  while  $emmc = k_c^2$ .
REAL(SP), PARAMETER :: CA=0.0003_sp      The accuracy is the square of CA.
INTEGER(I4B), PARAMETER :: MAXIT=13
INTEGER(I4B) :: i,ii,l
REAL(SP) :: a,b,c,d,emc,u
REAL(SP), DIMENSION(MAXIT) :: em,en
LOGICAL(LGT) :: bo
emc=emmc
u=uu
if (emc /= 0.0) then
  bo=(emc < 0.0)
  if (bo) then
    d=1.0_sp-emc
    emc=-emc/d
    d=sqrt(d)
    u=d*u
  end if
  a=1.0
  dn=1.0
  do i=1,MAXIT
    l=i
    em(i)=a
    emc=sqrt(emc)
    en(i)=emc
    c=0.5_sp*(a+emc)
    if (abs(a-emc) <= CA*a) exit
    emc=a*emc
    a=c
  end do
  if (i > MAXIT) call nrerror('sncndn: convergence failed')
  u=c*u
  sn=sin(u)
  cn=cos(u)
  if (sn /= 0.0) then
    a=cn/sn
    c=a*c
    do ii=1,1,-1
      b=em(ii)

```

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```

        a=c*a
        c=dn*c
        dn=(en(ii)+a)/(b+a)
        a=c/b
    end do
    a=1.0_sp/sqrt(c**2+1.0_sp)
    sn=sign(a,sn)
    cn=c*sn
end if
if (bo) then
    a=dn
    dn=cn
    cn=a
    sn=sn/d
end if
else
    cn=1.0_sp/cosh(u)
    dn=cn
    sn=tanh(u)
end if
END SUBROUTINE sncndn

```

\* \* \*

**MODULE hypgeo\_info**

```

USE nrtype
COMPLEX(SPC) :: hypgeo_aa,hypgeo_bb,hypgeo_cc,hypgeo_dz,hypgeo_z0
END MODULE hypgeo_info

```

**FUNCTION hypgeo(a,b,c,z)**

```

USE nrtype
USE hypgeo_info
USE nr, ONLY : bsstep,hypdrv,hypser,odeint
IMPLICIT NONE
COMPLEX(SPC), INTENT(IN) :: a,b,c,z
COMPLEX(SPC) :: hypgeo
REAL(SP), PARAMETER :: EPS=1.0e-6_sp
    Complex hypergeometric function  ${}_2F_1$  for complex  $a, b, c$ , and  $z$ , by direct integration of
    the hypergeometric equation in the complex plane. The branch cut is taken to lie along the
    real axis,  $\text{Re } z > 1$ .
    Parameter: EPS is an accuracy parameter.
COMPLEX(SPC), DIMENSION(2) :: y
REAL(SP), DIMENSION(4) :: ry
if (real(z)**2+aimag(z)**2 <= 0.25) then      Use series...
    call hypser(a,b,c,z,hypgeo,y(2))
    RETURN
else if (real(z) < 0.0) then                  ...or pick a starting point for the path
    hypgeo_z0=cplx(-0.5_sp,0.0_sp,kind=spc)    integration.
else if (real(z) <= 1.0) then
    hypgeo_z0=cplx(0.5_sp,0.0_sp,kind=spc)
else
    hypgeo_z0=cplx(0.0_sp,sign(0.5_sp,aimag(z)),kind=spc)
end if
hypgeo_aa=a                                Load the module variables, used to pass
hypgeo_bb=b                                parameters "over the head" of odeint
hypgeo_cc=c                                to hypdrv.
hypgeo_dz=z-hypgeo_z0
call hypser(hypgeo_aa,hypgeo_bb,hypgeo_cc,hypgeo_z0,y(1),y(2))
    Get starting function and derivative.
ry(1:4:2)=real(y)

```

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```

ry(2:4:2)=aimag(y)
call odeint(ry,0.0_sp,1.0_sp,EPS,0.1_sp,0.0001_sp,hypdrv,bsstep)
  The arguments to odeint are the vector of independent variables, the starting and ending
  values of the dependent variable, the accuracy parameter, an initial guess for stepsize, a
  minimum stepsize, and the names of the derivative routine and the (here Bulirsch-Stoer)
  stepping routine.
y=cmplx(ry(1:4:2),ry(2:4:2),kind=spc)
hypgeo=y(1)
END FUNCTION hypgeo

```

```

SUBROUTINE hypser(a,b,c,z,series,deriv)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
COMPLEX(SPC), INTENT(IN) :: a,b,c,z
COMPLEX(SPC), INTENT(OUT) :: series,deriv
  Returns the hypergeometric series  ${}_2F_1$  and its derivative, iterating to machine accuracy.
  For  $\text{cabs}(z) \leq 1/2$  convergence is quite rapid.
INTEGER(I4B) :: n
INTEGER(I4B), PARAMETER :: MAXIT=1000
COMPLEX(SPC) :: aa,bb,cc,fac,temp
deriv=cmplx(0.0_sp,0.0_sp,kind=spc)
fac=cmplx(1.0_sp,0.0_sp,kind=spc)
temp=fac
aa=a
bb=b
cc=c
do n=1,MAXIT
  fac=((aa*bb)/cc)*fac
  deriv=deriv+fac
  fac=fac*z/n
  series=temp+fac
  if (series == temp) RETURN
  temp=series
  aa=aa+1.0
  bb=bb+1.0
  cc=cc+1.0
end do
call nrerror('hypser: convergence failure')
END SUBROUTINE hypser

```

```

SUBROUTINE hypdrv(s,ry,rdyds)
USE nrtype
USE hypgeo_info
IMPLICIT NONE
REAL(SP), INTENT(IN) :: s
REAL(SP), DIMENSION(:), INTENT(IN) :: ry
REAL(SP), DIMENSION(:), INTENT(OUT) :: rdyds
  Derivative subroutine for the hypergeometric equation; see text equation (5.14.4).
COMPLEX(SPC), DIMENSION(2) :: y,dyds
COMPLEX(SPC) :: z
y=cmplx(ry(1:4:2),ry(2:4:2),kind=spc)
z=hypgeo_z0+s*hypgeo_dz
dyds(1)=y(2)*hypgeo_dz
dyds(2)=((hypgeo_aa*hypgeo_bb)*y(1)-(hypgeo_cc-&
  (hypgeo_aa+hypgeo_bb)+1.0_sp)*z)*y(2))*hypgeo_dz/(z*(1.0_sp-z))
rdyds(1:4:2)=real(dyds)
rdyds(2:4:2)=aimag(dyds)
END SUBROUTINE hypdrv

```

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**f90** Notice that the real array (of length 4) `ry` is immediately mapped into a complex array of length 2, and that the process is reversed at the end of the routine with `rdyds`. In Fortran 77 no such mapping is necessary: the calling program sends real arguments, and the Fortran 77 `hypdrv` simply interprets what is sent as complex. Fortran 90's stronger typing does not encourage (and, practically, does not allow) this convenience; but it is a small price to pay for the vastly increased error-checking capabilities of a strongly typed language.

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## Chapter B7. Random Numbers

One might think that good random number generators, including those in Volume 1, should last forever. The world of computing changes very rapidly, however:

- When Volume 1 was published, it was unusual, except on the fastest supercomputers, to “exhaust” a 32-bit random number generator, that is, to call for all  $2^{32}$  sequential random values in its periodic sequence. Now, this is feasible, and not uncommon, on fast desktop workstations. A useful generator today must have a minimum of 64 bits of state space, and generally somewhat more.
- Before Fortran 90, the Fortran language had no standardized calling sequence for random numbers. Now, although there is still no standard *algorithm* defined by the language (rightly, we think), there is at least a standard calling sequence, exemplified in the intrinsics `random_number` and `random_seed`.
- The rise of parallel computing places new algorithmic demands on random generators. The classic algorithms, which compute each random value from the previous one, evidently need generalization to a parallel environment.
- New algorithms and techniques have been discovered, in some cases significantly faster than their predecessors.

These are the reasons that we have decided to implement, in Fortran 90, different uniform random number generators from those in Volume 1’s Fortran 77 implementations. We hasten to add that there is nothing wrong with any of the generators in Volume 1. That volume’s `ran0` and `ran1` routines are, to our knowledge, completely adequate as 32-bit generators; `ran2` has a 64-bit state space, and our previous offer of \$1000 for *any* demonstrated failure in the algorithm has never yet been claimed (see [1]).

Before we launch into the discussion of parallelizable generators with Fortran 90 calling conventions, we want to attend to the continuing needs of longtime “`x=ran(idum)`” users with purely serial machines. If you are a satisfied user of Volume 1’s `ran0`, `ran1`, or `ran2` Fortran 77 versions, you are in this group. The following routine, `ran`, preserves those routines’ calling conventions, is considerably faster than `ran2`, and does not suffer from the old `ran0` or `ran1`’s 32-bit period exhaustion limitation. It is completely portable to all Fortran 90 environments. We recommend `ran` as the plug-compatible replacement for the old `ran0`, `ran1`, and `ran2`, and we happily offer exactly the same \$1000 reward terms as were (and are still) offered on the old `ran2`.

```

FUNCTION ran(idum)
IMPLICIT NONE
INTEGER, PARAMETER :: K4B=selected_int_kind(9)
INTEGER(K4B), INTENT(INOUT) :: idum
REAL :: ran
  "Minimal" random number generator of Park and Miller combined with a Marsaglia shift
  sequence. Returns a uniform random deviate between 0.0 and 1.0 (exclusive of the endpoint
  values). This fully portable, scalar generator has the "traditional" (not Fortran 90) calling
  sequence with a random deviate as the returned function value: call with idum a negative
  integer to initialize; thereafter, do not alter idum except to reinitialize. The period of this
  generator is about  $3.1 \times 10^{18}$ .
INTEGER(K4B), PARAMETER :: IA=16807,IM=2147483647,IQ=127773,IR=2836
REAL, SAVE :: am
INTEGER(K4B), SAVE :: ix=-1,iy=-1,k
if (idum <= 0 .or. iy < 0) then
  am=nearest(1.0,-1.0)/IM
  iy=ior(ieor(888889999,abs(idum)),1)
  ix=ieor(777755555,abs(idum))
  idum=abs(idum)+1
end if
ix=ieor(ix,ishft(ix,13))
ix=ieor(ix,ishft(ix,-17))
ix=ieor(ix,ishft(ix,5))
k=iy/IQ
iy=IA*(iy-k*IQ)-IR*k
if (iy < 0) iy=iy+IM
ran=am*ior(iand(IM,ieor(ix,iy)),1)
END FUNCTION ran

```

Initialize.

Set idum positive.

Marsaglia shift sequence with period  $2^{32} - 1$ .

Park-Miller sequence by Schrage's method, period  $2^{31} - 2$ .

Combine the two generators with masking to ensure nonzero value.

This is a good place to discuss a new bit of algorithmics that has crept into `ran`, above, and even more strongly affects all of our new random number generators, below. Consider:

```

ix=ieor(ix,ishft(ix,13))
ix=ieor(ix,ishft(ix,-17))
ix=ieor(ix,ishft(ix,5))

```

These lines update a 32-bit integer `ix`, which cycles pseudo-randomly through a full period of  $2^{32} - 1$  values (excluding zero) before repeating. Generators of this type have been extensively explored by Marsaglia (see [2]), who has kindly communicated some additional results to us in advance of publication. For convenience, we will refer to generators of this sort as "Marsaglia shift registers."

Useful properties of Marsaglia shift registers are (i) they are very fast on most machines, since they use only fast logical operations, and (ii) the bit-mixing that they induce is quite different in character from that induced by arithmetic operations such as are used in linear congruential generators (see Volume 1) or lagged Fibonacci generators (see below). Thus, the combination of a Marsaglia shift register with another, algorithmically quite different generator is a powerful way to suppress any residual correlations or other weaknesses in the other generator. Indeed, Marsaglia finds (and we concur) that the above generator (with constants 13, -17, 5, as shown) is *by itself* about as good as any 32-bit random generator.


Here is a very brief outline of the theory behind these generators: Consider the 32 bits of the integer as components in a vector of length 32, in a linear space where addition and multiplication are done modulo 2. Noting that exclusive-or (`ieor`) is the same as addition, each of the three lines in the updating can be written as the action of a  $32 \times 32$  matrix on a vector, where the matrix is all zeros except for

ones on the diagonal, and on exactly one super- or subdiagonal (corresponding to positive or negative second arguments in `ishft`). Denote this matrix as  $\mathbf{S}_k$ , where  $k$  is the shift argument. Then, one full step of updating (three lines of code, above) corresponds to multiplication by the matrix  $\mathbf{T} \equiv \mathbf{S}_{k_3} \mathbf{S}_{k_2} \mathbf{S}_{k_1}$ .

One next needs to find triples of integers  $(k_1, k_2, k_3)$ , for example  $(13, -17, 5)$ , that give the full  $M \equiv 2^{32} - 1$  period. Necessary and sufficient conditions are that  $\mathbf{T}^M = \mathbf{1}$  (the identity matrix), and that  $\mathbf{T}^N \neq \mathbf{1}$  for these five values of  $N$ :  $N = 3 \times 5 \times 17 \times 257$ ,  $N = 3 \times 5 \times 17 \times 65537$ ,  $N = 3 \times 5 \times 257 \times 65537$ ,  $N = 3 \times 17 \times 257 \times 65537$ ,  $N = 5 \times 17 \times 257 \times 65537$ . (Note that each of the five prime factors of  $M$  is omitted one at a time to get the five values of  $N$ .) The required large powers of  $\mathbf{T}$  are readily computed by successive squarings, requiring only on the order of  $32^3 \log M$  operations. With this machinery, one can find full-period triples  $(k_1, k_2, k_3)$  by exhaustive search, at reasonable cost.

Not all such triples are equally good as generators of random integers, however. Marsaglia subjects candidate values to a battery of tests for randomness, and we have ourselves applied various tests. This stage of winnowing is as much art as science, because all 32-bit generators can be made to exhibit signs of failure due to period exhaustion (if for no other reason). “Good” triples, in order of our preference, are  $(13, -17, 5)$ ,  $(5, -13, 6)$ ,  $(5, -9, 7)$ ,  $(13, -17, 15)$ ,  $(16, -7, 11)$ . When a full-period triple is good, its reverse is also full-period, and also generally good. A good *quadruple* due to Marsaglia (generalizing the above in the obvious way) is  $(-4, 8, -1, 5)$ . We would not recommend relying on any single Marsaglia shift generator (nor on any other simple generator) *by itself*. Two or more generators, of quite different types, should be combined [1].

\* \* \*

 Let us now discuss explicitly the needs of *parallel* random number generators. The general scheme, from the user’s perspective, is that of Fortran 90’s intrinsic `random_number`: A statement like `call ran1(harvest)` (where `ran1` will be one of our portable replacements for the compiler-dependent `random_number`) should fill the real array `harvest` with pseudo-random real values in the range  $(0, 1)$ . Of course, we want the underlying machinery to be completely parallel, that is, no do-loops of order  $N \equiv \text{size}(\text{harvest})$ .

A first design decision is whether to replicate the state-space across the parallel dimension  $N$ , i.e., whether to reserve storage for essentially  $N$  scalar generators. Although there are various schemes that avoid doing this (e.g., mapping a single, smaller, state space into  $N$  different output values on each call), we think that it is a memory cost well worth paying in return for achieving a less exotic (and thus better tested) algorithm. However, this choice dictates that we must keep the state space *per component* quite small. We have settled on five or fewer 32-bit words of state space per component as a reasonable limit. Some otherwise interesting and well tested methods (such as Knuth’s subtractive generator, implemented in Volume 1 as `ran3`) are ruled out by this constraint.

A second design decision is how to initialize the parallel state space, so that different parallel components produce different sequences, and so that there is an acceptable degree of randomness *across* the parallel dimension, as well as *between successive calls* of the generator. Each component starts its life with one and only one unique identifier, its component index  $n$  in the range  $1 \dots N$ . One is

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tempted simply to hash the values  $n$  into the corresponding components of initial state space. “Random” hashing is a bad idea, however, because different  $n$ 's will produce identical 32-bit hash results by chance when  $N$  is no larger than  $\sim 2^{16}$ . We therefore prefer to use a kind of reversible pseudo-encryption (similar to the routine `psdes` in Volume 1 and below) which guarantees causally that different  $n$ 's produce different state space initializations.

**f90** The machinery for allocating, deallocating, and initializing the state space, including provision of a user interface for getting or putting the contents of the state space (as in the intrinsic `random_seed`) is fairly complicated. Rather than duplicate it in each different random generator that we provide, we have consolidated it in a single module, `ran_state`, whose contents we will now discuss. Such a discussion is necessarily technical, if not arcane; on first reading, you may wish to skip ahead to the actual new routines `ran0`, `ran1`, and `ran2`. If you do so, you will need to know only that `ran_state` provides each vector random routine with five 32-bit vectors of state information, denoted `iran`, `jran`, `kran`, `mran`, `nran`. (The overloaded scalar generators have five corresponding 32-bit scalars, denoted `iran0`, etc.)

#### MODULE `ran_state`

This module supports the random number routines `ran0`, `ran1`, `ran2`, and `ran3`. It provides each generator with five integers (for vector versions, five vectors of integers), for use as internal state space. The first three integers (`iran`, `jran`, `kran`) are maintained as nonnegative values, while the last two (`mran`, `nran`) have 32-bit nonzero values. Also provided by this module is support for initializing or reinitializing the state space to a desired standard sequence number, hashing the initial values to random values, and allocating and deallocating the internal workspace.

```
USE nrtype
IMPLICIT NONE
INTEGER, PARAMETER :: K4B=selected_int_kind(9)
Independent of the usual integer kind I4B, we need a kind value for (ideally) 32-bit integers.
INTEGER(K4B), PARAMETER :: hg=huge(1_K4B), hgm=-hg, hgng=hgm-1
INTEGER(K4B), SAVE :: lenran=0, seq=0
INTEGER(K4B), SAVE :: iran0,jran0,kran0,nran0,mran0,rans
INTEGER(K4B), DIMENSION(:,:), POINTER, SAVE :: ranseeds
INTEGER(K4B), DIMENSION(:), POINTER, SAVE :: iran,jran,kran, &
    nran,mran,ranv
REAL(SP), SAVE :: amm
INTERFACE ran_hash
    Scalar and vector versions of the hashing procedure.
MODULE PROCEDURE ran_hash_s, ran_hash_v
END INTERFACE
CONTAINS
```

(We here intersperse discussion with the listing of the module.) The module defines `K4B` as an integer `KIND` that is intended to be 32 bits. If your machine doesn't have 32-bit integers (hard to believe!) this will be caught later, and an error message generated. The definition of the parameters `hg`, `hgm`, and `hgng` makes an assumption about 32-bit integers that goes beyond the strict Fortran 90 integer model, that the magnitude of the most negative representable integer is greater by one than that of the most positive representable integer. This is a property of the *two's complement arithmetic* that is used on virtually all modern machines (see, e.g., [3]).

The global variables `rans` (for scalar) and `ranv` (for vector) are used by all of our routines to store the *integer* value associated with the most recently returned call. You can access these (with a “`USE ran_state`” statement) if you want integer, rather than real, random deviates.

The first routine, `ran_init`, is called by routines later in the chapter to initialize their state space. It is *not* intended to be called from a user's program.

```

SUBROUTINE ran_init(length)
USE nrtype; USE nrutil, ONLY : arth,nrerror,reallocate
IMPLICIT NONE
INTEGER(K4B), INTENT(IN) :: length
    Initialize or reinitialize the random generator state space to vectors of size length. The
    saved variable seq is hashed (via calls to the module routine ran_hash) to create unique
    starting seeds, different for each vector component.
INTEGER(K4B) :: new,j,hgt
if (length < lenran) RETURN          Simply return if enough space is already al-
hgt=hg                                located.
    The following lines check that kind value K4B is in fact a 32-bit integer with the usual properties
    that we expect it to have (under negation and wrap-around addition). If all of these tests are
    satisfied, then the routines that use this module are portable, even though they go beyond
    Fortran 90's integer model.
if (hg /= 2147483647) call nrerror('ran_init: arith assump 1 fails')
if (hgng >= 0) call nrerror('ran_init: arith assump 2 fails')
if (hgt+1 /= hgng) call nrerror('ran_init: arith assump 3 fails')
if (not(hg) >= 0) call nrerror('ran_init: arith assump 4 fails')
if (not(hgng) < 0) call nrerror('ran_init: arith assump 5 fails')
if (hg+hgng >= 0) call nrerror('ran_init: arith assump 6 fails')
if (not(-1_k4b) < 0) call nrerror('ran_init: arith assump 7 fails')
if (not(0_k4b) >= 0) call nrerror('ran_init: arith assump 8 fails')
if (not(1_k4b) >= 0) call nrerror('ran_init: arith assump 9 fails')
if (lenran > 0) then                  Reallocate space, or ...
    ranseeds=>reallocate(ranseeds,length,5)
    ranv=>reallocate(ranv,length-1)
    new=lenran+1
else                                  allocate space.
    allocate(ranseeds(length,5))
    allocate(ranv(length-1))
    new=1                              Index of first location not yet initialized.
    amm=nearest(1.0_sp,-1.0_sp)/hgng
    Use of nearest is to ensure that returned random deviates are strictly less than 1.0.
    if (amm*hgng >= 1.0 .or. amm*hgng <= 0.0) &
        call nrerror('ran_init: arith assump 10 fails')
end if
    Set starting values, unique by seq and vector component.
ranseeds(new:,1)=seq
ranseeds(new:,2:5)=spread(arth(new,1,size(ranseeds(new:,1))),2,4)
do j=1,4                               Hash them.
    call ran_hash(ranseeds(new:,j),ranseeds(new:,j+1))
end do
where (ranseeds(new:,1:3) < 0) &         Enforce nonnegativity.
    ranseeds(new:,1:3)=not(ranseeds(new:,1:3))
where (ranseeds(new:,4:5) == 0) ranseeds(new:,4:5)=1   Enforce nonzero.
if (new == 1) then                     Set scalar seeds.
    iran0=ranseeds(1,1)
    jran0=ranseeds(1,2)
    kran0=ranseeds(1,3)
    mran0=ranseeds(1,4)
    nran0=ranseeds(1,5)
    rans=nrans0
end if
if (length > 1) then                   Point to vector seeds.
    iran => ranseeds(2:,1)
    jran => ranseeds(2:,2)
    kran => ranseeds(2:,3)
    mran => ranseeds(2:,4)
    nran => ranseeds(2:,5)
    ranv = nrans

```

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```
end if
lenran=length
END SUBROUTINE ran_init
```

**f90** `hgt=hg ... if (hgt+1 /= hgng)` Bit of dirty laundry here! We are testing whether the most positive integer `hg` wraps around to the most negative integer `hgng` when 1 is added to it. We can't just write `hg+1`, since some compilers will evaluate this at compile time and return an overflow error message. If your compiler sees through the charade of the temporary variable `hgt`, you'll have to find another way to trick it.

`amm=nearest(1.0_sp,-1.0_sp)/hgng...` Logically, `amm` should be a parameter; but the `nearest` intrinsic is trouble-prone in the initialization expression for a parameter (named constant), so we compute this at run time. We then check that `amm`, when multiplied by the largest possible negative integer, does not equal or exceed unity. (Our random deviates are guaranteed never to equal zero or unity exactly.)

You might wonder why `amm` is negative, and why we multiply it by negative integers to get positive random deviates. The answer, which will become manifest in the random generators given below, is that we want to use the fast `not` operation on integers to convert them to nonzero values of all one sign. This is possible if the conversion is to negative values, since `not(i)` is negative for all nonnegative `i`. If the conversion were to positive values, we would have problems both with zero (its sign bit is already positive) and `hgng` (since `not(hgng)` is generally zero).

```
iran0=ranseeds(1,1) ...
iran => ranseeds(2:,1)...
```

The initial state information is stored in `ranseeds`, a two-dimensional array whose column (second) index ranges from 1 to 5 over the state variables. `ranseeds(1, :)` is reserved for scalar random generators, while `ranseeds(2:, :)` is for vector-parallel generators. The `ranseeds` array is made available to vector generators through the pointers `iran`, `jran`, `kran`, `mran`, and `nran`. The corresponding scalar values, `iran0`, ..., `nran0` are simply global variables, not pointers, because the overhead of addressing a scalar through a pointer is often too great. (We will have to copy these scalar values back into `ranseeds` when it, rarely, needs to be addressed as an array.)

`call ran_hash(...)` Unique, and random, initial state information is obtained by putting a user-settable “sequence number” into `iran`, a component number into `jran`, and hashing this pair. Then `jran` and `kran` are hashed, `kran` and `mran` are hashed, and so forth.

```
SUBROUTINE ran_deallocate
  User interface to release the workspace used by the random number routines.
  if (lenran > 0) then
    deallocate(ranseeds,ranv)
    nullify(ranseeds,ranv,iran,jran,kran,mran,nran)
    lenran = 0
  end if
END SUBROUTINE ran_deallocate
```

The above routine is supplied as a user interface for deallocating all the state space storage.

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```

SUBROUTINE ran_seed(sequence,size,put,get)
IMPLICIT NONE
INTEGER, OPTIONAL, INTENT(IN) :: sequence
INTEGER, OPTIONAL, INTENT(OUT) :: size
INTEGER, DIMENSION(:), OPTIONAL, INTENT(IN) :: put
INTEGER, DIMENSION(:), OPTIONAL, INTENT(OUT) :: get
  User interface for seeding the random number routines. Syntax is exactly like Fortran 90's
  random_seed routine, with one additional argument keyword: sequence, set to any inte-
  ger value, causes an immediate new initialization, seeded by that integer.
if (present(size)) then
  size=5*lenran
else if (present(put)) then
  if (lenran == 0) RETURN
  ranseeds=reshape(put,shape(ranseeds))
  where (ranseeds(:,1:3) < 0) ranseeds(:,1:3)=not(ranseeds(:,1:3))
  Enforce nonnegativity and nonzero conditions on any user-supplied seeds.
  where (ranseeds(:,4:5) == 0) ranseeds(:,4:5)=1
  iran0=ranseeds(1,1)
  jran0=ranseeds(1,2)
  kran0=ranseeds(1,3)
  mran0=ranseeds(1,4)
  nran0=ranseeds(1,5)
else if (present(get)) then
  if (lenran == 0) RETURN
  ranseeds(1,1:5)=(/ iran0,jran0,kran0,mran0,nran0 /)
  get=reshape(ranseeds,shape(get))
else if (present(sequence)) then
  call ran_deallocate
  seq=sequence
end if
END SUBROUTINE ran_seed

```



```

ranseeds=reshape(put,shape(ranseeds)) ...
get=reshape(ranseeds,shape(get))

```

Fortran 90's convention is that random state space is a one-dimensional array, so we map to this on both the get and put keywords.

```

iran0=...jran0=...kran0=...
ranseeds(1,1:5)=(/ iran0,jran0,kran0,mran0,nran0 /)

```

It's much more convenient to set a vector from a bunch of scalars than the other way around.

```

SUBROUTINE ran_hash_s(il,ir)
IMPLICIT NONE
INTEGER(K4B), INTENT(INOUT) :: il,ir
  DES-like hashing of two 32-bit integers, using shifts, xor's, and adds to make the internal
  nonlinear function.
INTEGER(K4B) :: is,j
do j=1,4
  is=ir
  ir=ieor(ir,ishft(ir,5))+1422217823
  ir=ieor(ir,ishft(ir,-16))+1842055030
  ir=ieor(ir,ishft(ir,9))+80567781
  ir=ieor(il,ir)
  il=is
end do
END SUBROUTINE ran_hash_s

```

The various constants are chosen to give good bit mixing and should not be changed.

```

SUBROUTINE ran_hash_v(il,ir)
IMPLICIT NONE
INTEGER(K4B), DIMENSION(:), INTENT(INOUT) :: il,ir
  Vector version of ran_hash_s.
INTEGER(K4B), DIMENSION(size(il)) :: is
INTEGER(K4B) :: j
do j=1,4
  is=ir
  ir=ieor(ir,ishft(ir,5))+1422217823
  ir=ieor(ir,ishft(ir,-16))+1842055030
  ir=ieor(ir,ishft(ir,9))+80567781
  ir=ieor(il,ir)
  il=is
end do
END SUBROUTINE ran_hash_v

END MODULE ran_state

```

The lines

```

ir=ieor(ir,ishft(ir,5))+1422217823
ir=ieor(ir,ishft(ir,-16))+1842055030
ir=ieor(ir,ishft(ir,9))+80567781

```

are *not* a Marsaglia shift sequence, though they resemble one. Instead, they implement a fast, nonlinear function on `ir` that we use as the “S-box” in a DES-like hashing algorithm. (See Volume 1, §7.5.) The triplet (5, −16, 9) is *not* chosen to give a full period Marsaglia sequence — it doesn’t. Instead it is chosen as being particularly good at separating in Hamming distance (i.e., number of nonidentical bits) two initially close values of `ir` (e.g., differing by only one bit). The large integer constants are chosen by a similar criterion. Note that the wrap-around of addition without generating an overflow error condition, which was tested in `ran_init`, is relied upon here.

\* \* \*

```

SUBROUTINE ran0_s(harvest)
USE nrtype
USE ran_state, ONLY: K4B, amm, lenran, ran_init, iran0, jran0, kran0, nran0, rans
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: harvest
  Lagged Fibonacci generator combined with a Marsaglia shift sequence. Returns as harvest
  a uniform random deviate between 0.0 and 1.0 (exclusive of the endpoint values). This gen-
  erator has the same calling and initialization conventions as Fortran 90’s random_number
  routine. Use ran_seed to initialize or reinitialize to a particular sequence. The period of
  this generator is about  $2.0 \times 10^{28}$ , and it fully vectorizes. Validity of the integer model
  assumed by this generator is tested at initialization.
if (lenran < 1) call ran_init(1)
rans=iran0-kran0
if (rans < 0) rans=rans+2147483579_k4b
iran0=jran0
jran0=kran0
kran0=rans
nran0=ieor(nran0,ishft(nran0,13))
nran0=ieor(nran0,ishft(nran0,-17))
nran0=ieor(nran0,ishft(nran0,5))
rans=ieor(nran0,rans)
harvest=amm*merge(rans,not(rans), rans<0 )
END SUBROUTINE ran0_s

```

Initialization routine in `ran_state`.  
Update Fibonacci generator, which  
has period  $p^2 + p + 1$ ,  $p = 2^{31} - 69$ .

Update Marsaglia shift sequence with  
period  $2^{32} - 1$ .

Combine the generators.  
Make the result positive definite (note  
that `amm` is negative).

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```

SUBROUTINE ran0_v(harvest)
USE nrtype
USE ran_state, ONLY: K4B, amm, lenran, ran_init, iran, jran, kran, nran, ranv
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(OUT) :: harvest
INTEGER(K4B) :: n
n=size(harvest)
if (lenran < n+1) call ran_init(n+1)
ranv(1:n)=iran(1:n)-kran(1:n)
where (ranv(1:n) < 0) ranv(1:n)=ranv(1:n)+2147483579_k4b
iran(1:n)=jran(1:n)
jran(1:n)=kran(1:n)
kran(1:n)=ranv(1:n)
nran(1:n)=ieor(nran(1:n), ishft(nran(1:n), 13))
nran(1:n)=ieor(nran(1:n), ishft(nran(1:n), -17))
nran(1:n)=ieor(nran(1:n), ishft(nran(1:n), 5))
ranv(1:n)=ieor(nran(1:n), ranv(1:n))
harvest=amm*merge(ranv(1:n), not(ranv(1:n)), ranv(1:n)<0)
END SUBROUTINE ran0_v

```

This is the simplest, and fastest, of the generators provided. It combines a subtractive Fibonacci generator (Number 6 in ref. [1], and one of the generators in Marsaglia and Zaman's `mzran`) with a Marsaglia shift sequence. On typical machines it is only 20% or so faster than `ran1`, however; so we recommend the latter preferentially. While we know of no weakness in `ran0`, we are not offering a prize for finding a weakness. `ran0` does have the feature, useful if you have a machine with nonstandard arithmetic, that it does not go beyond Fortran 90's assumed integer model.

Note that `ran0_s` and `ran0_v` are overloaded by the module `nr` onto the single name `ran0` (and similarly for the routines below).

\* \* \*

```

SUBROUTINE ran1_s(harvest)
USE nrtype
USE ran_state, ONLY: K4B, amm, lenran, ran_init, &
  iran0, jran0, kran0, nran0, mran0, rans
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: harvest
  Lagged Fibonacci generator combined with two Marsaglia shift sequences. On output, returns as harvest a uniform random deviate between 0.0 and 1.0 (exclusive of the endpoint values). This generator has the same calling and initialization conventions as Fortran 90's random_number routine. Use ran_seed to initialize or reinitialize to a particular sequence. The period of this generator is about  $8.5 \times 10^{37}$ , and it fully vectorizes. Validity of the integer model assumed by this generator is tested at initialization.
if (lenran < 1) call ran_init(1)
rans=iran0-kran0
if (rans < 0) rans=rans+2147483579_k4b
iran0=jran0
jran0=kran0
kran0=rans
nran0=ieor(nran0, ishft(nran0, 13))
nran0=ieor(nran0, ishft(nran0, -17))
nran0=ieor(nran0, ishft(nran0, 5))
  Once only per cycle, advance sequence by 1, shortening its period to  $2^{32} - 2$ .
if (nran0 == 1) nran0=270369_k4b
mran0=ieor(mran0, ishft(mran0, 5))
mran0=ieor(mran0, ishft(mran0, -13))
mran0=ieor(mran0, ishft(mran0, 6))

```

Initialization routine in `ran_state`.

Update Fibonacci generator, which has period  $p^2 + p + 1$ ,  $p = 2^{31} - 69$ .

Update Marsaglia shift sequence.

Update Marsaglia shift sequence with period  $2^{32} - 1$ .

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```
rans=ieor(nran0,rans)+mran0
```

Combine the generators. The above statement has wrap-around addition.

```
harvest=amm*merge(rans,not(rans), rans<0 )      Make the result positive definite (note
END SUBROUTINE ran1_s                          that amm is negative).
```

```
SUBROUTINE ran1_v(harvest)
USE nrtype
USE ran_state, ONLY: K4B,amm,lenran,ran_init, &
   iran,jran,kran,nran,mran,ranv
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(OUT) :: harvest
INTEGER(K4B) :: n
n=size(harvest)
if (lenran < n+1) call ran_init(n+1)
ranv(1:n)=iran(1:n)-kran(1:n)
where (ranv(1:n) < 0) ranv(1:n)=ranv(1:n)+2147483579_k4b
iran(1:n)=jran(1:n)
jran(1:n)=kran(1:n)
kran(1:n)=ranv(1:n)
nran(1:n)=ieor(nran(1:n),ishft(nran(1:n),13))
nran(1:n)=ieor(nran(1:n),ishft(nran(1:n),-17))
nran(1:n)=ieor(nran(1:n),ishft(nran(1:n),5))
where (nran(1:n) == 1) nran(1:n)=270369_k4b
mran(1:n)=ieor(mran(1:n),ishft(mran(1:n),5))
mran(1:n)=ieor(mran(1:n),ishft(mran(1:n),-13))
mran(1:n)=ieor(mran(1:n),ishft(mran(1:n),6))
ranv(1:n)=ieor(nran(1:n),ranv(1:n))+mran(1:n)
harvest=amm*merge(ranv(1:n),not(ranv(1:n)), ranv(1:n)<0 )
END SUBROUTINE ran1_v
```

The routine `ran1` combines *three* fast generators: the two used in `ran0`, plus an additional (different) Marsaglia shift sequence. The last generator is combined via an addition that can wrap-around.

We think that, within the limits of its floating-point precision, `ran1` provides perfect random numbers. We will pay \$1000 to the first reader who convinces us otherwise (by exhibiting a statistical test that `ran1` fails in a nontrivial way, excluding the ordinary limitations of a floating-point representation).

\* \* \*

```
SUBROUTINE ran2_s(harvest)
USE nrtype
USE ran_state, ONLY: K4B,amm,lenran,ran_init, &
   iran0,jran0,kran0,nran0,mran0,rans
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: harvest
Lagged Fibonacci generator combined with a Marsaglia shift sequence and a linear con-
gruential generator. Returns as harvest a uniform random deviate between 0.0 and 1.0
(exclusive of the endpoint values). This generator has the same calling and initialization
conventions as Fortran 90's random_number routine. Use ran_seed to initialize or reini-
tialize to a particular sequence. The period of this generator is about  $8.5 \times 10^{37}$ , and it fully
vectorizes. Validity of the integer model assumed by this generator is tested at initialization.
if (lenran < 1) call ran_init(1)      Initialization routine in ran_state.
rans=iran0-kran0                      Update Fibonacci generator, which
if (rans < 0) rans=rans+2147483579_k4b has period  $p^2 + p + 1$ ,  $p = 2^{31} -$ 
iran0=jran0                          69.
jran0=kran0
kran0=rans
```

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```

nran0=ieor(nran0,ishft(nran0,13))           Update Marsaglia shift sequence with
nran0=ieor(nran0,ishft(nran0,-17))         period  $2^{32} - 1$ .
nran0=ieor(nran0,ishft(nran0,5))
rans=iand(mran0,65535)
  Update the sequence  $m \leftarrow 69069m + 820265819 \bmod 2^{32}$  using shifts instead of multiplies.
  Wrap-around addition (tested at initialization) is used.
mran0=ishft(3533*ishft(mran0,-16)+rans,16)+ &
  3533*rans+820265819_k4b
rans=ieor(nran0,kran0)+mran0               Combine the generators.
harvest=amm*merge(rans,not(rans), rans<0 ) Make the result positive definite (note
END SUBROUTINE ran2_s                       that amm is negative).

```

```

SUBROUTINE ran2_v(harvest)
USE nrtype
USE ran_state, ONLY: K4B,amm,lenran,ran_init, &
  iran,jran,kran,nran,mran,ranv
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(OUT) :: harvest
INTEGER(K4B) :: n
n=size(harvest)
if (lenran < n+1) call ran_init(n+1)
ranv(1:n)=iran(1:n)-kran(1:n)
where (ranv(1:n) < 0) ranv(1:n)=ranv(1:n)+2147483579_k4b
iran(1:n)=jran(1:n)
jran(1:n)=kran(1:n)
kran(1:n)=ranv(1:n)
nran(1:n)=ieor(nran(1:n),ishft(nran(1:n),13))
nran(1:n)=ieor(nran(1:n),ishft(nran(1:n),-17))
nran(1:n)=ieor(nran(1:n),ishft(nran(1:n),5))
ranv(1:n)=iand(mran(1:n),65535)
mran(1:n)=ishft(3533*ishft(mran(1:n),-16)+ranv(1:n),16)+ &
  3533*ranv(1:n)+820265819_k4b
ranv(1:n)=ieor(nran(1:n),kran(1:n))+mran(1:n)
harvest=amm*merge(ranv(1:n),not(ranv(1:n)), ranv(1:n)<0 )
END SUBROUTINE ran2_v

```

ran2, for use by readers whose caution is extreme, also combines three generators. The difference from ran1 is that each generator is based on a completely different method from the other two. The third generator, in this case, is a linear congruential generator, modulo  $2^{32}$ . This generator relies extensively on wrap-around addition (which is automatically tested at initialization). On machines with fast arithmetic, ran2 is on the order of only 20% slower than ran1. We offer a \$1000 bounty on ran2, with the same terms as for ran1, above.

\* \* \*

```

SUBROUTINE expdev_s(harvest)
USE nrtype
USE nr, ONLY : ran1
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: harvest
  Returns in harvest an exponentially distributed, positive, random deviate of unit mean,
  using ran1 as the source of uniform deviates.
REAL(SP) :: dum
call ran1(dum)
harvest=-log(dum)           We use the fact that ran1 never returns exactly 0 or 1.
END SUBROUTINE expdev_s

```

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```

SUBROUTINE expdev_v(harvest)
USE nrtype
USE nr, ONLY : ran1
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(OUT) :: harvest
REAL(SP), DIMENSION(size(harvest)) :: dum
call ran1(dum)
harvest=-log(dum)
END SUBROUTINE expdev_v

```

**f**<sub>90</sub> call ran1(dum) The only noteworthy thing about this line is its simplicity: Once all the machinery is in place, the random number generators are self-initializing (to the sequence defined by seq = 0), and (via overloading) usable with both scalar and vector arguments.

\* \* \*

```

SUBROUTINE gasdev_s(harvest)
USE nrtype
USE nr, ONLY : ran1
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: harvest
  Returns in harvest a normally distributed deviate with zero mean and unit variance, using
  ran1 as the source of uniform deviates.
REAL(SP) :: rsq,v1,v2
REAL(SP), SAVE :: g
LOGICAL, SAVE :: gaus_stored=.false.
if (gaus_stored) then
  harvest=g
  gaus_stored=.false.
else
  do
    call ran1(v1)
    call ran1(v2)
    v1=2.0_sp*v1-1.0_sp
    v2=2.0_sp*v2-1.0_sp
    rsq=v1**2+v2**2
    if (rsq > 0.0 .and. rsq < 1.0) exit
  end do
  rsq=sqrt(-2.0_sp*log(rsq)/rsq)
  harvest=v1*rsq
  g=v2*rsq
  gaus_stored=.true.
end if
END SUBROUTINE gasdev_s

```

We have an extra deviate handy,  
so return it,  
and unset the flag.  
We don't have an extra deviate handy, so  
pick two uniform numbers in the square ex-  
tending from -1 to +1 in each direction,  
see if they are in the unit circle,  
otherwise try again.  
Now make the Box-Muller transformation to  
get two normal deviates. Return one and  
save the other for next time.  
Set flag.

```

SUBROUTINE gasdev_v(harvest)
USE nrtype; USE nrutil, ONLY : array_copy
USE nr, ONLY : ran1
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(OUT) :: harvest
REAL(SP), DIMENSION(size(harvest)) :: rsq,v1,v2
REAL(SP), ALLOCATABLE, DIMENSION(:), SAVE :: g
INTEGER(I4B) :: n,ng,nn,m
INTEGER(I4B), SAVE :: last_allocated=0
LOGICAL, SAVE :: gaus_stored=.false.
LOGICAL, DIMENSION(size(harvest)) :: mask
n=size(harvest)
if (n /= last_allocated) then


```

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```

    if (last_allocated /= 0) deallocate(g)
    allocate(g(n))
    last_allocated=n
    gaus_stored=.false.
end if
if (gaus_stored) then
    harvest=g
    gaus_stored=.false.
else
    ng=1
    do
        if (ng > n) exit
        call ran1(v1(ng:n))
        call ran1(v2(ng:n))
        v1(ng:n)=2.0_sp*v1(ng:n)-1.0_sp
        v2(ng:n)=2.0_sp*v2(ng:n)-1.0_sp
        rsq(ng:n)=v1(ng:n)**2+v2(ng:n)**2
        mask(ng:n)=(rsq(ng:n)>0.0 .and. rsq(ng:n)<1.0)
        call array_copy(pack(v1(ng:n),mask(ng:n)),v1(ng:),nn,m)
        v2(ng:ng+nn-1)=pack(v2(ng:n),mask(ng:n))
        rsq(ng:ng+nn-1)=pack(rsq(ng:n),mask(ng:n))
        ng=ng+nn
    end do
    rsq=sqrt(-2.0_sp*log(rsq)/rsq)
    harvest=v1*rsq
    g=v2*rsq
    gaus_stored=.true.
end if
END SUBROUTINE gasdev_v

```

 if (n /= last\_allocated) ... We make the assumption that, in most cases, the size of harvest will not change between successive calls. Therefore, if it *does* change, we don't try to save the previously generated deviates that, half the time, will be around. If your use has rapidly varying sizes (or, even worse, calls alternating between two different sizes), you should remedy this inefficiency in the obvious way.

call array\_copy(pack(v1(ng:n),mask(ng:n)),v1(ng:),nn,m) This is a variant of the pack-unpack method (see note to `factr1`, p. 1087). Different here is that we don't care which random deviates end up in which component. Thus, we can simply keep packing successful returns into `v1` and `v2` until they are full.

 Note also the use of `array_copy`, since we don't know in advance the length of the array returned by `pack`.

\* \* \*

```

FUNCTION gamdev(ia)
USE nrtype; USE nrutil, ONLY : assert
USE nr, ONLY : ran1
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: ia
REAL(SP) :: gamdev

```

Returns a deviate distributed as a gamma distribution of integer order `ia`, i.e., a waiting time to the `ia`th event in a Poisson process of unit mean, using `ran1` as the source of uniform deviates.

```

REAL(SP) :: am,e,h,s,x,y,v(2),arr(5)
call assert(ia >= 1, 'gamdev arg?')
if (ia < 6) then

```

Use direct method, adding waiting times.

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```

    call ran1(arr(1:ia))
    x=-log(product(arr(1:ia)))
else
    do
        call ran1(v)
        v(2)=2.0_sp*v(2)-1.0_sp
        if (dot_product(v,v) > 1.0) cycle
        y=v(2)/v(1)
        am=ia-1
        s=sqrt(2.0_sp*am+1.0_sp)
        x=s*y+am
        if (x <= 0.0) cycle
        e=(1.0_sp+y**2)*exp(am*log(x/am)-s*y)
        call ran1(h)
        if (h <= e) exit
    end do
end if
gamdev=x
END FUNCTION gamdev

```

Use rejection method.

These three lines generate the tangent of a random angle, i.e., are equivalent to  $y = \tan(\pi \text{ran}(\text{idum}))$ .

We decide whether to reject  $x$ :  
 Reject in region of zero probability.  
 Ratio of probability function to comparison function.  
 Reject on basis of a second uniform deviate.



$x = -\log(\text{product}(\text{arr}(1:\text{ia})))$  Why take the log of the product instead of the sum of the logs? Because log is assumed to be slower than multiply.



We don't have vector versions of the less commonly used deviate generators, gamdev, poidev, and bnlddev.

\* \* \*

```

FUNCTION poidev(xm)
USE nrtype
USE nr, ONLY : gammaln,ran1
IMPLICIT NONE
REAL(SP), INTENT(IN) :: xm
REAL(SP) :: poidev
    Returns as a floating-point number an integer value that is a random deviate drawn from a
    Poisson distribution of mean xm, using ran1 as a source of uniform random deviates.
REAL(SP) :: em,harvest,t,y
REAL(SP), SAVE :: alxm,g,oldm=-1.0_sp,sq
    oldm is a flag for whether xm has changed since last call.
if (xm < 12.0) then
    Use direct method.
    if (xm /= oldm) then
        oldm=xm
        g=exp(-xm)
        If xm is new, compute the exponential.
    end if
    em=-1
    t=1.0
    do
        em=em+1.0_sp
        call ran1(harvest)
        t=t*harvest
        if (t <= g) exit
    end do
else
    Use rejection method.
    if (xm /= oldm) then
        If xm has changed since the last call, then pre-
        oldm=xm
        sq=sqrt(2.0_sp*xm)
        alxm=log(xm)
        g=xm*alxm-gammaln(xm+1.0_sp)
        The function gammaln is the natural log of the
        gamma function, as given in §6.1.
    end if
    do

```

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```

do
  call ran1(harvest)           y is a deviate from a Lorentzian comparison
  y=tan(PI*harvest)           function.
  em=sq*y+xm                  em is y, shifted and scaled.
  if (em >= 0.0) exit         Reject if in regime of zero probability.
end do
em=int(em)                    The trick for integer-valued distributions.
t=0.9_sp*(1.0_sp+y**2)*exp(em*alxm-gammln(em+1.0_sp)-g)
  The ratio of the desired distribution to the comparison function; we accept or reject
  by comparing it to another uniform deviate. The factor 0.9 is chosen so that t never
  exceeds 1.
call ran1(harvest)
if (harvest <= t) exit
end do
end if
poidev=em
END FUNCTION poidev

```

\* \* \*

```

FUNCTION bnldev(pp,n)
USE nrtype
USE nr, ONLY : gammln,ran1
IMPLICIT NONE
REAL(SP), INTENT(IN) :: pp
INTEGER(I4B), INTENT(IN) :: n
REAL(SP) :: bnldev
  Returns as a floating-point number an integer value that is a random deviate drawn from a
  binomial distribution of n trials each of probability pp, using ran1 as a source of uniform
  random deviates.
INTEGER(I4B) :: j
INTEGER(I4B), SAVE :: nold=-1
REAL(SP) :: am,em,g,h,p,sq,t,y,arr(24)
REAL(SP), SAVE :: pc,plog,pcllog,en,oldg,pold=-1.0      Arguments from previous calls.
p=merge(pp,1.0_sp-pp, pp <= 0.5_sp )
  The binomial distribution is invariant under changing pp to 1.-pp, if we also change the
  answer to n minus itself; we'll remember to do this below.
am=n*p           This is the mean of the deviate to be produced.
if (n < 25) then Use the direct method while n is not too large.
  call ran1(arr(1:n))
  bnldev=count(arr(1:n)<p)
  This can require up to 25 calls to ran1.
else if (am < 1.0) then
  g=exp(-am)
  t=1.0
  If fewer than one event is expected out of 25
  do j=0,n
    call ran1(h)
    t=t*h
    or more trials, then the distribution is quite
    if (t < g) exit
    accurately Poisson. Use direct Poisson method.
  end do
  bnldev=merge(j,n, j <= n)
else
  Use the rejection method.
  if (n /= nold) then
    en=n
    oldg=gammln(en+1.0_sp)
    nold=n
    If n has changed, then compute useful quanti-
    ties.
  end if
  if (p /= pold) then
    pc=1.0_sp-p
    plog=log(p)
    pcllog=log(pc)
    pold=p
    If p has changed, then compute useful quanti-
    ties.

```

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```

end if
sq=sqrt(2.0_sp*am*pc)
do
  call ran1(h)
  y=tan(PI*h)
  em=sq*y+am
  if (em < 0.0 .or. em >= en+1.0_sp) cycle   Reject.
  em=int(em)                               Trick for integer-valued distribution.
  t=1.2_sp*sq*(1.0_sp+y**2)*exp(oldg-gammln(en+1.0_sp)-&
    gammln(en-em+1.0_sp)+em*plog+(en-em)*pclog)
  call ran1(h)
  if (h <= t) exit                         Reject. This happens about 1.5 times per devi-
  end do                                     ate, on average.
bnldev=em
end if
if (p /= pp) bnldev=n-bnldev               Remember to undo the symmetry transforma-
END FUNCTION bnldev                        tion.

```

\* \* \*

**f90** The routines `psdes` and `psdes_safe` both perform *exactly* the same hashing as was done by the Fortran 77 routine `psdes`. The difference is that `psdes` makes assumptions about arithmetic that go beyond the strict Fortran 90 model, while `psdes_safe` makes no such assumptions. The disadvantage of `psdes_safe` is that it is significantly slower, performing most of its arithmetic in double-precision reals that are then converted to integers with Fortran 90's modulo intrinsic.

In fact the nonsafe version, `psdes`, works fine on almost all machines and compilers that we have tried. There is a reason for this: Our assumed integer model is the same as the C language unsigned `int`, and virtually all modern computers and compilers have a lot of C hidden inside. If `psdes` and `psdes_safe` produce identical output on your system for any hundred or so different input values, you can be quite confident about using the faster version exclusively.

At the other end of things, note that in the very unlikely case that your system fails on the `ran_hash` routine in the `ran_state` module (you will have learned this from error messages generated by `ran_init`), you can substitute `psdes_safe` for `ran_hash`: They are plug-compatible.

```

SUBROUTINE psdes_s(lword,rword)
USE nrtype
IMPLICIT NONE
INTEGER(I4B), INTENT(INOUT) :: lword,rword
INTEGER(I4B), PARAMETER :: NITER=4
  "Pseudo-DES" hashing of the 64-bit word (lword,irword). Both 32-bit arguments are
  returned hashed on all bits. Note that this version of the routine assumes properties of
  integer arithmetic that go beyond the Fortran 90 model, though they are compatible with
  unsigned integers in C.
INTEGER(I4B), DIMENSION(4), SAVE :: C1,C2
DATA C1 /Z'BAA96887',Z'1E17D32C',Z'03BCDC3C',Z'0F33D1B2'/
DATA C2 /Z'4B0F3B58',Z'E874F0C3',Z'6955C5A6',Z'55A7CA46'/
INTEGER(I4B) :: i,ia,ib,iswap,itmph,itmpl
do i=1,NITER
  Perform niter iterations of DES logic, using a simpler
  iswap=rword                                     (noncryptographic) nonlinear function instead of DES's.
  ia=ieor(rword,C1(i))                           The bit-rich constants C1 and (below) C2 guarantee lots
  itmpl=iand(ia,65535)                             of nonlinear mixing.
  itmph=iand(ishft(ia,-16),65535)

```

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```

        ib=itmpl**2+not(itmph**2)
        ia=ior(ishft(ib,16),iand(ishft(ib,-16),65535))
        rword=ieor(lword,ieor(C2(i),ia)+itmpl*itmph)
        lword=iswap
    end do
END SUBROUTINE psdes_s

```

```

SUBROUTINE psdes_v(lword,rword)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
INTEGER(I4B), DIMENSION(:), INTENT(INOUT) :: lword,rword
INTEGER(I4B), PARAMETER :: NITER=4
INTEGER(I4B), DIMENSION(4), SAVE :: C1,C2
DATA C1 /Z'BAA96887',Z'1E17D32C',Z'03BCDC3C',Z'0F33D1B2'/
DATA C2 /Z'4B0F3B58',Z'E874FOC3',Z'6955C5A6',Z'55A7CA46'/
INTEGER(I4B), DIMENSION(size(lword)) :: ia,ib,iswap,itmph,itmpl
INTEGER(I4B) :: i
i=assert_eq(size(lword),size(rword),'psdes_v')
do i=1,NITER
    iswap=rword
    ia=ieor(rword,C1(i))
    itmpl=iand(ia,65535)
    itmph=iand(ishft(ia,-16),65535)
    ib=itmpl**2+not(itmph**2)
    ia=ior(ishft(ib,16),iand(ishft(ib,-16),65535))
    rword=ieor(lword,ieor(C2(i),ia)+itmpl*itmph)
    lword=iswap
end do
END SUBROUTINE psdes_v

```

```

SUBROUTINE psdes_safe_s(lword,rword)
USE nrtype
IMPLICIT NONE
INTEGER(I4B), INTENT(INOUT) :: lword,rword
INTEGER(I4B), PARAMETER :: NITER=4
    "Pseudo-DES" hashing of the 64-bit word (lword,irword). Both 32-bit arguments are
    returned hashed on all bits. This is a slower version of the routine that makes no assumptions
    outside of the Fortran 90 integer model.
INTEGER(I4B), DIMENSION(4), SAVE :: C1,C2
DATA C1 /Z'BAA96887',Z'1E17D32C',Z'03BCDC3C',Z'0F33D1B2'/
DATA C2 /Z'4B0F3B58',Z'E874FOC3',Z'6955C5A6',Z'55A7CA46'/
INTEGER(I4B) :: i,ia,ib,iswap
REAL(DP) :: alo,ahi
do i=1,NITER
    iswap=rword
    ia=ieor(rword,C1(i))
    alo=real(iand(ia,65535),dp)
    ahi=real(iand(ishft(ia,-16),65535),dp)
    ib=modint(alo*alo+real(not(modint(ahi*ahi)),dp))
    ia=ior(ishft(ib,16),iand(ishft(ib,-16),65535))
    rword=ieor(lword,modint(real(ieor(C2(i),ia),dp)+alo*ahi))
    lword=iswap
end do
CONTAINS
FUNCTION modint(x)
REAL(DP), INTENT(IN) :: x
INTEGER(I4B) :: modint
REAL(DP) :: a
REAL(DP), PARAMETER :: big=huge(modint), base=big+big+2.0_dp
a=modulo(x,base)

```

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```

if (a > big) a=a-base
modint=nint(a,kind=i4b)
END FUNCTION modint
END SUBROUTINE psdes_safe_s

```

```

SUBROUTINE psdes_safe_v(lword,rword)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
INTEGER(I4B), DIMENSION(:), INTENT(INOUT) :: lword,rword
INTEGER(I4B), PARAMETER :: NITER=4
INTEGER(I4B), SAVE :: C1(4),C2(4)
DATA C1 /Z'BAA96887',Z'1E17D32C',Z'03BCDC3C',Z'0F33D1B2'/
DATA C2 /Z'4B0F3B58',Z'E874FOC3',Z'6955C5A6',Z'55A7CA46'/
INTEGER(I4B), DIMENSION(size(lword)) :: ia,ib,iswap
REAL(DP), DIMENSION(size(lword)) :: alo,ahi
INTEGER(I4B) :: i
i=assert_eq(size(lword),size(rword),'psdes_safe_v')
do i=1,NITER
  iswap=rword
  ia=ieor(rword,C1(i))
  alo=real(iand(ia,65535),dp)
  ahi=real(iand(ishft(ia,-16),65535),dp)
  ib=modint(alo*alo+real(not(modint(ahi*ahi)),dp))
  ia=ior(ishft(ib,16),iand(ishft(ib,-16),65535))
  rword=ieor(lword,modint(real(ieor(C2(i),ia),dp)+alo*ahi))
  lword=iswap
end do
CONTAINS
FUNCTION modint(x)
REAL(DP), DIMENSION(:), INTENT(IN) :: x
INTEGER(I4B), DIMENSION(size(x)) :: modint
REAL(DP), DIMENSION(size(x)) :: a
REAL(DP), PARAMETER :: big=huge(modint), base=big+big+2.0_dp
a=modulo(x,base)
where (a > big) a=a-base
modint=nint(a,kind=i4b)
END FUNCTION modint
END SUBROUTINE psdes_safe_v

```



FUNCTION modint(x) This embedded routine takes a double-precision real argument, and returns it as an integer mod  $2^{32}$  (correctly wrapping it to negative to take into account that Fortran 90 has no unsigned integers).

\* \* \*

```

SUBROUTINE ran3_s(harvest)
USE nrtype
USE ran_state, ONLY: K4B,amm,lenran,ran_init,ran_hash,mran0,nran0,rans
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: harvest
  Random number generation by DES-like hashing of two 32-bit words, using the algorithm
  ran_hash. Returns as harvest a uniform random deviate between 0.0 and 1.0 (exclusive
  of the endpoint values).
INTEGER(K4B) :: temp
if (lenran < 1) call ran_init(1)
nran0=ieor(nran0,ishft(nran0,13))
nran0=ieor(nran0,ishft(nran0,-17))
nran0=ieor(nran0,ishft(nran0,5))
if (nran0 == 1) nran0=270369_k4b

```

Initialize.

Two Marsaglia shift sequences are maintained as input to the hashing. The period of the combined generator is about  $1.8 \times 10^{19}$ .

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```

rans=nrano
mran0=ieor(mran0,ishft(mran0,5))
mran0=ieor(mran0,ishft(mran0,-13))
mran0=ieor(mran0,ishft(mran0,6))
temp=mran0
call ran_hash(temp,rans)
harvest=amm*merge(rans,not(rans), rans<0 )
END SUBROUTINE ran3_s

```

Hash.  
Make the result positive definite (note that amm is negative).

```

SUBROUTINE ran3_v(harvest)
USE nrtype
USE ran_state, ONLY: K4B,amm,lenran,ran_init,ran_hash,mran,nran,ranv
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(OUT) :: harvest
INTEGER(K4B), DIMENSION(size(harvest)) :: temp
INTEGER(K4B) :: n
n=size(harvest)
if (lenran < n+1) call ran_init(n+1)
nran(1:n)=ieor(nran(1:n),ishft(nran(1:n),13))
nran(1:n)=ieor(nran(1:n),ishft(nran(1:n),-17))
nran(1:n)=ieor(nran(1:n),ishft(nran(1:n),5))
where (nran(1:n) == 1) nran(1:n)=270369_k4b
ranv(1:n)=nran(1:n)
mran(1:n)=ieor(mran(1:n),ishft(mran(1:n),5))
mran(1:n)=ieor(mran(1:n),ishft(mran(1:n),-13))
mran(1:n)=ieor(mran(1:n),ishft(mran(1:n),6))
temp=mran(1:n)
call ran_hash(temp,ranv(1:n))
harvest=amm*merge(ranv(1:n),not(ranv(1:n)), ranv(1:n)<0 )
END SUBROUTINE ran3_v

```

As given, `ran3` uses the `ran_hash` function in the module `ran_state` as its DES surrogate. That function is sufficiently fast to make `ran3` only about a factor of 2 slower than our baseline recommended generator `ran1`. The slower routine `psdes` and (even slower) `psdes_safe` are plug-compatible with `ran_hash`, and could be substituted for it in this routine.

\* \* \*

```

FUNCTION irbit1(iseed)
USE nrtype
IMPLICIT NONE
INTEGER(I4B), INTENT(INOUT) :: iseed
INTEGER(I4B) :: irbit1
    Returns as an integer a random bit, based on the 18 low-significance bits in iseed (which
    is modified for the next call).
if (btest(iseed,17) .neqv. btest(iseed,4) .neqv. btest(iseed,1) &
    .neqv. btest(iseed,0)) then
    iseed=ibset(ishft(iseed,1),0)
    irbit1=1
else
    iseed=ishft(iseed,1)
    irbit1=0
end if
END FUNCTION irbit1

```

Leftshift the seed and put a 1 in its bit 1.  
But if the XOR calculation gave a 0, then put that in bit 1 instead.

```

FUNCTION irbit2(iseed)
USE nrtype
IMPLICIT NONE
INTEGER(I4B), INTENT(INOUT) :: iseed
INTEGER(I4B) :: irbit2
  Returns as an integer a random bit, based on the 18 low-significance bits in iseed (which
  is modified for the next call).
INTEGER(I4B), PARAMETER :: IB1=1,IB2=2,IB5=16,MASK=IB1+IB2+IB5
if (btest(iseed,17)) then      Change all masked bits, shift, and put 1 into bit 1.
  iseed=ibset(ishft(ieor(iseed,MASK),1),0)
  irbit2=1
else                            Shift and put 0 into bit 1.
  iseed=ibclr(ishft(iseed,1),0)
  irbit2=0
end if
END FUNCTION irbit2

```

\* \* \*

```

SUBROUTINE sobseq(x,init)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(OUT) :: x
INTEGER(I4B), OPTIONAL, INTENT(IN) :: init
INTEGER(I4B), PARAMETER :: MAXBIT=30,MAXDIM=6
  When the optional integer init is present, internally initializes a set of MAXBIT direction
  numbers for each of MAXDIM different Sobol' sequences. Otherwise returns as the vector x
  of length N the next values from N of these sequences. (N must not be changed between
  initializations.)
REAL(SP), SAVE :: fac
INTEGER(I4B) :: i,im,ipp,j,k,l
INTEGER(I4B), DIMENSION(:,:), ALLOCATABLE :: iu
INTEGER(I4B), SAVE :: in
INTEGER(I4B), DIMENSION(MAXDIM), SAVE :: ip,ix,mdeg
INTEGER(I4B), DIMENSION(MAXDIM*MAXBIT), SAVE :: iv
DATA ip /0,1,1,2,1,4/, mdeg /1,2,3,3,4,4/, ix /6*0/
DATA iv /6*1,3,1,3,3,1,1,5,7,7,3,3,5,15,11,5,15,13,9,156*0/
if (present(init)) then      Initialize, don't return a vector.
  ix=0
  in=0
  if (iv(1) /= 1) RETURN
  fac=1.0_sp/2.0_sp**MAXBIT
  allocate(iu(MAXDIM,MAXBIT))
  iu=reshape(iv,shape(iu))      To allow both 1D and 2D addressing.
  do k=1,MAXDIM
    do j=1,mdeg(k)              Stored values require only normalization.
      iu(k,j)=iu(k,j)*2**(MAXBIT-j)
    end do
    do j=mdeg(k)+1,MAXBIT      Use the recurrence to get other values.
      ipp=ip(k)
      i=iu(k,j-mdeg(k))
      i=ieor(i,i/2**mdeg(k))
      do l=mdeg(k)-1,1,-1
        if (btest(ipp,0)) i=ieor(i,iu(k,j-1))
        ipp=ipp/2
      end do
      iu(k,j)=i
    end do
  end do
  iv=reshape(iu,shape(iv))
  deallocate(iu)

```

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```

else                                     Calculate the next vector in the sequence.
  im=in
  do j=1,MAXBIT                          Find the rightmost zero bit.
    if (.not. btest(im,0)) exit
    im=im/2
  end do
  if (j > MAXBIT) call nrerror('MAXBIT too small in sobseq')
  im=(j-1)*MAXDIM
  j=min(size(x),MAXDIM)
  ix(1:j)=ieor(ix(1:j),iv(1+im:j+im))
  XOR the appropriate direction number into each component of the vector and convert
  to a floating number.
  x(1:j)=ix(1:j)*fac
  in=in+1                                Increment the counter.
end if
END SUBROUTINE sobseq

```

**f90** if (present(init)) then ... allocate(iu(...)) ... iu=reshape(...)  
 Wanting to avoid the deprecated EQUIVALENCE statement, we must reshape iv into a two-dimensional array, then un-reshape it after we are done. This is done only once, at initialization time, so there is no serious inefficiency introduced.

\* \* \*

```

SUBROUTINE vegas(region,func,init,ncall,itmx,nprn,tgral,sd,chi2a)
USE nrtype
USE nr, ONLY : ran1
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: region
INTEGER(I4B), INTENT(IN) :: init,ncall,itmx,nprn
REAL(SP), INTENT(OUT) :: tgral,sd,chi2a
INTERFACE
  FUNCTION func(pt,wgt)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), DIMENSION(:), INTENT(IN) :: pt
    REAL(SP), INTENT(IN) :: wgt
    REAL(SP) :: func
  END FUNCTION func
END INTERFACE
REAL(SP), PARAMETER :: ALPH=1.5_sp,TINY=1.0e-30_sp
INTEGER(I4B), PARAMETER :: MXDIM=10,NDMX=50
  Performs Monte Carlo integration of a user-supplied d-dimensional function func over a
  rectangular volume specified by region, a vector of length 2d consisting of d "lower left"
  coordinates of the region followed by d "upper right" coordinates. The integration consists of
  itmx iterations, each with approximately ncall calls to the function. After each iteration
  the grid is refined; more than 5 or 10 iterations are rarely useful. The input flag init
  signals whether this call is a new start, or a subsequent call for additional iterations (see
  comments below). The input flag nprn (normally 0) controls the amount of diagnostic
  output. Returned answers are tgral (the best estimate of the integral), sd (its standard
  deviation), and chi2a ( $\chi^2$  per degree of freedom, an indicator of whether consistent results
  are being obtained). See text for further details.
INTEGER(I4B), SAVE :: i,it,j,k,mds,nd,ndim,ndo,ng,npg          Best make everything static,
INTEG(I4B), DIMENSION(MXDIM), SAVE :: ia,kg                  allowing restarts.
REAL(SP), SAVE :: calls,dv2g,dxg,f,f2,f2b,fb,rc,ti,tsi,wgt,xjac,xn,xnd,xo,harvest
REAL(SP), DIMENSION(NDMX,MXDIM), SAVE :: d,di,xi
REAL(SP), DIMENSION(MXDIM), SAVE :: dt,dx,x
REAL(SP), DIMENSION(NDMX), SAVE :: r,xin
REAL(DP), SAVE :: schi,si,swgt

```

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```

ndim=size(region)/2
if (init <= 0) then
    mds=1
    ndo=1
    xi(1,:)=1.0
end if
if (init <= 1) then
    si=0.0
    swgt=0.0
    schi=0.0
end if
if (init <= 2) then
    nd=NDMX
    ng=1
    if (mds /= 0) then
        ng=(ncall/2.0_sp+0.25_sp)**(1.0_sp/ndim)
        mds=1
        if ((2*ng-NDMX) >= 0) then
            mds=-1
            npg=ng/NDMX+1
            nd=ng/npg
            ng=npg*nd
        end if
    end if
    k=ng**ndim
    npg=max(ncall/k,2)
    calls=real(npg,sp)*real(k,sp)
    dxg=1.0_sp/ng
    dv2g=(calls*dxg**ndim)**2/npg/npg/(npg-1.0_sp)
    xnd=nd
    dxg=dxg*xnd
    dx(1:ndim)=region(1+ndim:2*ndim)-region(1:ndim)
    xjac=1.0_sp/calls*product(dx(1:ndim))
    if (nd /= ndo) then
        r(1:max(nd,ndo))=1.0
        do j=1,ndim
            call rebin(ndo/xnd,nd,r,xin,xi(:,j))
        end do
        ndo=nd
    end if
    if (nprn >= 0) write(*,200) ndim,calls,it,itmx,nprn,&
        ALPH,mds,nd,(j,region(j),j,region(j+ndim),j=1,ndim)
end if
do it=1,itmx
    ti=0.0
    tsi=0.0
    kg(:)=1
    d(1:nd,:)=0.0
    di(1:nd,:)=0.0
    iterate: do
        fb=0.0
        f2b=0.0
        do k=1,npg
            wgt=xjac
            do j=1,ndim
                call ran1(harvest)
                xn=(kg(j)-harvest)*dxg+1.0_sp
                ia(j)=max(min(int(xn),NDMX),1)
                if (ia(j) > 1) then
                    xo=xi(ia(j),j)-xi(ia(j)-1,j)
                    rc=xi(ia(j)-1,j)+(xn-ia(j))*xo
                else
                    xo=xi(ia(j),j)
                    rc=(xn-ia(j))*xo
                end if
            end do
        end do
    end do

```

Normal entry. Enter here on a cold start.  
Change to mds=0 to disable stratified sampling, i.e., use importance sampling only.

Enter here to inherit the grid from a previous call, but not its answers.

Enter here to inherit the previous grid and its answers.

Set up for stratification.

Do binning if necessary.

Main iteration loop. Can enter here (init ≥ 3) to do an additional itmx iterations with all other parameters unchanged.

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```

        end if
        x(j)=region(j)+rc*dx(j)
        wgt=wgt*xo*xnd
    end do
    f=wgt*func(x(1:ndim),wgt)
    f2=f*f
    fb=fb+f
    f2b=f2b+f2
    do j=1,ndim
        di(ia(j),j)=di(ia(j),j)+f
        if (mds >= 0) d(ia(j),j)=d(ia(j),j)+f2
    end do
end do
f2b=sqrt(f2b*npg)
f2b=(f2b-fb)*(f2b+fb)
if (f2b <= 0.0) f2b=TINY
ti=ti+fb
tsi=tsi+f2b
if (mds < 0) then
    do j=1,ndim
        d(ia(j),j)=d(ia(j),j)+f2b
    end do
end if
do k=ndim,1,-1
    kg(k)=mod(kg(k),ng)+1
    if (kg(k) /= 1) cycle iterate
end do
exit iterate
end do iterate
tsi=tsi*dv2g
wgt=1.0_sp/tsi
si=si+real(wgt,dp)*real(ti,dp)
schi=schi+real(wgt,dp)*real(ti,dp)**2
swgt=swgt+real(wgt,dp)
tgral=si/swgt
chi2a=max((schi-si*tgral)/(it-0.99_dp),0.0_dp)
sd=sqrt(1.0_sp/swgt)
tsi=sqrt(tsi)
if (nprn >= 0) then
    write(*,201) it,ti,tsi,tgral,sd,chi2a
    if (nprn /= 0) then
        do j=1,ndim
            write(*,202) j,(xi(i,j),di(i,j),&
                i=1+nprn/2,nd,nprn)
        end do
    end if
end if
do j=1,ndim
    xo=d(1,j)
    xn=d(2,j)
    d(1,j)=(xo+xn)/2.0_sp
    dt(j)=d(1,j)
    do i=2,nd-1
        rc=xo+xn
        xo=xn
        xn=d(i+1,j)
        d(i,j)=(rc+xn)/3.0_sp
        dt(j)=dt(j)+d(i,j)
    end do
    d(nd,j)=(xo+xn)/2.0_sp
    dt(j)=dt(j)+d(nd,j)
end do
where (d(1:nd,:) < TINY) d(1:nd,:)=TINY
do j=1,ndim

```

Use stratified sampling.

Compute final results for this iteration.

Refine the grid. Consult references to understand the subtlety of this procedure. The refinement is damped, to avoid rapid, destabilizing changes, and also compressed in range by the exponent ALPH.

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```

        r(1:nd)=((1.0_sp-d(1:nd,j)/dt(j))/(log(dt(j))-log(d(1:nd,j))))**ALPH
        rc=sum(r(1:nd))
        call rebin(rc/xnd,nd,r,xin,xi(:,j))
    end do
end do
200 format(/' input parameters for vegas: ndim=',i3,' ncall=',f8.0&
/28x,' it=',i5,' itmx=',i5&
/28x,' nprn=',i3,' alph=',f5.2/28x,' mds=',i3,' nd=',i4&
/(30x,'x1(',i2,')= ',g11.4,' xu(',i2,')= ',g11.4))
201 format(/' iteration no.',I3,': ',,'integral =',g14.7,' +/- ',g9.2,&
/' all iterations: integral =',g14.7,' +/- ',g9.2,&
' chi**2/it' 'n =',g9.2)
202 format(/' data for axis ',I2/' X delta i ',&
' x delta i ', ' x delta i ',&
/(1x,f7.5,1x,g11.4,5x,f7.5,1x,g11.4,5x,f7.5,1x,g11.4))
CONTAINS
SUBROUTINE rebin(rc,nd,r,xin,xi)
IMPLICIT NONE
REAL(SP), INTENT(IN) :: rc
INTEGER(I4B), INTENT(IN) :: nd
REAL(SP), DIMENSION(:), INTENT(IN) :: r
REAL(SP), DIMENSION(:), INTENT(OUT) :: xin
REAL(SP), DIMENSION(:), INTENT(INOUT) :: xi
    Utility routine used by vegas, to rebin a vector of densities xi into new bins defined by
    a vector r.
INTEGER(I4B) :: i,k
REAL(SP) :: dr,xn,xo
k=0
xo=0.0
dr=0.0
do i=1,nd-1
    do
        if (rc <= dr) exit
        k=k+1
        dr=dr+r(k)
    end do
    if (k > 1) xo=xi(k-1)
    xn=xi(k)
    dr=dr-rc
    xin(i)=xn-(xn-xo)*dr/r(k)
end do
xi(1:nd-1)=xin(1:nd-1)
xi(nd)=1.0
END SUBROUTINE rebin
END SUBROUTINE vegas

```

\* \* \*

```

RECURSIVE SUBROUTINE miser(func,regn,ndim,npts,dith,ave,var)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
INTERFACE
    FUNCTION func(x)
        USE nrtype
        IMPLICIT NONE
        REAL(SP) :: func
        REAL(SP), DIMENSION(:), INTENT(IN) :: x
    END FUNCTION func
END INTERFACE
REAL(SP), DIMENSION(:), INTENT(IN) :: regn
INTEGER(I4B), INTENT(IN) :: ndim,npts

```

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```

REAL(SP), INTENT(IN) :: dith
REAL(SP), INTENT(OUT) :: ave,var
REAL(SP), PARAMETER :: PFAC=0.1_sp,TINY=1.0e-30_sp,BIG=1.0e30_sp
INTEGER(I4B), PARAMETER :: MNPT=15,MNBS=60
  Monte Carlo samples a user-supplied ndim-dimensional function func in a rectangular
  volume specified by region, a 2×ndim vector consisting of ndim "lower-left" coordinates
  of the region followed by ndim "upper-right" coordinates. The function is sampled a total
  of npts times, at locations determined by the method of recursive stratified sampling. The
  mean value of the function in the region is returned as ave; an estimate of the statistical
  uncertainty of ave (square of standard deviation) is returned as var. The input parameter
  dith should normally be set to zero, but can be set to (e.g.) 0.1 if func's active region
  falls on the boundary of a power-of-2 subdivision of region.
  Parameters: PFAC is the fraction of remaining function evaluations used at each stage to
  explore the variance of func. At least MNPT function evaluations are performed in any
  terminal subregion; a subregion is further bisected only if at least MNBS function evaluations
  are available.
REAL(SP), DIMENSION(:), ALLOCATABLE :: regn_temp
INTEGER(I4B) :: j,jb,n,ndum,npre,nptl,nptr
INTEGER(I4B), SAVE :: iran=0
REAL(SP) :: avel,varl,frac1,fval,rgl,rgm,rgr,&
  s,sigl,siglb,sigr,sigrb,sm,sm2,subm,sumr
REAL(SP), DIMENSION(:), ALLOCATABLE :: fmaxl,fmaxr,fminl,fminr,pt,rmid
ndum=assert_eq(size(regn),2*ndim,'miser')
allocate(pt(ndim))
if (npts < MNBS) then
  Too few points to bisect; do straight Monte
  sm=0.0
  sm2=0.0
  do n=1,npts
    call ranpt(pt,regn)
    fval=func(pt)
    sm=sm+fval
    sm2=sm2+fval**2
  end do
  ave=sm/npts
  var=max(TINY,(sm2-sm**2/npts)/npts**2)
else
  Do the preliminary (uniform) sampling.
  npre=max(int(npts*PFAC),MNPT)
  allocate(rmid(ndim),fmaxl(ndim),fmaxr(ndim),fminl(ndim),fminr(ndim))
  fminl(:)=BIG
  fminr(:)=BIG
  fmaxl(:)=-BIG
  fmaxr(:)=-BIG
  do j=1,ndim
    iran=mod(iran*2661+36979,175000)
    s=sign(dith,real(iran-87500,sp))
    rmid(j)=(0.5_sp+s)*regn(j)+(0.5_sp-s)*regn(ndim+j)
  end do
  do n=1,npre
    Loop over the points in the sample.
    call ranpt(pt,regn)
    fval=func(pt)
    where (pt <= rmid)
      Find the left and right bounds for each di-
      fminl=min(fminl,fval)
      fmaxl=max(fmaxl,fval)
      mension.
    elsewhere
      fminr=min(fminr,fval)
      fmaxr=max(fmaxr,fval)
    end where
  end do
  Choose which dimension jb to bisect.
  subm=BIG
  jb=0
  siglb=1.0
  sigrb=1.0
  do j=1,ndim
    if (fmaxl(j) > fminl(j) .and. fmaxr(j) > fminr(j)) then

```

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```

sigl=max(TINY,(fmaxl(j)-fminl(j))*(2.0_sp/3.0_sp))
sigr=max(TINY,(fmaxr(j)-fminr(j))*(2.0_sp/3.0_sp))
sumr=sigl+sigr      Equation (7.8.24); see text.
if (sumr <= sumb) then
    sumb=sumr
    jb=j
    siglb=sigl
    sigrb=sigr
end if
end if
end do
deallocate(fminr,fminl,fmaxr,fmaxl)
if (jb == 0) jb=1+(ndim*iran)/175000      MNPT may be too small.
rgl=regn(jb)      Apportion the remaining points between left
rgm=rmid(jb)      and right.
rgr=regn(ndim+jb)
fracl=abs((rgm-rgl)/(rgr-rgl))
nptl=(MNPT+(npts-npre-2*MNPT)*fracl*siglb/ &      Equation (7.8.23).
      (fracl*siglb+(1.0_sp-fracl)*sigrb))
nptr=npts-npre-nptl
allocate(regn_temp(2*ndim))
regn_temp(:)=regn(:)
regn_temp(ndim+jb)=rmid(jb)      Set region to left.
call miser(func,regn_temp,ndim,nptl,dith,avel,varl)
    Dispatch recursive call; will return back here eventually.
regn_temp(jb)=rmid(jb)
regn_temp(ndim+jb)=regndim+jb)      Set region to right.
call miser(func,regn_temp,ndim,nptr,dith,ave,var)
    Dispatch recursive call; will return back here eventually.
deallocate(regn_temp)
ave=fracl*avel+(1-fracl)*ave      Combine left and right regions by equation
var=fracl*fracl*varl+(1-fracl)*(1-fracl)*var      (7.8.11) (1st line).
deallocate(rmid)
end if
deallocate(pt)
CONTAINS
SUBROUTINE ranpt(pt,region)
USE nr, ONLY : ran1
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(OUT) :: pt
REAL(SP), DIMENSION(:), INTENT(IN) :: region
    Returns a uniformly random point pt in a rectangular region of dimension d. Used by
    miser; calls ran1 for uniform deviates.
INTEGER(I4B) :: n
call ran1(pt)
n=size(pt)
pt(1:n)=region(1:n)+(region(n+1:2*n)-region(1:n))*pt(1:n)
END SUBROUTINE ranpt
END SUBROUTINE miser

```

**f90** The Fortran 90 version of this routine is much more straightforward than the Fortran 77 version, because Fortran 90 allows recursion. (In fact, this routine is modeled on the C version of `miser`, which was recursive from the start.)

#### CITED REFERENCES AND FURTHER READING:

- Marsaglia, G., and Zaman, A. 1994, *Computers in Physics*, vol. 8, pp. 117–121. [1]  
Marsaglia, G. 1985, *Linear Algebra and Its Applications*, vol. 67, pp. 147–156. [2]  
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## Chapter B8.    Sorting



Caution! If you are expecting to sort efficiently on a parallel machine, whether its parallelism is small-scale or massive, you almost certainly want to use library routines that are specific to your hardware.

We include in this chapter translations into Fortran 90 of the general purpose *serial* sorting routines that are in Volume 1, augmented by several new routines that give pedagogical demonstrations of how parallel sorts can be achieved with Fortran 90 parallel constructions and intrinsics. However, we intend the above word “pedagogical” to be taken seriously: these new, supposedly parallel, routines are *not* likely to be competitive with machine-specific library routines. Neither do they compete successfully on serial machines with the all-serial routines provided (namely `sort`, `sort2`, `sort3`, `indexx`, and `select`).

\*    \*    \*

```
SUBROUTINE sort_pick(arr)
USE nrtype
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
  Sorts an array arr into ascending numerical order, by straight insertion. arr is replaced
  on output by its sorted rearrangement.
INTEGER(I4B) :: i,j,n
REAL(SP) :: a
n=size(arr)
do j=2,n
  a=arr(j)
  do i=j-1,1,-1
    if (arr(i) <= a) exit
    arr(i+1)=arr(i)
  end do
  arr(i+1)=a
end do
END SUBROUTINE sort_pick
```

Not only is `sort_pick` (renamed from Volume 1’s `piksrt`) *not parallelizable*, but also, even worse, it is an  $N^2$  routine. It is meant to be invoked only for the most trivial sorting jobs, say,  $N < 20$ .

\*    \*    \*

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```

SUBROUTINE sort_shell(arr)
USE nrtype
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
    Sorts an array arr into ascending numerical order by Shell's method (diminishing increment
    sort). arr is replaced on output by its sorted rearrangement.
INTEGER(I4B) :: i,j,inc,n
REAL(SP) :: v
n=size(arr)
inc=1
do
    Determine the starting increment.
    inc=3*inc+1
    if (inc > n) exit
end do
do
    Loop over the partial sorts.
    inc=inc/3
    do i=inc+1,n
        Outer loop of straight insertion.
        v=arr(i)
        j=i
        do
            Inner loop of straight insertion.
            if (arr(j-inc) <= v) exit
            arr(j)=arr(j-inc)
            j=j-inc
            if (j <= inc) exit
        end do
        arr(j)=v
    end do
    if (inc <= 1) exit
end do
END SUBROUTINE sort_shell

```

The routine `sort_shell` is renamed from Volume 1's `shell`. Shell's Method, a diminishing increment sort, is not directly parallelizable. However, one can write a fully parallel routine (though not an especially fast one — see remarks at beginning of this chapter) in much the same spirit:

```

SUBROUTINE sort_byreshape(arr)
USE nrtype; USE nrutil, ONLY : swap
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
    Sort an array arr by bubble sorting a succession of reshapes into array slices. The method
    is similar to Shell sort, but allows parallelization within the vectorized masked swap calls.
REAL(SP), DIMENSION(:, :), ALLOCATABLE :: tab
REAL(SP), PARAMETER :: big=huge(arr)
INTEGER(I4B) :: inc,n,m
n=size(arr)
inc=1
do
    Find the largest increment that fits.
    inc=2*inc+1
    if (inc > n) exit
end do
do
    Loop over the different shapes for the reshaped
    array.
    inc=inc/2
    m=(n+inc-1)/inc
    allocate(tab(inc,m))
    Allocate space and reshape the array. big en-
    tab=reshape(arr, (/inc,m/), (/big/))
    sures that fill elements stay at the
    do
        Bubble sort all the rows in parallel.
        call swap(tab(:,1:m-1:2),tab(:,2:m:2), &
            tab(:,1:m-1:2)>tab(:,2:m:2))
        call swap(tab(:,2:m-1:2),tab(:,3:m:2), &
            tab(:,2:m-1:2)>tab(:,3:m:2))
    end do
end do

```

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```

        if (all(tab(:,1:m-1) <= tab(:,2:m))) exit
    end do
    arr=reshape(tab,shape(arr))      Put the array back together for the next shape.
    deallocate(tab)
    if (inc <= 1) exit
end do
END SUBROUTINE sort_byreshape

```



The basic idea is to reshape the given one-dimensional array into a succession of two-dimensional arrays, starting with “tall and narrow” (many rows, few columns), and ending up with “short and wide” (many columns, few rows). At each stage we sort all the rows in parallel by a bubble sort, giving something close to Shell’s diminishing increments.

\* \* \*

We now arrive at those routines, based on the Quicksort algorithm, that we actually intend for use with general  $N$  on serial machines:

```

SUBROUTINE sort(arr)
USE nrtype; USE nrutil, ONLY : swap,nrerror
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
INTEGER(I4B), PARAMETER :: NN=15, NSTACK=50
    Sorts an array arr into ascending numerical order using the Quicksort algorithm. arr is
    replaced on output by its sorted rearrangement.
    Parameters: NN is the size of subarrays sorted by straight insertion and NSTACK is the
    required auxiliary storage.
REAL(SP) :: a
INTEGER(I4B) :: n,k,i,j,jstack,l,r
INTEGER(I4B), DIMENSION(NSTACK) :: istack
n=size(arr)
jstack=0
l=1
r=n
do
    if (r-l < NN) then                Insertion sort when subarray small enough.
        do j=l+1,r
            a=arr(j)
            do i=j-1,l,-1
                if (arr(i) <= a) exit
                arr(i+1)=arr(i)
            end do
            arr(i+1)=a
        end do
        if (jstack == 0) RETURN
        r=istack(jstack)              Pop stack and begin a new round of partition-
        l=istack(jstack-1)            ing.
        jstack=jstack-2
    else                               Choose median of left, center, and right elements
        k=(l+r)/2                      as partitioning element a. Also rearrange so
        call swap(arr(k),arr(l+1))      that  $a(l) \leq a(l+1) \leq a(r)$ .
        call swap(arr(l),arr(r),arr(l)>arr(r))
        call swap(arr(l+1),arr(r),arr(l+1)>arr(r))
        call swap(arr(l),arr(l+1),arr(l)>arr(l+1))
        i=l+1                          Initialize pointers for partitioning.
        j=r
        a=arr(l+1)                      Partitioning element.
        do                               Here is the meat.
            do                          Scan up to find element  $\geq a$ .
                i=i+1
            end do
        end do
    end do
end do

```

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```

        if (arr(i) >= a) exit
    end do
    do
        Scan down to find element <= a.
        j=j-1
        if (arr(j) <= a) exit
    end do
    if (j < i) exit
    call swap(arr(i),arr(j))
        Pointers crossed. Exit with partitioning complete.
        Exchange elements.
    end do
    arr(l+1)=arr(j)
        Insert partitioning element.
    arr(j)=a
    jstack=jstack+2
    Push pointers to larger subarray on stack; process smaller subarray immediately.
    if (jstack > NSTACK) call nrerror('sort: NSTACK too small')
    if (r-i+1 >= j-1) then
        istack(jstack)=r
        istack(jstack-1)=i
        r=j-1
    else
        istack(jstack)=j-1
        istack(jstack-1)=l
        l=i
    end if
end if
end do
END SUBROUTINE sort

```

**f90** call swap(...) ... call swap(...) One might think twice about putting all these external function calls (to nrutil routines) in the inner loop of something as streamlined as a sort routine, but here they are executed only once for each partitioning.


call swap(arr(i),arr(j)) This call *is* in a loop, but not the innermost loop. Most modern machines are very fast at the “context changes” implied by subroutine calls and returns; but in a time-critical context you might code this swap in-line and see if there is any timing difference.

```

SUBROUTINE sort2(arr,slave)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : indexx
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr,slave
    Sorts an array arr into ascending order using Quicksort, while making the corresponding
    rearrangement of the same-size array slave. The sorting and rearrangement are performed
    by means of an index array.
INTEGER(I4B) :: ndum
INTEGER(I4B), DIMENSION(size(arr)) :: index
ndum=assert_eq(size(arr),size(slave),'sort2')
call indexx(arr,index)
    Make the index array.
arr=arr(index)
    Sort arr.
slave=slave(index)
    Rearrange slave.
END SUBROUTINE sort2

```

\* \* \*

 A close surrogate for the Quicksort partition-exchange algorithm can be coded, parallelizable, by using Fortran 90's pack intrinsic. On real compilers, unfortunately, the resulting code is not very efficient as compared with (on serial machines) the tightness of sort's inner loop, above, or (on parallel machines) supplied library sort routines. We illustrate the principle nevertheless in the following routine.

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```

RECURSIVE SUBROUTINE sort_bypack(arr)
USE nrtype; USE nrutil, ONLY : array_copy,swap
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
    Sort an array arr by recursively applying the Fortran 90 pack intrinsic. The method is
    similar to Quicksort, but this variant allows parallelization by the Fortran 90 compiler.
REAL(SP) :: a
INTEGER(I4B) :: n,k,nl,nerr
INTEGER(I4B), SAVE :: level=0
LOGICAL, DIMENSION(:), ALLOCATABLE, SAVE :: mask
REAL(SP), DIMENSION(:), ALLOCATABLE, SAVE :: temp
n=size(arr)
if (n <= 1) RETURN
k=(1+n)/2
call swap(arr(1),arr(k),arr(1)>arr(k))      Pivot element is median of first, middle,
call swap(arr(k),arr(n),arr(k)>arr(n))      and last.
call swap(arr(1),arr(k),arr(1)>arr(k))
if (n <= 3) RETURN
level=level+1                               Keep track of recursion level to avoid al-
if (level == 1) allocate(mask(n),temp(n))   location overhead.
a=arr(k)
mask(1:n) = (arr <= a)                       Which elements move to left?
mask(k) = .false.
call array_copy(pack(arr,mask(1:n)),temp,nl,nerr)  Move them.
mask(k) = .true.
temp(nl+2:n)=pack(arr,.not. mask(1:n))       Move others to right.
temp(nl+1)=a
arr=temp(1:n)
call sort_bypack(arr(1:nl))                  And recurse.
call sort_bypack(arr(nl+2:n))
if (level == 1) deallocate(mask,temp)
level=level-1
END SUBROUTINE sort_bypack

```

\* \* \*

The following routine, `sort_heap`, is renamed from Volume 1's `hpsort`.

```

SUBROUTINE sort_heap(arr)
USE nrtype
USE nrutil, ONLY : swap
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
    Sorts an array arr into ascending numerical order using the Heapsort algorithm. arr is
    replaced on output by its sorted rearrangement.
INTEGER(I4B) :: i,n
n=size(arr)
do i=n/2,1,-1
    The index i, which here determines the "left" range of the sift-down, i.e., the element to
    be sifted down, is decremented from n/2 down to 1 during the "hiring" (heap creation)
    phase.
    call sift_down(i,n)
end do
do i=n,2,-1
    Here the "right" range of the sift-down is decremented from n-1 down to 1 during the
    "retirement-and-promotion" (heap selection) phase.
    call swap(arr(1),arr(i))                Clear a space at the end of the array, and
    call sift_down(1,i-1)                   retire the top of the heap into it.
end do
CONTAINS
SUBROUTINE sift_down(l,r)
INTEGER(I4B), INTENT(IN) :: l,r

```

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```

    Carry out the sift-down on element arr(1) to maintain the heap structure.
INTEGER(I4B) :: j,jold
REAL(SP) :: a
a=arr(1)
jold=1
j=1+1
do
    "Do while j <= r:"
    if (j > r) exit
    if (j < r) then
        if (arr(j) < arr(j+1)) j=j+1    Compare to the better underling.
    end if
    if (a >= arr(j)) exit              Found a's level. Terminate the sift-down. Otherwise, demote a and continue.
    arr(jold)=arr(j)
    jold=j
    j=j+j
end do
arr(jold)=a                          Put a into its slot.
END SUBROUTINE sift_down
END SUBROUTINE sort_heap

```

\* \* \*

Another opportunity provided by Fortran 90 for a fully parallelizable sort, at least pedagogically, is to use the language's allowed access to the actual floating-point representation and to code a radix sort [1] on its bits. This is *not* efficient, but it illustrates some Fortran 90 language features perhaps worthy of study for other applications.

```

SUBROUTINE sort_radix(arr)
USE nrtype; USE nrutil, ONLY : array_copy,nrerror
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
    Sort an array arr by radix sort on its bits.
INTEGER(I4B), DIMENSION(size(arr)) :: narr,temp
LOGICAL, DIMENSION(size(arr)) :: msk
INTEGER(I4B) :: k,negm,ib,ia,n,nl,nerr
    Because we are going to transfer reals to integers, we must check that the number of bits
    is the same in each:
ib=bit_size(narr)
ia=ceiling(log(real(maxexponent(arr)-minexponent(arr),sp))/log(2.0_sp)) &
    + digits(arr)
if (ib /= ia) call nrerror('sort_radix: bit sizes not compatible')
negm=not(ishftc(1,-1))                Mask for all bits except sign bit.
n=size(arr)
narr=transfer(arr,narr,n)
where (btest(narr,ib-1)) narr=ieor(narr,negm)    Flip all bits on neg. numbers.
do k=0,ib-2
    Work from low- to high-order bits, and partition the array according to the value of the
    bit.
    msk=btest(narr,k)
    call array_copy(pack(narr,.not. msk),temp,nl,nerr)
    temp(nl+1:n)=pack(narr,msk)
    narr=temp
end do
msk=btest(narr,ib-1)                  The sign bit gets separate treatment, since here 1 comes before 0.
call array_copy(pack(narr,msk),temp,nl,nerr)
temp(nl+1:n)=pack(narr,.not. msk)
narr=temp
where (btest(narr,ib-1)) narr=ieor(narr,negm)    Unflip all bits on neg. numbers.
arr=transfer(narr,arr,n)
END SUBROUTINE sort_radix

```

\* \* \*

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We overload the generic name `indexx` with two specific implementations, one for SP floating values, the other for I4B integers. (You can of course add more overloadings if you need them.)

```

SUBROUTINE indexx_sp(arr,index)
USE nrtype; USE nrutil, ONLY : arth,assert_eq,nrerror,swap
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: arr
INTEGER(I4B), DIMENSION(:), INTENT(OUT) :: index
INTEGER(I4B), PARAMETER :: NN=15, NSTACK=50
    Indexes an array arr, i.e., outputs the array index of length N such that arr(index(j))
    is in ascending order for j = 1,2,...,N. The input quantity arr is not changed.
REAL(SP) :: a
INTEGER(I4B) :: n,k,i,j,indext,jstack,l,r
INTEGER(I4B), DIMENSION(NSTACK) :: istack
n=assert_eq(size(index),size(arr),'indexx_sp')
index=arth(1,1,n)
jstack=0
l=1
r=n
do
    if (r-l < NN) then
        do j=l+1,r
            indext=index(j)
            a=arr(indext)
            do i=j-1,l,-1
                if (arr(index(i)) <= a) exit
                index(i+1)=index(i)
            end do
            index(i+1)=indext
        end do
        if (jstack == 0) RETURN
        r=istack(jstack)
        l=istack(jstack-1)
        jstack=jstack-2
    else
        k=(l+r)/2
        call swap(index(k),index(l+1))
        call icomp_xchg(index(l),index(r))
        call icomp_xchg(index(l+1),index(r))
        call icomp_xchg(index(l),index(l+1))
        i=l+1
        j=r
        indext=index(l+1)
        a=arr(indext)
        do
            do
                i=i+1
                if (arr(index(i)) >= a) exit
            end do
            do
                j=j-1
                if (arr(index(j)) <= a) exit
            end do
            if (j < i) exit
            call swap(index(i),index(j))
        end do
        index(l+1)=index(j)
        index(j)=indext
        jstack=jstack+2
        if (jstack > NSTACK) call nrerror('indexx: NSTACK too small')
        if (r-i+1 >= j-1) then
            istack(jstack)=r
        end if
    end if
end do

```

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```

        istack(jstack-1)=i
        r=j-1
    else
        istack(jstack)=j-1
        istack(jstack-1)=l
        l=i
    end if
end if
end do
CONTAINS
SUBROUTINE icomp_xchg(i,j)
INTEGER(I4B), INTENT(INOUT) :: i,j
INTEGER(I4B) :: swp
if (arr(j) < arr(i)) then
    swp=i
    i=j
    j=swp
end if
END SUBROUTINE icomp_xchg
END SUBROUTINE indexx_sp

SUBROUTINE indexx_i4b(iarr,index)
USE nrtype; USE nrutil, ONLY : arth,assert_eq,nrerror,swap
IMPLICIT NONE
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: iarr
INTEGER(I4B), DIMENSION(:), INTENT(OUT) :: index
INTEGER(I4B), PARAMETER :: NN=15, NSTACK=50
INTEGER(I4B) :: a
INTEGER(I4B) :: n,k,i,j,indext,jstack,l,r
INTEGER(I4B), DIMENSION(NSTACK) :: istack
n=assert_eq(size(index),size(iarr),'indexx_sp')
index=arth(1,1,n)
jstack=0
l=1
r=n
do
    if (r-l < NN) then
        do j=l+1,r
            indext=index(j)
            a=iarr(indext)
            do i=j-1,1,-1
                if (iarr(index(i)) <= a) exit
                index(i+1)=index(i)
            end do
            index(i+1)=indext
        end do
        if (jstack == 0) RETURN
        r=istack(jstack)
        l=istack(jstack-1)
        jstack=jstack-2
    else
        k=(l+r)/2
        call swap(index(k),index(l+1))
        call icomp_xchg(index(l),index(r))
        call icomp_xchg(index(l+1),index(r))
        call icomp_xchg(index(l),index(l+1))
        i=l+1
        j=r
        indext=index(l+1)
        a=iarr(indext)
        do
            do

```

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```

        i=i+1
        if (iarr(index(i)) >= a) exit
    end do
    do
        j=j-1
        if (iarr(index(j)) <= a) exit
    end do
    if (j < i) exit
    call swap(index(i),index(j))
end do
index(l+1)=index(j)
index(j)=index(l)
jstack=jstack+2
if (jstack > NSTACK) call nrerror('indexx: NSTACK too small')
if (r-i+1 >= j-1) then
    istack(jstack)=r
    istack(jstack-1)=i
    r=j-1
else
    istack(jstack)=j-1
    istack(jstack-1)=l
    l=i
end if
end if
end do
CONTAINS
SUBROUTINE icoomp_xchg(i,j)
INTEGER(I4B), INTENT(INOUT) :: i,j
INTEGER(I4B) :: swp
if (iarr(j) < iarr(i)) then
    swp=i
    i=j
    j=swp
end if
END SUBROUTINE icoomp_xchg
END SUBROUTINE indexx_i4b

```

\* \* \*

```

SUBROUTINE sort3(arr,slave1,slave2)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : indexx
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr,slave1,slave2
    Sorts an array arr into ascending order using Quicksort, while making the corresponding
    rearrangement of the same-size arrays slave1 and slave2. The sorting and rearrangement
    are performed by means of an index array.
INTEGER(I4B) :: ndum
INTEGER(I4B), DIMENSION(size(arr)) :: index
ndum=assert_eq(size(arr),size(slave1),size(slave2),'sort3')
call indexx(arr,index)      Make the index array.
arr=arr(index)             Sort arr.
slave1=slave1(index)       Rearrange slave1,
slave2=slave2(index)       and slave2.
END SUBROUTINE sort3

```

\* \* \*

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```

FUNCTION rank(index)
USE nrtype; USE nrutil, ONLY : arth
IMPLICIT NONE
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: index
INTEGER(I4B), DIMENSION(size(index)) :: rank
  Given index as output from the routine indexx, this routine returns a same-size array
  rank, the corresponding table of ranks.
rank(index(:))=arth(1,1,size(index))
END FUNCTION rank

```

\* \* \*



Just as in the case of `sort`, where an approximation of the underlying Quicksort partition-exchange algorithm can be captured with the Fortran 90 pack intrinsic, the same can be done with `indexx`. As before, although it is in principle parallelizable by the compiler, it is likely not competitive with library routines.

```

RECURSIVE SUBROUTINE index_bypack(arr,index,partial)
USE nrtype; USE nrutil, ONLY : array_copy,arth,assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: arr
INTEGER(I4B), DIMENSION(:), INTENT(INOUT) :: index
INTEGER, OPTIONAL, INTENT(IN) :: partial
  Indexes an array arr, i.e., outputs the array index of length N such that arr(index(j))
  is in ascending order for j = 1,2,...,N. The method is to apply recursively the Fortran
  90 pack intrinsic. This is similar to Quicksort, but allows parallelization by the Fortran 90
  compiler. partial is an optional argument that is used only internally on the recursive calls.
REAL(SP) :: a
INTEGER(I4B) :: n,k,nl,indx,nerr
INTEGER(I4B), SAVE :: level=0
LOGICAL, DIMENSION(:), ALLOCATABLE, SAVE :: mask
INTEGER(I4B), DIMENSION(:), ALLOCATABLE, SAVE :: temp
if (present(partial)) then
  n=size(index)
else
  n=assert_eq(size(index),size(arr),'indexx_bypack')
  indx=arth(1,1,n)
end if
if (n <= 1) RETURN
k=(1+n)/2
call icomp_xchg(index(1),index(k))      Pivot element is median of first, mid-
call icomp_xchg(index(k),index(n))      dle, and last.
call icomp_xchg(index(1),index(k))
if (n <= 3) RETURN
level=level+1
if (level == 1) allocate(mask(n),temp(n))  Keep track of recursion level to avoid
indx=indx(k)                               allocation overhead.
a=arr(indx)
mask(1:n) = (arr(index) <= a)             Which elements move to left?
mask(k) = .false.
call array_copy(pack(index,mask(1:n)),temp,nl,nerr)  Move them.
mask(k) = .true.
temp(nl+2:n)=pack(index,.not. mask(1:n))  Move others to right.
temp(nl+1)=indx
indx=temp(1:n)
call index_bypack(arr,index(1:nl),partial=1)  And recurse.
call index_bypack(arr,index(nl+2:n),partial=1)
if (level == 1) deallocate(mask,temp)
level=level-1

```

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CONTAINS

```

SUBROUTINE icomp_xchg(i,j)
IMPLICIT NONE
INTEGER(I4B), INTENT(INOUT) :: i,j
  Swap or don't swap integer arguments, depending on the ordering of their corresponding
  elements in an array arr.
INTEGER(I4B) :: swp
if (arr(j) < arr(i)) then
  swp=i
  i=j
  j=swp
end if
END SUBROUTINE icomp_xchg
END SUBROUTINE index_bypack

```

\* \* \*

```

FUNCTION select(k,arr)
USE nrtype; USE nrutil, ONLY : assert,swap
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: k
REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
REAL(SP) :: select
  Returns the kth smallest value in the array arr. The input array will be rearranged to have
  this value in location arr(k), with all smaller elements moved to arr(1:k-1) (in arbitrary
  order) and all larger elements in arr(k+1:) (also in arbitrary order).
INTEGER(I4B) :: i,r,j,l,n
REAL(SP) :: a
n=size(arr)
call assert(k >= 1, k <= n, 'select args')
l=1
r=n
do
  if (r-l <= 1) then
    Active partition contains 1 or 2 elements.
    if (r-l == 1) call swap(arr(l),arr(r),arr(l)>arr(r)) Active partition con-
    select=arr(k) tains 2 elements.
    RETURN
  else
    Choose median of left, center, and right elements
    i=(l+r)/2 as partitioning element a. Also rearrange so
    call swap(arr(i),arr(l+1)) that arr(l) ≤ arr(l+1) ≤ arr(r).
    call swap(arr(l),arr(r),arr(l)>arr(r))
    call swap(arr(l+1),arr(r),arr(l+1)>arr(r))
    call swap(arr(l),arr(l+1),arr(l)>arr(l+1))
    i=l+1 Initialize pointers for partitioning.
    j=r
    a=arr(l+1) Partitioning element.
    do Here is the meat.
      do Scan up to find element > a.
        i=i+1
        if (arr(i) >= a) exit
      end do
      do Scan down to find element < a.
        j=j-1
        if (arr(j) <= a) exit
      end do
      if (j < i) exit Pointers crossed. Exit with partitioning complete.
      call swap(arr(i),arr(j)) Exchange elements.
    end do
    arr(l+1)=arr(j) Insert partitioning element.
    arr(j)=a
    if (j >= k) r=j-1 Keep active the partition that contains the kth
    element.
  end do
end do

```

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```

        if (j <= k) l=i
    end if
end do
END FUNCTION select

```

\* \* \*

The following routine, `select_inplace`, is renamed from Volume 1's `selip`.

```

FUNCTION select_inplace(k,arr)
USE nrtype
USE nr, ONLY : select
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: k
REAL(SP), DIMENSION(:), INTENT(IN) :: arr
REAL(SP) :: select_inplace
    Returns the kth smallest value in the array arr, without altering the input array. In Fortran
    90's assumed memory-rich environment, we just call select in scratch space.
REAL(SP), DIMENSION(size(arr)) :: tarr
tarr=arr
select_inplace=select(k,tarr)
END FUNCTION select_inplace

```

**F**90 Volume 1's `selip` routine uses an entirely different algorithm, for the purpose of avoiding any additional memory allocation beyond that of the input array. Fortran 90 presumes a richer memory environment, so `select_inplace` simply does the obvious (destructive) selection in scratch space. You can of course use the old `selip` if your in-core or in-cache memory is at a premium.

```

FUNCTION select_bypack(k,arr)
USE nrtype; USE nrutil, ONLY : array_copy,assert,swap
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: k
REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
REAL(SP) :: select_bypack
    Returns the kth smallest value in the array arr. The input array will be rearranged to have
    this value in location arr(k), with all smaller elements moved to arr(1:k-1) (in arbitrary
    order) and all larger elements in arr(k+1:) (also in arbitrary order). This implementation
    allows parallelization in the Fortran 90 pack intrinsic.
LOGICAL, DIMENSION(size(arr)) :: mask
REAL(SP), DIMENSION(size(arr)) :: temp
INTEGER(I4B) :: i,r,j,l,n,nl,nerr
REAL(SP) :: a
n=size(arr)
call assert(k >= 1, k <= n, 'select_bypack args')
l=1
r=n
do
    if (r-l <= 1) exit
    i=(l+r)/2
    call swap(arr(l),arr(i),arr(l)>arr(i))
    call swap(arr(i),arr(r),arr(i)>arr(r))
    call swap(arr(l),arr(i),arr(l)>arr(i))
    a=arr(i)
    mask(1:r) = (arr(1:r) <= a)
    mask(i) = .false.
    call array_copy(pack(arr(1:r),mask(1:r)),temp(1:),nl,nerr)
    j=l+nl

```

Initial left and right bounds.

Keep partitioning until desired element is found.

Pivot element is median of first, middle, and last.

Which elements move to left?

Move them.

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```

mask(i) = .true.
temp(j+1:r)=pack(arr(1:r),.not. mask(1:r))      Move others to right.
temp(j)=a
arr(1:r)=temp(1:r)
if (k > j) then                                Reset bounds to whichever side
    l=j+1                                       has the desired element.
else if (k < j) then
    r=j-1
else
    l=j
    r=j
end if
end do
if (r-1 == 1) call swap(arr(1),arr(r),arr(1)>arr(r))  Case of only two left.
select_bypack=arr(k)
END FUNCTION select_bypack

```



The above routine `select_bypack` is parallelizable, but as discussed above (`sort_bypack`, `index_bypack`) it is generally not very efficient.

\* \* \*

The following routine, `select_heap`, is renamed from Volume 1's `hpsel`.

```

SUBROUTINE select_heap(arr,heap)
USE nrtype; USE nrutil, ONLY : nrerror,swap
USE nr, ONLY : sort
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: arr
REAL(SP), DIMENSION(:), INTENT(OUT) :: heap
  Returns in heap, an array of length M, the largest M elements of the array arr of length
  N, with heap(1) guaranteed to be the the Mth largest element. The array arr is not
  altered. For efficiency, this routine should be used only when M ≪ N.
INTEGER(I4B) :: i,j,k,m,n
m=size(heap)
n=size(arr)
if (m > n/2 .or. m < 1) call nrerror('probable misuse of select_heap')
heap=arr(1:m)
call sort(heap)                                Create initial heap by overkill! We assume m ≪ n.
do i=m+1,n                                     For each remaining element...
  if (arr(i) > heap(1)) then                    Put it on the heap?
    heap(1)=arr(i)
    j=1
    do                                          Sift down.
      k=2*j
      if (k > m) exit
      if (k /= m) then
        if (heap(k) > heap(k+1)) k=k+1
      end if
      if (heap(j) <= heap(k)) exit
      call swap(heap(k),heap(j))
      j=k
    end do
  end if
end do
END SUBROUTINE select_heap

```

\* \* \*

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```

FUNCTION eclass(lista,listb,n)
USE nrtype; USE nrutil, ONLY : arth,assert_eq
IMPLICIT NONE
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: lista,listb
INTEGER(I4B), INTENT(IN) :: n
INTEGER(I4B), DIMENSION(n) :: eclass
  Given  $M$  equivalences between pairs of  $n$  individual elements in the form of the input arrays
  lista and listb of length  $M$ , this routine returns in an array of length  $n$  the number
  of the equivalence class of each of the  $n$  elements, integers between 1 and  $n$  (not all such
  integers used).
INTEGER :: j,k,l,m
m=assert_eq(size(lista),size(listb),'eclass')
eclass(1:n)=arth(1,1,n)      Initialize each element its own class.
do l=1,m                    For each piece of input information...
  j=lista(l)
  do                        Track first element up to its ancestor.
    if (eclass(j) == j) exit
    j=eclass(j)
  end do
  k=listb(l)
  do                        Track second element up to its ancestor.
    if (eclass(k) == k) exit
    k=eclass(k)
  end do
  if (j /= k) eclass(j)=k   If they are not already related, make them so.
end do
do j=1,n                    Final sweep up to highest ancestors.
  do
    if (eclass(j) == eclass(eclass(j))) exit
    eclass(j)=eclass(eclass(j))
  end do
end do
END FUNCTION eclass

FUNCTION eclazz(equiv,n)
USE nrtype; USE nrutil, ONLY : arth
IMPLICIT NONE
INTERFACE
  FUNCTION equiv(i,j)
  USE nrtype
  IMPLICIT NONE
  LOGICAL(LGT) :: equiv
  INTEGER(I4B), INTENT(IN) :: i,j
  END FUNCTION equiv
END INTERFACE
INTEGER(I4B), INTENT(IN) :: n
INTEGER(I4B), DIMENSION(n) :: eclazz
  Given a user-supplied logical function equiv that tells whether a pair of elements, each
  in the range 1..n, are related, return in an array of length n equivalence class numbers
  for each element.
INTEGER :: i,j
eclazz(1:n)=arth(1,1,n)
do i=2,n                    Loop over first element of all pairs.
  do j=1,i-1                Loop over second element of all pairs.
    eclazz(j)=eclazz(eclazz(j)) Sweep it up this much.
    if (equiv(i,j)) eclazz(eclazz(eclazz(j)))=i
    Good exercise for the reader to figure out why this much ancestry is necessary!
  end do
end do
do i=1,n                    Only this much sweeping is needed finally.
  eclazz(i)=eclazz(eclazz(i))
end do
END FUNCTION eclazz

```

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## Chapter B9. Root Finding and Nonlinear Sets of Equations

```

SUBROUTINE scrsho(func)
USE nrtype
IMPLICIT NONE
INTERFACE
  FUNCTION func(x)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: x
  REAL(SP) :: func
  END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: ISCR=60, JSCR=21
  For interactive "dumb terminal" use. Produce a crude graph of the function func over the
  prompted-for interval x1,x2. Query for another plot until the user signals satisfaction.
  Parameters: Number of horizontal and vertical positions in display.
INTEGER(I4B) :: i,j,jz
REAL(SP) :: dx,dyj,x,x1,x2,ybig,ysml
REAL(SP), DIMENSION(ISCR) :: y
CHARACTER(1), DIMENSION(ISCR, JSCR) :: scr
CHARACTER(1) :: blank=' ',zero='-',yy='1',xx='-',ff='x'
do
  write (*,*) ' Enter x1,x2 (= to stop)'          Query for another plot; quit if x1=x2.
  read (*,*) x1,x2
  if (x1 == x2) RETURN
  scr(1,1:JSCR)=yy                                Fill vertical sides with character '1'.
  scr(ISCR,1:JSCR)=yy
  scr(2:ISCR-1,1)=xx                              Fill top, bottom with character '-'.
  scr(2:ISCR-1, JSCR)=xx
  scr(2:ISCR-1,2:JSCR-1)=blank                    Fill interior with blanks.
  dx=(x2-x1)/(ISCR-1)
  x=x1
  do i=1,ISCR                                    Evaluate the function at equal intervals.
    y(i)=func(x)
    x=x+dx
  end do
  ysml=min(minval(y(:)),0.0_sp)                    Limits will include 0.
  ybig=max(maxval(y(:)),0.0_sp)
  if (ybig == ysml) ybig=ysml+1.0                 Be sure to separate top and bottom.
  dyj=(JSCR-1)/(ybig-ysml)
  jz=1-ysml*dyj                                   Note which row corresponds to 0.
  scr(1:ISCR, jz)=zero
  do i=1,ISCR                                    Place an indicator at function height and 0.
    j=1+(y(i)-ysml)*dyj
    scr(i,j)=ff
  end do
  write (*,'(1x,1p,e10.3,1x,80a1)') ybig,(scr(i,JSCR),i=1,ISCR)
  do j=JSCR-1,2,-1                               Display.
    write (*,'(12x,80a1)') (scr(i,j),i=1,ISCR)
  end do
  write (*,'(1x,1p,e10.3,1x,80a1)') ysml,(scr(i,1),i=1,ISCR)

```

```

write (*,'(12x,1p,e10.3,40x,e10.3)') x1,x2
end do
END SUBROUTINE scrsho

```

**f90** CHARACTER(1), DIMENSION(ISCR,JSCR) :: scr In Fortran 90, the length of variables of type character should be declared as CHARACTER(1) or CHARACTER(len=1) (for a variable of length 1), rather than the older form CHARACTER\*1. While the older form is still legal syntax, the newer one is more consistent with the syntax of other type declarations. (For variables of length 1, you can actually omit the length specifier entirely, and just say CHARACTER.)

\* \* \*

```

SUBROUTINE zbrac(func,x1,x2,succes)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(INOUT) :: x1,x2
LOGICAL(LGT), INTENT(OUT) :: succes
INTERFACE
  FUNCTION func(x)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: x
  REAL(SP) :: func
  END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: NTRY=50
REAL(SP), PARAMETER :: FACTOR=1.6_sp

```

Given a function func and an initial guessed range x1 to x2, the routine expands the range geometrically until a root is bracketed by the returned values x1 and x2 (in which case succes returns as .true.) or until the range becomes unacceptably large (in which case succes returns as .false.).

```

INTEGER(I4B) :: j
REAL(SP) :: f1,f2
if (x1 == x2) call nrerror('zbrac: you have to guess an initial range')
f1=func(x1)
f2=func(x2)
succes=.true.
do j=1,NTRY
  if ((f1 > 0.0 .and. f2 < 0.0) .or. &
      (f1 < 0.0 .and. f2 > 0.0)) RETURN
  if (abs(f1) < abs(f2)) then
    x1=x1+FACTOR*(x1-x2)
    f1=func(x1)
  else
    x2=x2+FACTOR*(x2-x1)
    f2=func(x2)
  end if
end do
succes=.false.
END SUBROUTINE zbrac

```

\* \* \*

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```

SUBROUTINE zbrak(func,x1,x2,n,xb1,xb2,nb)
USE nrtype; USE nrutil, ONLY : arth
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
INTEGER(I4B), INTENT(OUT) :: nb
REAL(SP), INTENT(IN) :: x1,x2
REAL(SP), DIMENSION(:), POINTER :: xb1,xb2
INTERFACE
  FUNCTION func(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: func
  END FUNCTION func
END INTERFACE
Given a function func defined on the interval from x1-x2 subdivide the interval into n
equally spaced segments, and search for zero crossings of the function. nb is returned as
the number of bracketing pairs xb1(1:nb), xb2(1:nb) that are found. xb1 and xb2 are
pointers to arrays of length nb that are dynamically allocated by the routine.
INTEGER(I4B) :: i
REAL(SP) :: dx
REAL(SP), DIMENSION(0:n) :: f,x
LOGICAL(LGT), DIMENSION(1:n) :: mask
LOGICAL(LGT), SAVE :: init=.true.
if (init) then
  init=.false.
  nullify(xb1,xb2)
end if
if (associated(xb1)) deallocate(xb1)
if (associated(xb2)) deallocate(xb2)
dx=(x2-x1)/n
x=x1+dx*arth(0,1,n+1)
do i=0,n
  f(i)=func(x(i))
end do
mask=f(1:n)*f(0:n-1) <= 0.0
nb=count(mask)
allocate(xb1(nb),xb2(nb))
xb1(1:nb)=pack(x(0:n-1),mask)
xb2(1:nb)=pack(x(1:n),mask)
END SUBROUTINE zbrak

```

Determine the spacing appropriate to the mesh.

Evaluate the function at the mesh points.

Record where the sign changes occur.  
Number of sign changes.

Store the bounds of each bracket.



This routine shows how to return arrays `xb1` and `xb2` whose size is not known in advance. The coding is explained in the subsection on pointers in §21.5.

\* \* \*

```

FUNCTION rtbis(func,x1,x2,xacc)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x1,x2,xacc
REAL(SP) :: rtbis
INTERFACE
  FUNCTION func(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: func
  END FUNCTION func
END INTERFACE

```

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```

INTEGER(I4B), PARAMETER :: MAXIT=40
  Using bisection, find the root of a function func known to lie between x1 and x2. The
  root, returned as rtbis, will be refined until its accuracy is  $\pm x_{\text{acc}}$ .
  Parameter: MAXIT is the maximum allowed number of bisections.
INTEGER(I4B) :: j
REAL(SP) :: dx,f,fmid,xmid
fmid=func(x2)
f=func(x1)
if (f*fmid >= 0.0) call nrerror('rtbis: root must be bracketed')
if (f < 0.0) then          Orient the search so that f>0 lies at x+dx.
  rtbis=x1
  dx=x2-x1
else
  rtbis=x2
  dx=x1-x2
end if
do j=1,MAXIT              Bisection loop.
  dx=dx*0.5_sp
  xmid=rtbis+dx
  fmid=func(xmid)
  if (fmid <= 0.0) rtbis=xmid
  if (abs(dx) < xacc .or. fmid == 0.0) RETURN
end do
call nrerror('rtbis: too many bisections')
END FUNCTION rtbis

```

\* \* \*

```

FUNCTION rtfisp(func,x1,x2,xacc)
USE nrtype; USE nrutil, ONLY : nrerror,swap
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x1,x2,xacc
REAL(SP) :: rtfisp
INTERFACE
  FUNCTION func(x)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: x
  REAL(SP) :: func
  END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: MAXIT=30
  Using the false position method, find the root of a function func known to lie between x1
  and x2. The root, returned as rtfisp, is refined until its accuracy is  $\pm x_{\text{acc}}$ .
  Parameter: MAXIT is the maximum allowed number of iterations.
INTEGER(I4B) :: j
REAL(SP) :: del,dx,f,fh,fl,xh,xl
fl=func(x1)
fh=func(x2)
if ((fl > 0.0 .and. fh > 0.0) .or. &
    (fl < 0.0 .and. fh < 0.0)) call &
  nrerror('rtfisp: root must be bracketed between arguments')
if (fl < 0.0) then          Identify the limits so that x1 corresponds to
  xl=x1                      the low side.
  xh=x2
else
  xl=x2
  xh=x1
  call swap(fl,fh)
end if
dx=xh-xl

```

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```

do j=1,MAXIT
    rtflsp=x1+dx*f1/(f1-fh)
    f=func(rtflsp)
    if (f < 0.0) then
        del=x1-rtflsp
        x1=rtflsp
        fl=f
    else
        del=xh-rtflsp
        xh=rtflsp
        fh=f
    end if
    dx=xh-x1
    if (abs(del) < xacc .or. f == 0.0) RETURN
end do
call nrerror('rtflsp exceed maximum iterations')
END FUNCTION rtflsp

```

False position loop.  
 Increment with respect to latest value.  
 Replace appropriate limit.  
 Convergence.

\* \* \*

```

FUNCTION rtsec(func,x1,x2,xacc)
USE nrtype; USE nrutil, ONLY : nrerror,swap
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x1,x2,xacc
REAL(SP) :: rtsec
INTERFACE
    FUNCTION func(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: func
    END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: MAXIT=30

```

Using the secant method, find the root of a function `func` thought to lie between `x1` and `x2`. The root, returned as `rtsec`, is refined until its accuracy is  $\pm xacc$ .  
 Parameter: `MAXIT` is the maximum allowed number of iterations.

```

INTEGER(I4B) :: j
REAL(SP) :: dx,f,fl,x1
fl=func(x1)
f=func(x2)
if (abs(fl) < abs(f)) then
    rtsec=x1
    x1=x2
    call swap(fl,f)
else
    x1=x1
    rtsec=x2
end if
do j=1,MAXIT
    dx=(x1-rtsec)*f/(f-fl)
    x1=rtsec
    fl=f
    rtsec=rtsec+dx
    f=func(rtsec)
    if (abs(dx) < xacc .or. f == 0.0) RETURN
end do
call nrerror('rtsec: exceed maximum iterations')
END FUNCTION rtsec

```

Pick the bound with the smaller function value  
 as the most recent guess.  
 Secant loop.  
 Increment with respect to latest value.  
 Convergence.

\* \* \*



```

FUNCTION zriddr(func,x1,x2,xacc)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x1,x2,xacc
REAL(SP) :: zriddr
INTERFACE
  FUNCTION func(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: func
  END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: MAXIT=60
  Using Ridders' method, return the root of a function func known to lie between x1 and
  x2. The root, returned as zriddr, will be refined to an approximate accuracy xacc.
REAL(SP), PARAMETER :: UNUSED=-1.11e30_sp
INTEGER(I4B) :: j
REAL(SP) :: fh,fl,fm,fnew,s,xh,xl,xm,xnew
fl=func(x1)
fh=func(x2)
if ((fl > 0.0 .and. fh < 0.0) .or. (fl < 0.0 .and. fh > 0.0)) then
  xl=x1
  xh=x2
  zriddr=UNUSED
  do j=1,MAXIT
    xm=0.5_sp*(xl+xh)
    fm=func(xm)
    s=sqrt(fm**2-fl*fh)
    if (s == 0.0) RETURN
    xnew=xm+(xm-xl)*(sign(1.0_sp,fl-fh)*fm/s)
    if (abs(xnew-zriddr) <= xacc) RETURN
    zriddr=xnew
    fnew=func(zriddr)
    if (fnew == 0.0) RETURN
    if (sign(fm,fnew) /= fm) then
      xl=xm
      fl=fm
      xh=zriddr
      fh=fnew
    else if (sign(fl,fnew) /= fl) then
      xh=zriddr
      fh=fnew
    else if (sign(fh,fnew) /= fh) then
      xl=zriddr
      fl=fnew
    else
      call nrerror('zriddr: never get here')
    end if
    if (abs(xh-xl) <= xacc) RETURN
  end do
  call nrerror('zriddr: exceeded maximum iterations')
else if (fl == 0.0) then
  zriddr=x1
else if (fh == 0.0) then
  zriddr=x2
else
  call nrerror('zriddr: root must be bracketed')
end if
END FUNCTION zriddr

```

\* \* \*

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```

FUNCTION zbrent(func,x1,x2,tol)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x1,x2,tol
REAL(SP) :: zbrent
INTERFACE
  FUNCTION func(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: func
  END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: ITMAX=100
REAL(SP), PARAMETER :: EPS=epsilon(x1)
  Using Brent's method, find the root of a function func known to lie between x1 and x2.
  The root, returned as zbrent, will be refined until its accuracy is tol.
  Parameters: Maximum allowed number of iterations, and machine floating-point precision.
INTEGER(I4B) :: iter
REAL(SP) :: a,b,c,d,e,fa,fb,fc,p,q,r,s,tol1,xm
a=x1
b=x2
fa=func(a)
fb=func(b)
if ((fa > 0.0 .and. fb > 0.0) .or. (fa < 0.0 .and. fb < 0.0)) &
  call nrerror('root must be bracketed for zbrent')
c=b
fc=fb
do iter=1,ITMAX
  if ((fb > 0.0 .and. fc > 0.0) .or. (fb < 0.0 .and. fc < 0.0)) then
    c=a
    fc=fa
    d=b-a
    e=d
    Rename a, b, c and adjust bounding interval d.
  end if
  if (abs(fc) < abs(fb)) then
    a=b
    b=c
    c=a
    fa=fb
    fb=fc
    fc=fa
  end if
  tol1=2.0_sp*EPS*abs(b)+0.5_sp*tol
  xm=0.5_sp*(c-b)
  Convergence check.
  if (abs(xm) <= tol1 .or. fb == 0.0) then
    zbrent=b
    RETURN
  end if
  if (abs(e) >= tol1 .and. abs(fa) > abs(fb)) then
    s=fb/fa
    Attempt inverse quadratic interpolation.
    if (a == c) then
      p=2.0_sp*xm*s
      q=1.0_sp-s
    else
      q=fa/fc
      r=fb/fc
      p=s*(2.0_sp*xm*q*(q-r)-(b-a)*(r-1.0_sp))
      q=(q-1.0_sp)*(r-1.0_sp)*(s-1.0_sp)
    end if
    if (p > 0.0) q=-q
    Check whether in bounds.
    p=abs(p)
    if (2.0_sp*p < min(3.0_sp*xm*q-abs(tol1*q),abs(e*q))) then
      e=d
      Accept interpolation.

```

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```

        d=p/q
    else
        d=xm
        e=d
        Interpolation failed; use bisection.
    end if
else
        Bounds decreasing too slowly; use bisection.
    d=xm
    e=d
end if
a=b
fa=fb
b=b+merge(d,sign(tol1,xm), abs(d) > tol1 )
fb=func(b)
Evaluate new trial root.
end do
call nrrror('zbrent: exceeded maximum iterations')
zbrent=b
END FUNCTION zbrent

```



REAL(SP), PARAMETER :: EPS=epsilon(x1) The routine `zbrent` works best when EPS is *exactly* the machine precision. The Fortran 90 intrinsic function `epsilon` allows us to code this in a portable fashion.

```

FUNCTION rtnewt(funcd,x1,x2,xacc)
USE nrtype; USE nrutil, ONLY : nrrror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x1,x2,xacc
REAL(SP) :: rtnewt
INTERFACE
    SUBROUTINE funcd(x,fval,fderiv)
        USE nrtype
        IMPLICIT NONE
        REAL(SP), INTENT(IN) :: x
        REAL(SP), INTENT(OUT) :: fval,fderiv
    END SUBROUTINE funcd
END INTERFACE
INTEGER(I4B), PARAMETER :: MAXIT=20

```

Using the Newton-Raphson method, find the root of a function known to lie in the interval  $[x1, x2]$ . The root `rtnewt` will be refined until its accuracy is known within  $\pm xacc$ . `funcd` is a user-supplied subroutine that returns both the function value and the first derivative of the function.

Parameter: `MAXIT` is the maximum number of iterations.

```

INTEGER(I4B) :: j
REAL(SP) :: df,dx,f
rtnewt=0.5_sp*(x1+x2)
Initial guess.
do j=1,MAXIT
    call funcd(rtnewt,f,df)
    dx=f/df
    rtnewt=rtnewt-dx
    if ((x1-rtnewt)*(rtnewt-x2) < 0.0)&
        call nrrror('rtnewt: values jumped out of brackets')
    if (abs(dx) < xacc) RETURN
        Convergence.
end do
call nrrror('rtnewt exceeded maximum iterations')
END FUNCTION rtnewt

```

\* \* \*

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```

FUNCTION rtsafe(funcd,x1,x2,xacc)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x1,x2,xacc
REAL(SP) :: rtsafe
INTERFACE
  SUBROUTINE funcd(x,fval,fderiv)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: x
  REAL(SP), INTENT(OUT) :: fval,fderiv
  END SUBROUTINE funcd
END INTERFACE
INTEGER(I4B), PARAMETER :: MAXIT=100
  Using a combination of Newton-Raphson and bisection, find the root of a function bracketed
  between x1 and x2. The root, returned as the function value rtsafe, will be refined until
  its accuracy is known within  $\pm xacc$ . funcd is a user-supplied subroutine that returns both
  the function value and the first derivative of the function.
  Parameter: MAXIT is the maximum allowed number of iterations.
INTEGER(I4B) :: j
REAL(SP) :: df,dx,dxold,f,fh,fl,temp,xh,xl
call funcd(x1,fl,df)
call funcd(x2,fh,df)
if ((fl > 0.0 .and. fh > 0.0) .or. &
    (fl < 0.0 .and. fh < 0.0)) &
  call nrerror('root must be bracketed in rtsafe')
if (fl == 0.0) then
  rtsafe=x1
  RETURN
else if (fh == 0.0) then
  rtsafe=x2
  RETURN
else if (fl < 0.0) then
  Orient the search so that  $f(x1) < 0$ .
  xl=x1
  xh=x2
else
  xh=x1
  xl=x2
end if
rtsafe=0.5_sp*(x1+x2)
dxold=abs(x2-x1)
dx=dxold
  Initialize the guess for root,
  the "stepsize before last,"
  and the last step.
call funcd(rtsafe,f,df)
do j=1,MAXIT
  Loop over allowed iterations.
  if (((rtsafe-xh)*df-f)*((rtsafe-xl)*df-f) > 0.0 .or. &
      abs(2.0_sp*f) > abs(dxold*df) ) then
    Bisect if Newton out of range, or not decreasing fast enough.
    dxold=dx
    dx=0.5_sp*(xh-xl)
    rtsafe=xl+dx
    if (xl == rtsafe) RETURN
      Change in root is negligible.
  else
    Newton step acceptable. Take it.
    dxold=dx
    dx=f/df
    temp=rtsafe
    rtsafe=rtsafe-dx
    if (temp == rtsafe) RETURN
  end if
  if (abs(dx) < xacc) RETURN
  Convergence criterion.
  call funcd(rtsafe,f,df)
  One new function evaluation per iteration.
  if (f < 0.0) then
    Maintain the bracket on the root.
    xl=rtsafe
  else
    xh=rtsafe

```

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```

    end if
end do
call nrerror('rtsafe: exceeded maximum iterations')
END FUNCTION rtsafe

          *   *   *

SUBROUTINE laguer(a,x,its)
USE nrtype; USE nrutil, ONLY : nrerror,poly,poly_term
IMPLICIT NONE
INTEGER(I4B), INTENT(OUT) :: its
COMPLEX(SPC), INTENT(INOUT) :: x
COMPLEX(SPC), DIMENSION(:), INTENT(IN) :: a
REAL(SP), PARAMETER :: EPS=epsilon(1.0_sp)
INTEGER(I4B), PARAMETER :: MR=8,MT=10,MAXIT=MT*MR
    Given an array of  $M + 1$  complex coefficients  $a$  of the polynomial  $\sum_{i=1}^{M+1} a(i)x^{i-1}$ , and
    given a complex value  $x$ , this routine improves  $x$  by Laguerre's method until it converges,
    within the achievable roundoff limit, to a root of the given polynomial. The number of
    iterations taken is returned as  $its$ .
    Parameters: EPS is the estimated fractional roundoff error. We try to break (rare) limit
    cycles with MR different fractional values, once every MT steps, for MAXIT total allowed
    iterations.
INTEGER(I4B) :: iter,m
REAL(SP) :: abx,abp,abm,err
COMPLEX(SPC) :: dx,x1,f,g,h,sq,gp,gm,g2
COMPLEX(SPC), DIMENSION(size(a)) :: b,d
REAL(SP), DIMENSION(MR) :: frac = &
    (/ 0.5_sp,0.25_sp,0.75_sp,0.13_sp,0.38_sp,0.62_sp,0.88_sp,1.0_sp /)
    Fractions used to break a limit cycle.
m=size(a)-1
do iter=1,MAXIT                                Loop over iterations up to allowed maximum.
    its=iter
    abx=abs(x)
    b(m+1:1:-1)=poly_term(a(m+1:1:-1),x)        Efficient computation of the polynomial
    d(m:1:-1)=poly_term(b(m+1:2:-1),x)          and its first two derivatives.
    f=poly(x,d(2:m))
    err=EPS*poly(abx,abs(b(1:m+1)))             Estimate of roundoff in evaluating polynomial.
    if (abs(b(1)) <= err) RETURN                We are on the root.
    g=d(1)/b(1)                                 The generic case: Use Laguerre's formula.
    g2=g*g
    h=g2-2.0_sp*f/b(1)
    sq=sqrt((m-1)*(m*h-g2))
    gp=g+sq
    gm=g-sq
    abp=abs(gp)
    abm=abs(gm)
    if (abp < abm) gp=gm
    if (max(abp,abm) > 0.0) then
        dx=m/gp
    else
        dx=exp(cmplx(log(1.0_sp+abx),iter,kind=spc))
    end if
    x1=x-dx
    if (x == x1) RETURN                          Converged.
    if (mod(iter,MT) /= 0) then
        x=x1
    else
        Every so often we take a fractional step, to
        break any limit cycle (itself a rare occur-
        end if
        x=x-dx*frac(iter/MT)
    end if
end do
call nrerror('laguer: too many iterations')
    Very unusual — can occur only for complex roots. Try a different starting guess for the root.
END SUBROUTINE laguer

```

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**f90** `b(m+1:1:-1)=poly_term...f=poly(x,d(2:m))` The `poly_term` function in `nrutil` tabulates the partial sums of a polynomial, while `poly` evaluates the polynomial at `x`. In this example, we use `poly_term` on the coefficient array in reverse order, so that the value of the polynomial ends up in `b(1)` and the value of its first derivative in `d(1)`.

`dx=exp(cmplx(log(1.0_sp+abx),iter,kind=spc))` The intrinsic function `cmplx` returns a quantity of type default complex unless the `kind` argument is present. To facilitate converting our routines from single to double precision, we always include the `kind` argument explicitly so that when you redefine `spc` in `nrtype` to be double-precision complex the conversions are carried out correctly.

```
* * *
```

```

SUBROUTINE zroots(a,roots,polish)
USE nrtype; USE nrutil, ONLY : assert_eq,poly_term
USE nr, ONLY : laguer,indexx
IMPLICIT NONE
COMPLEX(SPC), DIMENSION(:), INTENT(IN) :: a
COMPLEX(SPC), DIMENSION(:), INTENT(OUT) :: roots
LOGICAL(LGT), INTENT(IN) :: polish
REAL(SP), PARAMETER :: EPS=1.0e-6_sp
    Given the array of  $M + 1$  complex coefficients  $a$  of the polynomial  $\sum_{i=1}^{M+1} a(i)x^{i-1}$ , this
    routine successively calls laguer and finds all  $M$  complex roots. The logical variable
    polish should be input as .true. if polishing (also by Laguerre's method) is desired,
    .false. if the roots will be subsequently polished by other means.
    Parameter: EPS is a small number.
INTEGER(I4B) :: j,its,m
INTEGER(I4B), DIMENSION(size(roots)) :: indx
COMPLEX(SPC) :: x
COMPLEX(SPC), DIMENSION(size(a)) :: ad
m=assert_eq(size(roots),size(a)-1,'zroots')
ad(:)=a(:)                                Copy of coefficients for successive deflation.
do j=m,1,-1                                Loop over each root to be found.
    x=cmplx(0.0_sp,kind=spc)
    Start at zero to favor convergence to smallest remaining root.
    call laguer(ad(1:j+1),x,its)            Find the root.
    if (abs(aimag(x)) <= 2.0_sp*EPS**2*abs(real(x))) &
        x=cmplx(real(x),kind=spc)
    roots(j)=x
    ad(j:1:-1)=poly_term(ad(j+1:2:-1),x)    Forward deflation.
end do
if (polish) then
    do j=1,m                                Polish the roots using the undeflated coeffi-
        call laguer(a(:),roots(j),its)      cients.
    end do
end if
call indexx(real(roots),indx)              Sort roots by their real parts.
roots=roots(indx)
END SUBROUTINE zroots

```

**f90** `x=cmplx(0.0_sp,kind=spc)...x=cmplx(real(x),kind=spc)` See the discussion of why we include `kind=spc` just above. Note that while `real(x)` returns type default real if `x` is integer or real, it returns single or double precision correctly if `x` is complex.

\* \* \*

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```

SUBROUTINE zrhqr(a,rtr,rti)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
USE nr, ONLY : balanc,hqr,indx
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: a
REAL(SP), DIMENSION(:), INTENT(OUT) :: rtr,rti
  Find all the roots of a polynomial with real coefficients,  $\sum_{i=1}^{M+1} a(i)x^{i-1}$ , given the array
  of  $M + 1$  coefficients a. The method is to construct an upper Hessenberg matrix whose
  eigenvalues are the desired roots, and then use the routines balanc and hqr. The real and
  imaginary parts of the  $M$  roots are returned in rtr and rti, respectively.
INTEGER(I4B) :: k,m
INTEGER(I4B), DIMENSION(size(rtr)) :: indx
REAL(SP), DIMENSION(size(a)-1,size(a)-1) :: hess
m=assert_eq(size(rtr),size(rti),size(a)-1,'zrhqr')
if (a(m+1) == 0.0) call &
  nrerror('zrhqr: Last value of array a must not be 0')
hess(1,:)=-a(m:1:-1)/a(m+1)      Construct the matrix.
hess(2:m,:)=0.0
do k=1,m-1
  hess(k+1,k)=1.0
end do
call balanc(hess)                Find its eigenvalues.
call hqr(hess,rtr,rti)
call indx(rtr,indx)             Sort roots by their real parts.
rtr=rtr(indx)
rti=rti(indx)
END SUBROUTINE zrhqr

```

\* \* \*

```

SUBROUTINE qroot(p,b,c,eps)
USE nrtype; USE nrutil, ONLY : nrerror
USE nr, ONLY : poldiv
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: p
REAL(SP), INTENT(INOUT) :: b,c
REAL(SP), INTENT(IN) :: eps
INTEGER(I4B), PARAMETER :: ITMAX=20
REAL(SP), PARAMETER :: TINY=1.0e-6_sp
  Given an array of  $N$  coefficients p of a polynomial of degree  $N - 1$ , and trial values for the
  coefficients of a quadratic factor  $x^2 + bx + c$ , improve the solution until the coefficients
  b, c change by less than eps. The routine poldiv of §5.3 is used.
  Parameters: ITMAX is the maximum number of iterations, TINY is a small number.
INTEGER(I4B) :: iter,n
REAL(SP) :: delb,delc,div,r,rb,rc,s,rb,rc,s,rb,rc
REAL(SP), DIMENSION(3) :: d
REAL(SP), DIMENSION(size(p)) :: q,qq,rem
n=size(p)
d(3)=1.0
do iter=1,ITMAX
  d(2)=b
  d(1)=c
  call poldiv(p,d,q,rem)
  s=rem(1)                First division gives r, s.
  r=rem(2)
  call poldiv(q(1:n-1),d(:),qq(1:n-1),rem(1:n-1))
  sc=-rem(1)              Second division gives partial r, s with respect
  rc=-rem(2)              to c.
  sb=-c*rc
  rb=sc-b*rc
  div=1.0_sp/(sb*rc-sc*rb)  Solve 2x2 equation.

```

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```

delb=(r*sc-s*rc)*div
delc=(-r*sb+s*rb)*div
b=b+delb
c=c+delc
if ((abs(delb) <= eps*abs(b) .or. abs(b) < TINY) .and. &
    (abs(delc) <= eps*abs(c) .or. abs(c) < TINY)) RETURN Coefficients converged.
end do
call nrerror('qroot: too many iterations')
END SUBROUTINE qroot

```

\* \* \*

```

SUBROUTINE mnewt(ntrial,x,tolx,tolf,usrfun)
USE nrtype
USE nr, ONLY : lubksb,ludcmp
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: ntrial
REAL(SP), INTENT(IN) :: tolx,tolf
REAL(SP), DIMENSION(:), INTENT(INOUT) :: x
INTERFACE
SUBROUTINE usrfun(x,fvec,fjac)
USE nrtype
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(OUT) :: fvec
REAL(SP), DIMENSION(:,), INTENT(OUT) :: fjac
END SUBROUTINE usrfun
END INTERFACE
Given an initial guess x for a root in N dimensions, take ntrial Newton-Raphson steps to
improve the root. Stop if the root converges in either summed absolute variable increments
tolx or summed absolute function values tolf.
INTEGER(I4B) :: i
INTEGER(I4B), DIMENSION(size(x)) :: indx
REAL(SP) :: d
REAL(SP), DIMENSION(size(x)) :: fvec,p
REAL(SP), DIMENSION(size(x),size(x)) :: fjac
do i=1,ntrial
call usrfun(x,fvec,fjac)
User subroutine supplies function values at x in fvec and Jacobian matrix in fjac.
if (sum(abs(fvec)) <= tolf) RETURN Check function convergence.
p=-fvec Right-hand side of linear equations.
call ludcmp(fjac,indx,d) Solve linear equations using LU decom-
call lubksb(fjac,indx,p) position.
x=x+p Update solution.
if (sum(abs(p)) <= tolx) RETURN Check root convergence.
end do
END SUBROUTINE mnewt

```

\* \* \*

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```

SUBROUTINE lnsrch(xold,fold,g,p,x,f,stpmax,check,func)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror,vabs
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: xold,g
REAL(SP), DIMENSION(:), INTENT(INOUT) :: p
REAL(SP), INTENT(IN) :: fold,stpmax
REAL(SP), DIMENSION(:), INTENT(OUT) :: x
REAL(SP), INTENT(OUT) :: f
LOGICAL(LGT), INTENT(OUT) :: check
INTERFACE
  FUNCTION func(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP) :: func
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
  END FUNCTION func
END INTERFACE
REAL(SP), PARAMETER :: ALF=1.0e-4_sp,TOLX=epsilon(x)
  Given an  $N$ -dimensional point  $xold$ , the value of the function and gradient there,  $fold$ 
  and  $g$ , and a direction  $p$ , finds a new point  $x$  along the direction  $p$  from  $xold$  where the
  function  $func$  has decreased "sufficiently."  $xold$ ,  $g$ ,  $p$ , and  $x$  are all arrays of length  $N$ .
  The new function value is returned in  $f$ .  $stpmax$  is an input quantity that limits the length
  of the steps so that you do not try to evaluate the function in regions where it is undefined
  or subject to overflow.  $p$  is usually the Newton direction. The output quantity  $check$  is
  false on a normal exit. It is true when  $x$  is too close to  $xold$ . In a minimization algorithm,
  this usually signals convergence and can be ignored. However, in a zero-finding algorithm
  the calling program should check whether the convergence is spurious.
  Parameters: ALF ensures sufficient decrease in function value; TOLX is the convergence
  criterion on  $\Delta x$ .
INTEGER(I4B) :: ndum
REAL(SP) :: a,alam,alam2,alamin,b,disc,f2,pabs,rhs1,rhs2,slope,tmplam
ndum=assert_eq(size(g),size(p),size(x),size(xold),'lnsrch')
check=.false.
pabs=vabs(p(:))
if (pabs > stpmax) p(:)=p(:)*stpmax/pabs           Scale if attempted step is too big.
slope=dot_product(g,p)
if (slope >= 0.0) call nrerror('roundoff problem in lnsrch')
alamin=TOLX/maxval(abs(p(:)))/max(abs(xold(:)),1.0_sp)  Compute  $\lambda_{min}$ .
alam=1.0                                             Always try full Newton step first.
do                                                  Start of iteration loop.
  x(:)=xold(:)+alam*p(:)
  f=func(x)
  if (alam < alamin) then                          Convergence on  $\Delta x$ . For zero find-
    x(:)=xold(:)                                  ing, the calling program should
    check=.true.                                   verify the convergence.
    RETURN
  else if (f <= fold+ALF*alam*slope) then          Sufficient function decrease.
    RETURN
  else                                             Backtrack.
    if (alam == 1.0) then                          First time.
      tmplam=-slope/(2.0_sp*(f-fold-slope))
    else                                           Subsequent backtracks.
      rhs1=f-fold-alam*slope
      rhs2=f2-fold-alam2*slope
      a=(rhs1/alam**2-rhs2/alam2**2)/(alam-alam2)
      b=(-alam2*rhs1/alam**2+alam*rhs2/alam2**2)/&
        (alam-alam2)
      if (a == 0.0) then
        tmplam=-slope/(2.0_sp*b)
      else
        disc=b*b-3.0_sp*a*slope
        if (disc < 0.0) then
          tmplam=0.5_sp*alam
        else if (b <= 0.0) then

```

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```

        tmplam=(-b+sqrt(disc))/(3.0_sp*a)
    else
        tmplam=-slope/(b+sqrt(disc))
    end if
end if
end if
if (tmplam > 0.5_sp*alam) tmplam=0.5_sp*alam     $\lambda \leq 0.5\lambda_1$ .
end if
end if
alam2=alam
f2=f
alam=max(tmplam,0.1_sp*alam)                     $\lambda \geq 0.1\lambda_1$ .
end do                                           Try again.
END SUBROUTINE lnsrch

```

```

SUBROUTINE newt(x,check)
USE nrtype; USE nrutil, ONLY : nrerror,vabs
USE nr, ONLY : fdjac,lnsrch,lubksb,ludcmp
USE fminln                                     Communicates with fmin.
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: x
LOGICAL(LGT), INTENT(OUT) :: check
INTEGER(I4B), PARAMETER :: MAXITS=200
REAL(SP), PARAMETER :: TOLF=1.0e-4_sp,TOLMIN=1.0e-6_sp,TOLX=epsilon(x),&
    STPMX=100.0
    Given an initial guess x for a root in N dimensions, find the root by a globally convergent
    Newton's method. The length N vector of functions to be zeroed, called fvec in the rou-
    tine below, is returned by a user-supplied routine that must be called funcv and have the
    declaration FUNCTION funcv(x). The output quantity check is false on a normal return
    and true if the routine has converged to a local minimum of the function fmin defined
    below. In this case try restarting from a different initial guess.
    Parameters: MAXITS is the maximum number of iterations; TOLF sets the convergence
    criterion on function values; TOLMIN sets the criterion for deciding whether spurious con-
    vergence to a minimum of fmin has occurred; TOLX is the convergence criterion on dx;
    STPMX is the scaled maximum step length allowed in line searches.
INTEGER(I4B) :: its
INTEGER(I4B), DIMENSION(size(x)) :: indx
REAL(SP) :: d,f,fold,stpmax
REAL(SP), DIMENSION(size(x)) :: g,p,xold
REAL(SP), DIMENSION(size(x)), TARGET :: fvec
REAL(SP), DIMENSION(size(x),size(x)) :: fjac
fmin_fvecp=>fvec
f=fmin(x)                                     fvec is also computed by this call.
if (maxval(abs(fvec(:))) < 0.01_sp*TOLF) then    Test for initial guess being a root.
    check=.false.                               Use more stringent test than
    RETURN                                       simply TOLF.
end if
stpmax=STPMX*max(vabs(x(:)),real(size(x),sp))    Calculate stpmax for line searches.
do its=1,MAXITS                                Start of iteration loop.
    call fdjac(x,fvec,fjac)
        If analytic Jacobian is available, you can replace the routine fdjac below with your own
        routine.
    g(:)=matmul(fvec(:),fjac(:,:))              Compute  $\nabla f$  for the line search.
    xold(:)=x(:)                               Store x,
    fold=f                                      and f.
    p(:)=-fvec(:)                             Right-hand side for linear equations.
    call ludcmp(fjac,indx,d)                   Solve linear equations by LU decomposition.
    call lubksb(fjac,indx,p)
    call lnsrch(xold,fold,g,p,x,f,stpmax,check,fmin)
        lnsrch returns new x and f. It also calculates fvec at the new x when it calls fmin.
    if (maxval(abs(fvec(:))) < TOLF) then      Test for convergence on function val-
        check=.false.                          ues.
        RETURN

```

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```

end if
if (check) then
    Check for gradient of  $f$  zero, i.e., spurious
    check=(maxval(abs(g(:))*max(abs(x(:)),1.0_sp) / & convergence.
        max(f,0.5_sp*size(x))) < TOLMIN)
    RETURN
    Test for convergence on  $\delta x$ .
end if
if (maxval(abs(x(:)-xold(:))/max(abs(x(:)),1.0_sp)) < TOLX) &
    RETURN
end do
call nrerror('MAXITS exceeded in newt')
END SUBROUTINE newt

```

**f90** USE `fminln` Here we have an example of how to pass an array `fvec` to a function `fmin` without making it an argument of `fmin`. In the language of §21.5, we are using Method 2: We define a pointer `fmin_fvecp` in the module `fminln`:

```
REAL(SP), DIMENSION(:), POINTER :: fmin_fvecp
```

`fvec` itself is declared as an automatic array of the appropriate size in `newt`:

```
REAL(SP), DIMENSION(size(x)), TARGET :: fvec
```

On entry into `newt`, the pointer is associated:

```
fmin_fvecp=>fvec
```

The pointer is then used in `fmin` as a synonym for `fvec`. If you are sufficiently paranoid, you can test whether `fmin_fvecp` has in fact been associated on entry into `fmin`. Heeding our admonition always to deallocate memory when it no longer is needed, you may ask where the deallocation takes place in this example. Answer: On exit from `newt`, the automatic array `fvec` is automatically freed.

The Method 1 way of setting up this task is to declare an allocatable array in the module:

```
REAL(SP), DIMENSION(:), ALLOCATABLE :: fvec
```

On entry into `newt` we allocate it appropriately:

```
allocate(fvec,size(x))
```

and it can now be used in both `newt` and `fmin`. Of course, we must remember to deallocate explicitly `fvec` on exit from `newt`. If we forget, all kinds of bad things would happen on a second call to `newt`. The status of `fvec` on the first return from `newt` becomes undefined. The status cannot be tested with `if(allocated(...))`, and `fvec` may not be referenced in any way. If we tried to guard against this by adding the `SAVE` attribute to the declaration of `fvec`, then we would generate an error from trying to allocate an already-allocated array.

```

SUBROUTINE fdjac(x,fvec,df)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: fvec
REAL(SP), DIMENSION(:), INTENT(INOUT) :: x
REAL(SP), DIMENSION(:,:), INTENT(OUT) :: df
INTERFACE

```

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```

FUNCTION funcv(x)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), DIMENSION(:), INTENT(IN) :: x
  REAL(SP), DIMENSION(size(x)) :: funcv
END FUNCTION funcv
END INTERFACE
REAL(SP), PARAMETER :: EPS=1.0e-4_sp
  Computes forward-difference approximation to Jacobian. On input, x is the point at which
  the Jacobian is to be evaluated, and fvec is the vector of function values at the point,
  both arrays of length N. df is the N x N output Jacobian. FUNCTION funcv(x) is a
  fixed-name, user-supplied routine that returns the vector of functions at x.
  Parameter: EPS is the approximate square root of the machine precision.
INTEGER(I4B) :: j,n
REAL(SP), DIMENSION(size(x)) :: xsav,xph,h
n=assert_eq(size(x),size(fvec),size(df,1),size(df,2),'fdjac')
xsav=x
h=EPS*abs(xsav)
where (h == 0.0) h=EPS
xph=xsav+h
h=xph-xsav
do j=1,n
  x(j)=xph(j)
  df(:,j)=(funcv(x)-fvec(:))/h(j)
  x(j)=xsav(j)
end do
END SUBROUTINE fdjac

```

Trick to reduce finite precision error.

Forward difference formula.

**MODULE fminln**

```

USE nrtype; USE nrutil, ONLY : nrerror
REAL(SP), DIMENSION(:), POINTER :: fmin_fvecp
CONTAINS
FUNCTION fmin(x)
  IMPLICIT NONE
  REAL(SP), DIMENSION(:), INTENT(IN) :: x
  REAL(SP) :: fmin
  Returns  $f = \frac{1}{2} \mathbf{F} \cdot \mathbf{F}$  at x. FUNCTION funcv(x) is a fixed-name, user-supplied routine that
  returns the vector of functions at x. The pointer fmin_fvecp communicates the function
  values back to newt.
INTERFACE
  FUNCTION funcv(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: funcv
  END FUNCTION funcv
END INTERFACE
if (.not. associated(fmin_fvecp)) call &
  nrerror('fmin: problem with pointer for returned values')
fmin_fvecp=funcv(x)
fmin=0.5_sp*dot_product(fmin_fvecp,fmin_fvecp)
END FUNCTION fmin
END MODULE fminln

```

\* \* \*

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```

SUBROUTINE broydn(x,check)
USE nrtype; USE nrutil, ONLY : get_diag,lower_triangle,nrerror,&
    outerprod,put_diag,unit_matrix,vabs
USE nr, ONLY : fdjac,lnsrch,qrdcmp,qrupdt,rsolv
USE fminln                                     Communicates with fmin.
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: x
LOGICAL(LGT), INTENT(OUT) :: check
INTEGER(I4B), PARAMETER :: MAXITS=200
REAL(SP), PARAMETER :: EPS=epsilon(x),TOLF=1.0e-4_sp,TOLMIN=1.0e-6_sp,&
    TOLX=EPS,STPMX=100.0
    Given an initial guess  $x$  for a root in  $N$  dimensions, find the root by Broyden's method
    embedded in a globally convergent strategy. The length  $N$  vector of functions to be zeroed,
    called  $fvec$  in the routine below, is returned by a user-supplied routine that must be
    called  $funcv$  and have the declaration FUNCTION funcv(x). The subroutine  $fdjac$  and
    the function  $fmin$  from newt are used. The output quantity  $check$  is false on a normal
    return and true if the routine has converged to a local minimum of the function  $fmin$  or if
    Broyden's method can make no further progress. In this case try restarting from a different
    initial guess.
    Parameters: MAXITS is the maximum number of iterations; EPS is the machine precision;
    TOLF sets the convergence criterion on function values; TOLMIN sets the criterion for deciding
    whether spurious convergence to a minimum of  $fmin$  has occurred; TOLX is the convergence
    criterion on  $\delta x$ ; STPMX is the scaled maximum step length allowed in line
    searches.
INTEGER(I4B) :: i,its,k,n
REAL(SP) :: f,fold,stpmax
REAL(SP), DIMENSION(size(x)), TARGET :: fvec
REAL(SP), DIMENSION(size(x)) :: c,d,fvcold,g,p,s,t,w,xold
REAL(SP), DIMENSION(size(x),size(x)) :: qt,r
LOGICAL :: restrt,sing
fmin_fvecp=>fvec
n=size(x)
f=fmin(x)                                     fvec is also computed by this call.
if (maxval(abs(fvec(:))) < 0.01_sp*TOLF) then   Test for initial guess being a root.
    check=.false.                               Use more stringent test than
    RETURN                                       simply TOLF.
end if
stpmax=STPMX*max(vabs(x(:)),real(n,sp))        Calculate stpmax for line searches.
restrt=.true.                                  Ensure initial Jacobian gets computed.
do its=1,MAXITS                                Start of iteration loop.
    if (restrt) then
        call fdjac(x,fvec,r)                   Initialize or reinitialize Jacobian in r.
        call qrdcmp(r,c,d,sing)                 $QR$  decomposition of Jacobian.
        if (sing) call nrerror('singular Jacobian in broydn')
        call unit_matrix(qt)                   Form  $Q^T$  explicitly.
        do k=1,n-1
            if (c(k) /= 0.0) then
                qt(k:n,:) = qt(k:n,:) - outerprod(r(k:n,k), &
                    matmul(r(k:n,k), qt(k:n,:))) / c(k)
            end if
        end do
        where (lower_triangle(n,n)) r(:, :) = 0.0
        call put_diag(d(:), r(:, :))           Form  $R$  explicitly.
    else                                        Carry out Broyden update.
        s(:) = x(:) - xold(:)                   $s = \delta x$ .
        do i=1,n                                 $t = R \cdot s$ .
            t(i) = dot_product(r(i, i:n), s(i:n))
        end do
        w(:) = fvec(:) - fvcold(:) - matmul(t(:), qt(:, :))     $w = \delta F - B \cdot s$ .
        where (abs(w(:)) < EPS*(abs(fvec(:)) + abs(fvcold(:)))) &
            w(:) = 0.0                          Don't update with noisy components of
                                                 $w$ .
        if (any(w(:) /= 0.0)) then
            t(:) = matmul(qt(:, :), w(:))         $t = Q^T \cdot w$ .
            s(:) = s(:) / dot_product(s, s)      Store  $s/(s \cdot s)$  in  $s$ .
        end if
    end if
end do

```

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```

    call qrupdt(r,qt,t,s)           Update R and  $\mathbf{Q}^T$ .
    d(:)=get_diag(r(:,:))         Diagonal of R stored in d.
    if (any(d(:) == 0.0)) &
        call nrerror('r singular in broydn')
    end if
end if
end if
p(:)=-matmul(qt(:,:),fvec(:))    r.h.s. for linear equations is  $-\mathbf{Q}^T \cdot \mathbf{F}$ .
do i=1,n                         Compute  $\nabla f \approx (\mathbf{Q} \cdot \mathbf{R})^T \cdot \mathbf{F}$  for the line
    g(i)=-dot_product(r(1:i,i),p(1:i)) search.
end do
xold(:)=x(:)                     Store x, F, and f.
fvcold(:)=fvec(:)
fold=f
call rsolv(r,d,p)                Solve linear equations.
call lnsrch(xold,fold,g,p,x,f,stpmax,check,fmin)
    lnsrch returns new x and f. It also calculates fvec at the new x when it calls fmin.
if (maxval(abs(fvec(:))) < TOLF) then Test for convergence on function val-
    check=.false.                  ues.
    RETURN
end if
if (check) then                  True if line search failed to find a new
    if (restrt .or. maxval(abs(g(:))*max(abs(x(:)), & x.
        1.0_sp)/max(f,0.5_sp*n)) < TOLMIN) RETURN
        If restrt is true we have failure: We have already tried reinitializing the Jaco-
        bian. The other test is for gradient of f zero, i.e., spurious convergence.
        restrt=.true.              Try reinitializing the Jacobian.
    else                          Successful step; will use Broyden update
        restrt=.false.            for next step.
        if (maxval((abs(x(:)-xold(:)))/max(abs(x(:)), &
            1.0_sp)) < TOLX) RETURN Test for convergence on  $\delta x$ .
    end if
end do
call nrerror('MAXITS exceeded in broydn')
END SUBROUTINE broydn

```



USE `fminln` See discussion for `newt` on p. 1197.

`qt(k:n,:)=...outerprod...matmul` Another example of the coding of equation (22.1.6).

`where (lower_triangle(n,n))...` The `lower_triangle` function in `nrutil` returns a lower triangular logical mask. As used here, the mask is true everywhere in the lower triangle of an  $n \times n$  matrix, excluding the diagonal. An optional integer argument `extra` allows additional diagonals to be set to true. With `extra=1` the lower triangle including the diagonal would be true.

`call put_diag(d(:),r(:,:))` This subroutine in `nrutil` sets the diagonal values of the matrix `r` to the values of the vector `d`. It is overloaded so that `d` could be a scalar, in which case the scalar value would be broadcast onto the diagonal of `r`.

## Chapter B10. Minimization or Maximization of Functions

```

SUBROUTINE mnbrak(ax,bx,cx,fa,fb,fc,func)
USE nrtype; USE nrutil, ONLY : swap
IMPLICIT NONE
REAL(SP), INTENT(INOUT) :: ax,bx
REAL(SP), INTENT(OUT) :: cx,fa,fb,fc
INTERFACE
  FUNCTION func(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: func
  END FUNCTION func
END INTERFACE
REAL(SP), PARAMETER :: GOLD=1.618034_sp, GLIMIT=100.0_sp, TINY=1.0e-20_sp
  Given a function func, and given distinct initial points ax and bx, this routine searches
  in the downhill direction (defined by the function as evaluated at the initial points) and
  returns new points ax, bx, cx that bracket a minimum of the function. Also returned are
  the function values at the three points, fa, fb, and fc.
  Parameters: GOLD is the default ratio by which successive intervals are magnified; GLIMIT
  is the maximum magnification allowed for a parabolic-fit step.
REAL(SP) :: fu,q,r,u,ulim
fa=func(ax)
fb=func(bx)
if (fb > fa) then
  call swap(ax,bx)
  call swap(fa,fb)
end if
cx=bx+GOLD*(bx-ax)
fc=func(cx)
do
  if (fb < fc) RETURN
    Compute u by parabolic extrapolation from a, b, c. TINY is used to prevent any possible
    division by zero.
    r=(bx-ax)*(fb-fc)
    q=(bx-cx)*(fb-fa)
    u=bx-((bx-cx)*q-(bx-ax)*r)/(2.0_sp*sign(max(abs(q-r),TINY),q-r))
    ulim=bx+GLIMIT*(cx-bx)
    We won't go farther than this. Test various possibilities:
  if ((bx-u)*(u-cx) > 0.0) then
    fu=func(u)
    if (fu < fc) then
      ax=bx
      fa=fb
      bx=u
      fb=fu
      RETURN
    else if (fu > fb) then
      cx=u
      fc=fu
      RETURN

```

Switch roles of *a* and *b* so that we can go downhill in the direction from *a* to *b*.

First guess for *c*.

Do-while-loop: Keep returning here until we bracket.

Parabolic *u* is between *b* and *c*: try it.

Got a minimum between *b* and *c*.

Got a minimum between *a* and *u*.

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```

        end if
        u=cx+GOLD*(cx-bx)
        fu=func(u)
    else if ((cx-u)*(u-ulim) > 0.0) then
        fu=func(u)
        if (fu < fc) then
            bx=cx
            cx=u
            u=cx+GOLD*(cx-bx)
            call shft(fb,fc,fu,func(u))
        end if
    else if ((u-ulim)*(ulim-cx) >= 0.0) then
        u=ulim
        fu=func(u)
    else
        u=cx+GOLD*(cx-bx)
        fu=func(u)
    end if
    call shft(ax,bx,cx,u)
    call shft(fa,fb,fc,fu)
end do
CONTAINS
SUBROUTINE shft(a,b,c,d)
REAL(SP), INTENT(OUT) :: a
REAL(SP), INTENT(INOUT) :: b,c
REAL(SP), INTENT(IN) :: d
a=b
b=c
c=d
END SUBROUTINE shft
END SUBROUTINE mnbrak

```

**f**<sub>90</sub> call shft... There are three places in mnbrak where we need to shift four variables around. Rather than repeat code, we make shft an internal subroutine, coming after a CONTAINS statement. It is invisible to all procedures except mnbrak.

\* \* \*

```

FUNCTION golden(ax,bx,cx,func,tol,xmin)
USE nrtype
IMPLICIT NONE
REAL(SP), INTENT(IN) :: ax,bx,cx,tol
REAL(SP), INTENT(OUT) :: xmin
REAL(SP) :: golden
INTERFACE
    FUNCTION func(x)
        USE nrtype
        IMPLICIT NONE
        REAL(SP), INTENT(IN) :: x
        REAL(SP) :: func
    END FUNCTION func
END INTERFACE
REAL(SP), PARAMETER :: R=0.61803399_sp,C=1.0_sp-R

```

Given a function func, and given a bracketing triplet of abscissas ax, bx, cx (such that bx is between ax and cx, and func(bx) is less than both func(ax) and func(cx)), this routine performs a golden section search for the minimum, isolating it to a fractional precision of about tol. The abscissa of the minimum is returned as xmin, and the minimum

Parabolic fit was no use. Use default magnification.

Parabolic fit is between c and its allowed limit.

Limit parabolic u to maximum allowed value.

Reject parabolic u, use default magnification.

Eliminate oldest point and continue.

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function value is returned as `golden`, the returned function value.

Parameters: The golden ratios.

```
REAL(SP) :: f1,f2,x0,x1,x2,x3
x0=ax
x3=cx
if (abs(cx-bx) > abs(bx-ax)) then
  x1=bx
  x2=bx+C*(cx-bx)
else
  x2=bx
  x1=bx-C*(bx-ax)
end if
f1=func(x1)
f2=func(x2)
```

At any given time we will keep track of four points,  $x_0, x_1, x_2, x_3$ .  
Make  $x_0$  to  $x_1$  the smaller segment,  
and fill in the new point to be tried.

The initial function evaluations. Note that we never need to evaluate the function at the original endpoints.


```
do
  if (abs(x3-x0) <= tol*(abs(x1)+abs(x2))) exit
  if (f2 < f1) then
    call shft3(x0,x1,x2,R*x2+C*x3)
    call shft2(f1,f2,func(x2))
  else
    call shft3(x3,x2,x1,R*x1+C*x0)
    call shft2(f2,f1,func(x1))
  end if
end do
if (f1 < f2) then
  golden=f1
  xmin=x1
else
  golden=f2
  xmin=x2
end if
```

Do-while-loop: We keep returning here.  
exit  
One possible outcome,  
its housekeeping,  
and a new function evaluation.  
The other outcome,  
and its new function evaluation.  
Back to see if we are done.  
We are done. Output the best of the two  
current values.

CONTAINS

```
SUBROUTINE shft2(a,b,c)
REAL(SP), INTENT(OUT) :: a
REAL(SP), INTENT(INOUT) :: b
REAL(SP), INTENT(IN) :: c
a=b
b=c
END SUBROUTINE shft2
```

```
SUBROUTINE shft3(a,b,c,d)
REAL(SP), INTENT(OUT) :: a
REAL(SP), INTENT(INOUT) :: b,c
REAL(SP), INTENT(IN) :: d
a=b
b=c
c=d
END SUBROUTINE shft3
END FUNCTION golden
```

 call shft3...call shft2... See discussion of shft for mnbrak on p. 1202.

\* \* \*

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```

FUNCTION brent(ax,bx,cx,func,tol,xmin)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: ax,bx,cx,tol
REAL(SP), INTENT(OUT) :: xmin
REAL(SP) :: brent
INTERFACE
  FUNCTION func(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: func
  END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: ITMAX=100
REAL(SP), PARAMETER :: CGOLD=0.3819660_sp,ZEPS=1.0e-3_sp*epsilon(ax)
  Given a function func, and given a bracketing triplet of abscissas ax, bx, cx (such that bx
  is between ax and cx, and func(bx) is less than both func(ax) and func(cx)), this
  routine isolates the minimum to a fractional precision of about tol using Brent's method.
  The abscissa of the minimum is returned as xmin, and the minimum function value is
  returned as brent, the returned function value.
  Parameters: Maximum allowed number of iterations; golden ratio; and a small number that
  protects against trying to achieve fractional accuracy for a minimum that happens to be
  exactly zero.
INTEGER(I4B) :: iter
REAL(SP) :: a,b,d,e,etemp,fu,fv,fw,fx,p,q,r,tol1,tol2,u,v,w,x,xm
a=min(ax,cx)
b=max(ax,cx)
v=bx
w=v
x=v
e=0.0
fx=func(x)
fv=fx
fw=fx
do iter=1,ITMAX
  xm=0.5_sp*(a+b)
  tol1=tol*abs(x)+ZEPS
  tol2=2.0_sp*tol1
  if (abs(x-xm) <= (tol2-0.5_sp*(b-a))) then
    Test for done here.
    xmin=x
    brent=fx
    RETURN
  end if
  if (abs(e) > tol1) then
    Construct a trial parabolic fit.
    r=(x-w)*(fx-fv)
    q=(x-v)*(fx-fw)
    p=(x-v)*q-(x-w)*r
    q=2.0_sp*(q-r)
    if (q > 0.0) p=-p
    q=abs(q)
    etemp=e
    e=d
    if (abs(p) >= abs(0.5_sp*q*etemp) .or. &
        p <= q*(a-x) .or. p >= q*(b-x)) then
      The above conditions determine the acceptability of the parabolic fit. Here it is
      not o.k., so we take the golden section step into the larger of the two segments.
      e=merge(a-x,b-x, x >= xm )
      d=CGOLD*e
    else
      Take the parabolic step.
      d=p/q
      u=x+d
      if (u-a < tol2 .or. b-u < tol2) d=sign(tol1,xm-x)
    end if
  end if
  fu=func(x)
  if (abs(fu-fv) < abs(fv-fw)) then
    v=w
    w=x
    x=v
    e=fx-fv
  else
    v=x
    w=x
    x=v
    e=fx-fv
  end if
end do

```

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```

else
    e=merge(a-x,b-x, x >= xm )           Take the golden section step into the larger
    d=CGOLD*e                             of the two segments.
end if
u=merge(x+d,x+sign(tol1,d), abs(d) >= tol1 )
    Arrive here with d computed either from parabolic fit, or else from golden section.
fu=func(u)
    This is the one function evaluation per iteration.
if (fu <= fx) then                         Now we have to decide what to do with our
    if (u >= x) then                         function evaluation. Housekeeping follows:
        a=x
    else
        b=x
    end if
    call shft(v,w,x,u)
    call shft(fv,fw,fx,fu)
else
    if (u < x) then
        a=u
    else
        b=u
    end if
    if (fu <= fw .or. w == x) then
        v=w
        fv=fw
        w=u
        fw=fu
    else if (fu <= fv .or. v == x .or. v == w) then
        v=u
        fv=fu
    end if
end if
end do
call nrerror('brent: exceed maximum iterations') iteration.
CONTAINS

SUBROUTINE shft(a,b,c,d)
REAL(SP), INTENT(OUT) :: a
REAL(SP), INTENT(INOUT) :: b,c
REAL(SP), INTENT(IN) :: d
a=b
b=c
c=d
END SUBROUTINE shft
END FUNCTION brent

```

\* \* \*

```

FUNCTION dbrent(ax,bx,cx,func,dfunc,tol,xmin)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(IN) :: ax,bx,cx,tol
REAL(SP), INTENT(OUT) :: xmin
REAL(SP) :: dbrent
INTERFACE
    FUNCTION func(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: func
    END FUNCTION func
    FUNCTION dfunc(x)

```

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```

USE nrtype
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: dfunc
END FUNCTION dfunc
END INTERFACE
INTEGER(I4B), PARAMETER :: ITMAX=100
REAL(SP), PARAMETER :: ZEPS=1.0e-3_sp*epsilon(ax)
  Given a function func and its derivative function dfunc, and given a bracketing triplet of
  abscissas ax, bx, cx [such that bx is between ax and cx, and func(bx) is less than both
  func(ax) and func(cx)], this routine isolates the minimum to a fractional precision of
  about tol using a modification of Brent's method that uses derivatives. The abscissa of
  the minimum is returned as xmin, and the minimum function value is returned as dbrent,
  the returned function value.
  Parameters: Maximum allowed number of iterations, and a small number that protects
  against trying to achieve fractional accuracy for a minimum that happens to be exactly
  zero.
INTEGER(I4B) :: iter
REAL(SP) :: a,b,d,d1,d2,du,dv,dw,dx,e,fu,fv,fw,fx,olde,tol1,tol2,&
  u,u1,u2,v,w,x,xm
  Comments following will point out only differences from the routine brent. Read that
  routine first.
LOGICAL :: ok1,ok2
a=min(ax,cx)
b=max(ax,cx)
v=bx
w=v
x=v
e=0.0
fx=func(x)
fv=fx
fw=fx
dx=dfunc(x)
dv=dx
dw=dx
do iter=1,ITMAX
  xm=0.5_sp*(a+b)
  tol1=tol*abs(x)+ZEPS
  tol2=2.0_sp*tol1
  if (abs(x-xm) <= (tol2-0.5_sp*(b-a))) exit
  if (abs(e) > tol1) then
    d1=2.0_sp*(b-a)
    d2=d1
    if (dw /= dx) d1=(w-x)*dx/(dx-dw)
    if (dv /= dx) d2=(v-x)*dx/(dx-dv)
    Which of these two estimates of d shall we take? We will insist that they be within
    the bracket, and on the side pointed to by the derivative at x:
    u1=x+d1
    u2=x+d2
    ok1=((a-u1)*(u1-b) > 0.0) .and. (dx*d1 <= 0.0)
    ok2=((a-u2)*(u2-b) > 0.0) .and. (dx*d2 <= 0.0)
    olde=e
    e=d
    if (ok1 .or. ok2) then
      if (ok1 .and. ok2) then
        d=merge(d1,d2, abs(d1) < abs(d2))
      else
        d=merge(d1,d2,ok1)
      end if
      if (abs(d) <= abs(0.5_sp*olde)) then
        u=x+d
        if (u-a < tol2 .or. b-u < tol2) &
          d=sign(tol1,xm-x)
      else
        Will be used as flags for whether pro-
        posed steps are acceptable or not.

        All our housekeeping chores are dou-
        bled by the necessity of moving
        derivative values around as well
        as function values.

        Initialize these d's to an out-of-bracket
        value.

        Secant method with each point.

        Movement on the step before last.

        Take only an acceptable d, and if
        both are acceptable, then take
        the smallest one.
    end if
  end if
end do

```

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```

        e=merge(a,b, dx >= 0.0)-x
        Decide which segment by the sign of the derivative.
        d=0.5_sp*e                               Bisect, not golden section.
    end if
else
    e=merge(a,b, dx >= 0.0)-x
    d=0.5_sp*e                               Bisect, not golden section.
end if
else
    e=merge(a,b, dx >= 0.0)-x
    d=0.5_sp*e                               Bisect, not golden section.
end if
if (abs(d) >= tol1) then
    u=x+d
    fu=func(u)
else
    u=x+sign(tol1,d)
    fu=func(u)
    if (fu > fx) exit
end if
du=dfunc(u)
if (fu <= fx) then
    if (u >= x) then
        a=x
    else
        b=x
    end if
    call mov3(v,fv,dv,w,fw,dw)
    call mov3(w,fw,dw,x,fx,dx)
    call mov3(x,fx,dx,u,fu,du)
else
    if (u < x) then
        a=u
    else
        b=u
    end if
    if (fu <= fw .or. w == x) then
        call mov3(v,fv,dv,w,fw,dw)
        call mov3(w,fw,dw,u,fu,du)
    else if (fu <= fv .or. v == x .or. v == w) then
        call mov3(v,fv,dv,u,fu,du)
    end if
end if
end do
if (iter > ITMAX) call nerror('dbrent: exceeded maximum iterations')
xmin=x
dbrent=fx
CONTAINS
SUBROUTINE mov3(a,b,c,d,e,f)
REAL(SP), INTENT(IN) :: d,e,f
REAL(SP), INTENT(OUT) :: a,b,c
a=d
b=e
c=f
END SUBROUTINE mov3
END FUNCTION dbrent

```

\* \* \*

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```

SUBROUTINE amoeba(p,y,ftol,func,iter)
USE nrtype; USE nrutil, ONLY : assert_eq,imaxloc,iminloc,nrerror,swap
IMPLICIT NONE
INTEGER(I4B), INTENT(OUT) :: iter
REAL(SP), INTENT(IN) :: ftol
REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
REAL(SP), DIMENSION(:,.), INTENT(INOUT) :: p
INTERFACE
  FUNCTION func(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP) :: func
  END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: ITMAX=5000
REAL(SP), PARAMETER :: TINY=1.0e-10
  Minimization of the function func in  $N$  dimensions by the downhill simplex method of
  Nelder and Mead. The  $(N + 1) \times N$  matrix p is input. Its  $N + 1$  rows are  $N$ -dimensional
  vectors that are the vertices of the starting simplex. Also input is the vector y of length
   $N + 1$ , whose components must be preinitialized to the values of func evaluated at the
   $N + 1$  vertices (rows) of p; and ftol the fractional convergence tolerance to be achieved
  in the function value (n.b.!). On output, p and y will have been reset to  $N + 1$  new points
  all within ftol of a minimum function value, and iter gives the number of function
  evaluations taken.
  Parameters: The maximum allowed number of function evaluations, and a small number.
INTEGER(I4B) :: ihi,ndim           Global variables.
REAL(SP), DIMENSION(size(p,2)) :: psum
call amoeba_private
CONTAINS
SUBROUTINE amoeba_private
IMPLICIT NONE
INTEGER(I4B) :: i,ilo,inhi
REAL(SP) :: rtol,ysave,ytry,ytmp
ndim=assert_eq(size(p,2),size(p,1)-1,size(y)-1,'amoeba')
iter=0
psum(:)=sum(p(:,.),dim=1)
do
  ilo=iminloc(y(:))
  ihi=imaxloc(y(:))
  ytmp=y(ihi)
  y(ihi)=y(ilo)
  inhi=imaxloc(y(:))
  y(ihi)=ytmp
  rtol=2.0_sp*abs(y(ihi)-y(ilo))/(abs(y(ihi))+abs(y(ilo))+TINY)
  Compute the fractional range from highest to lowest and return if satisfactory.
  if (rtol < ftol) then
    call swap(y(1),y(ilo))
    call swap(p(1,:),p(ilo,:))
    RETURN
  end if
  if (iter >= ITMAX) call nrerror('ITMAX exceeded in amoeba')
  Begin a new iteration. First extrapolate by a factor -1 through the face of the simplex
  across from the high point, i.e., reflect the simplex from the high point.
  ytry=amotry(-1.0_sp)
  iter=iter+1
  if (ytry <= y(ilo)) then
    ytry=amotry(2.0_sp)
    iter=iter+1
    Gives a result better than the best point, so
    try an additional extrapolation by a fac-
    tor of 2.
  else if (ytry >= y(inhi)) then
    ysave=y(ihi)
    ytry=amotry(0.5_sp)
    iter=iter+1
    The reflected point is worse than the sec-
    ond highest, so look for an intermediate
    lower point, i.e., do a one-dimensional
    contraction.

```

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```

    if (ytry >= ysave) then
        Can't seem to get rid of that high point. Better contract around the lowest
        (best) point.
        p(:, :)=0.5_sp*(p(:, :)+spread(p(ilo, :), 1, size(p, 1)))
        do i=1, ndim+1
            if (i /= ilo) y(i)=func(p(i, :))
        end do
        iter=iter+ndim           Keep track of function evaluations.
        psum(:)=sum(p(:, :), dim=1)
    end if
end if
end do           Go back for the test of doneness and the next
END SUBROUTINE amoeba_private           iteration.

FUNCTION amotry(fac)
IMPLICIT NONE
REAL(SP), INTENT(IN) :: fac
REAL(SP) :: amotry
    Extrapolates by a factor fac through the face of the simplex across from the high point,
    tries it, and replaces the high point if the new point is better.
REAL(SP) :: fac1, fac2, ytry
REAL(SP), DIMENSION(size(p, 2)) :: ptry
fac1=(1.0_sp-fac)/ndim
fac2=fac1-fac
ptry(:)=psum(:)*fac1-p(ihi, :)*fac2
ytry=func(ptry)
if (ytry < y(ihi)) then           Evaluate the function at the trial point.
    y(ihi)=ytry                   If it's better than the highest, then replace
    psum(:)=psum(:)-p(ihi, :)+ptry(:)   the highest.
    p(ihi, :)=ptry(:)
end if
amotry=ytry
END FUNCTION amotry
END SUBROUTINE amoeba

```

**f90** The only action taken by the subroutine `amoeba` is to call the internal subroutine `amoeba_private`. Why this structure? The reason has to do with meeting the twin goals of data hiding (especially for “safe” scope of variables) and program readability. The situation is this: Logically, `amoeba` does most of the calculating, but calls an internal subroutine `amotry` at several different points, with several values of the parameter `fac`. However, `fac` is not the only piece of data that must be shared with `amotry`; the latter also needs access to several shared variables (`ihi`, `ndim`, `psum`) and arguments of `amoeba` (`p`, `y`, `func`).

The obvious (but not best) way of coding this would be to put the computational guts in `amoeba`, with `amotry` as the sole internal subprogram. Assuming that `fac` is passed as an argument to `amotry` (it being the parameter that is being rapidly altered), one must decide whether to pass all the other quantities to `amotry` (i) as additional arguments (as is done in the Fortran 77 version), or (ii) “automatically,” i.e., doing nothing except using the fact that an internal subprogram has automatic access to all of its host’s entities. Each of these choices has strong disadvantages. Choice (i) is inefficient (all those arguments) and also obscures the fact that `fac` is the primary changing argument. Choice (ii) makes the program extremely difficult to read, because it wouldn’t be obvious without careful cross-comparison of the routines *which* variables in `amoeba` are actually global variables that are used by `amotry`.

Choice (ii) is also “unsafe scoping” because it gives a nontrivially complicated internal subprogram, `amotry`, access to all the variables in its host. A common and difficult-to-find bug is the accidental alteration of a variable that one “thought”

was local, but is actually shared. (Simple variables like *i*, *j*, and *n* are the most common culprits.)

We are therefore led to reject both choice (i) and choice (ii) in favor of a structure previously described in the subsection on Scope, Visibility, and Data Hiding in §21.5. The guts of *amoeba* are put in *amoeba\_private*, a *sister routine* to *amotry*. These two siblings have mutually private name spaces. However, any variables that they need to share (including the top-level arguments of *amoeba*) are declared as variables in the enclosing *amoeba* routine. The presence of these “global variables” serves as a warning flag to the reader that data are shared between routines.

An alternative attractive way of coding the above situation would be to use a module containing *amoeba* and *amotry*. Everything would be declared private except the name *amoeba*. The global variables would be at the top level, and the arguments of *amoeba* that need to be passed to *amotry* would be handled by pointers among the global variables. Unfortunately, Fortran 90 does not support pointers to functions. Sigh!

`ilo=iminloc...ihi=imaxloc...` See discussion of these functions on p. 1017.

`call swap(y(1)...call swap(p(1,...))` Here the *swap* routine in *nrutil* is called once with a scalar argument and once with a vector argument. Inside *nrutil* scalar and vector versions have been overloaded onto the single name *swap*, hiding all the implementation details from the calling routine.

\* \* \*

```

SUBROUTINE powell(p,xi,ftol,iter,fret)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
USE nr, ONLY : linmin
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: p
REAL(SP), DIMENSION(:, :), INTENT(INOUT) :: xi
INTEGER(I4B), INTENT(OUT) :: iter
REAL(SP), INTENT(IN) :: ftol
REAL(SP), INTENT(OUT) :: fret
INTERFACE
  FUNCTION func(p)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), DIMENSION(:), INTENT(IN) :: p
  REAL(SP) :: func
  END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: ITMAX=200
REAL(SP), PARAMETER :: TINY=1.0e-25_sp
  Minimization of a function func of N variables. (func is not an argument, it is a fixed
  function name.) Input consists of an initial starting point p, a vector of length N; an
  initial  $N \times N$  matrix xi whose columns contain the initial set of directions (usually the N
  unit vectors); and ftol, the fractional tolerance in the function value such that failure to
  decrease by more than this amount on one iteration signals doneness. On output, p is set
  to the best point found, xi is the then-current direction set, fret is the returned function
  value at p, and iter is the number of iterations taken. The routine linmin is used.
  Parameters: Maximum allowed iterations, and a small number.
INTEGER(I4B) :: i,ibig,n
REAL(SP) :: del,fp,fptt,t
REAL(SP), DIMENSION(size(p)) :: pt,ptt,xit
n=assert_eq(size(p),size(xi,1),size(xi,2),'powell')
fret=func(p)

```



```

pt(:)=p(:)          Save the initial point.
iter=0
do
  iter=iter+1
  fp=fret
  ibig=0
  del=0.0           Will be the biggest function decrease.
  do i=1,n         Loop over all directions in the set.
    xit(:)=xi(:,i) Copy the direction,
    fptt=fret
    call linmin(p,xit,fret) minimize along it,
    if (fptt-fret > del) then and record it if it is the largest decrease so
      del=fptt-fret         far.
      ibig=i
    end if
  end do
  if (2.0_sp*(fp-fret) <= ftol*(abs(fp)+abs(fret))+TINY) RETURN
  Termination criterion.
  if (iter == ITMAX) call &
    nrerror('powell exceeding maximum iterations')
  ptt(:)=2.0_sp*p(:)-pt(:) Construct the extrapolated point and the av-
  xit(:)=p(:)-pt(:)       erage direction moved. Save the old start-
  pt(:)=p(:)              ing point.
  fptt=func(ptt)          Function value at extrapolated point.
  if (fptt >= fp) cycle   One reason not to use new direction.
  t=2.0_sp*(fp-2.0_sp*fret+fptt)*(fp-fret-del)**2-del*(fp-fptt)**2
  if (t >= 0.0) cycle    Other reason not to use new direction.
  call linmin(p,xit,fret) Move to minimum of the new direction,
  xi(:,ibig)=xi(:,n)    and save the new direction.
  xi(:,n)=xit(:)
end do                 Back for another iteration.
END SUBROUTINE powell

```

\* \* \*

```

MODULE f1dim_mod      Used for communication from linmin to f1dim.
USE nrtype
INTEGER(I4B) :: ncom
REAL(SP), DIMENSION(:), POINTER :: pcom,xicom
CONTAINS
FUNCTION f1dim(x)
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: f1dim
  Used by linmin as the one-dimensional function passed to mnbrak and Brent.
INTERFACE
  FUNCTION func(x)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: x
  REAL(SP) :: func
  END FUNCTION func
END INTERFACE
REAL(SP), DIMENSION(:), ALLOCATABLE :: xt
allocate(xt(ncom))
xt(:)=pcom(:)+x*xicom(:)
f1dim=func(xt)
deallocate(xt)
END FUNCTION f1dim
END MODULE f1dim_mod

```

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```

SUBROUTINE linmin(p,xi,fret)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : mnbrak,brent
USE f1dim_mod
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: fret
REAL(SP), DIMENSION(:), TARGET, INTENT(INOUT) :: p,xi
REAL(SP), PARAMETER :: TOL=1.0e-4_sp
    Given an  $N$ -dimensional point  $p$  and an  $N$ -dimensional direction  $xi$ , both vectors of length
     $N$ , moves and resets  $p$  to where the fixed-name function  $func$  takes on a minimum along
    the direction  $xi$  from  $p$ , and replaces  $xi$  by the actual vector displacement that  $p$  was
    moved. Also returns as  $fret$  the value of  $func$  at the returned location  $p$ . This is actually
    all accomplished by calling the routines  $mnbrak$  and  $brent$ .
    Parameter: Tolerance passed to  $brent$ .
REAL(SP) :: ax,bx,fa,fb,fx,xmin,xx
ncom=assert_eq(size(p),size(xi),'linmin')
pcom=>p          Communicate the global variables to f1dim.
xicom=>xi
ax=0.0          Initial guess for brackets.
xx=1.0
call mnbrak(ax,xx,bx,fa,fb,fx,f1dim)
fret=brent(ax,xx,bx,f1dim,TOL,xmin)
xi=xmin*xi      Construct the vector results to return.
p=p+xi
END SUBROUTINE linmin

```

**f90** USE f1dim\_mod At first sight this situation is like the one involving USE fminln in newt on p. 1197: We want to pass arrays  $p$  and  $xi$  from  $linmin$  to  $f1dim$  without having them be arguments of  $f1dim$ . If you recall the discussion in §21.5 and on p. 1197, there are two ways of effecting this: via pointers or via allocatable arrays. There is an important difference here, however. The arrays  $p$  and  $xi$  are themselves arguments of  $linmin$ , and so cannot be allocatable arrays in the module. If we did want to use allocatable arrays in the module, we would have to copy  $p$  and  $xi$  into them. The pointer implementation is much more elegant, since no unnecessary copying is required. The construction here is identical to the one in  $fminln$  and  $newt$ , except that  $p$  and  $xi$  are arguments instead of automatic arrays.

\* \* \*

```

MODULE df1dim_mod          Used for communication from dlinmin to f1dim and df1dim.
USE nrtype
INTEGER(I4B) :: ncom
REAL(SP), DIMENSION(:), POINTER :: pcom,xicom
CONTAINS
FUNCTION f1dim(x)
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: f1dim
    Used by dlinmin as the one-dimensional function passed to mnbrak.
INTERFACE
    FUNCTION func(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP) :: func
    END FUNCTION func
END INTERFACE
REAL(SP), DIMENSION(:), ALLOCATABLE :: xt

```

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```

allocate(xt(ncom))
xt(:)=pcom(:)+x*xicom(:)
f1dim=func(xt)
deallocate(xt)
END FUNCTION f1dim

FUNCTION df1dim(x)
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP) :: df1dim
  Used by dlinmin as the one-dimensional function passed to dbrent.
INTERFACE
  FUNCTION dfunc(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: dfunc
  END FUNCTION dfunc
END INTERFACE
REAL(SP), DIMENSION(:), ALLOCATABLE :: xt,df
allocate(xt(ncom),df(ncom))
xt(:)=pcom(:)+x*xicom(:)
df(:)=dfunc(xt)
df1dim=dot_product(df,xicom)
deallocate(xt,df)
END FUNCTION df1dim
END MODULE df1dim_mod

```

```

SUBROUTINE dlinmin(p,xi,fret)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : mnbrak,dbrent
USE df1dim_mod
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: fret
REAL(SP), DIMENSION(:), TARGET :: p,xi
REAL(SP), PARAMETER :: TOL=1.0e-4_sp
  Given an  $N$ -dimensional point  $p$  and an  $N$ -dimensional direction  $xi$ , both vectors of length
   $N$ , moves and resets  $p$  to where the fixed-name function  $func$  takes on a minimum along
  the direction  $xi$  from  $p$ , and replaces  $xi$  by the actual vector displacement that  $p$  was
  moved. Also returns as  $fret$  the value of  $func$  at the returned location  $p$ . This is actually
  all accomplished by calling the routines  $mnbrak$  and  $dbrent$ .  $dfunc$  is a fixed-name user-
  supplied function that computes the gradient of  $func$ .
  Parameter: Tolerance passed to  $dbrent$ .
REAL(SP) :: ax,bx,fa,fb,fx,xmin,xx
ncom=assert_eq(size(p),size(xi),'dlinmin')
pcom=>p      Communicate the global variables to f1dim.
xicom=>xi
ax=0.0      Initial guess for brackets.
xx=1.0
call mnbrak(ax,xx,bx,fa,fb,fx,f1dim)
fret=dbrent(ax,xx,bx,f1dim,df1dim,TOL,xmin)
xi=xmin*xi  Construct the vector results to return.
p=p+xi
END SUBROUTINE dlinmin

```



USE df1dim\_mod See discussion of USE f1dim\_mod on p. 1212.

★ ★ ★

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```

SUBROUTINE frprmn(p,ftol,iter,fret)
USE nrtype; USE nrutil, ONLY : nrerror
USE nr, ONLY : linmin
IMPLICIT NONE
INTEGER(I4B), INTENT(OUT) :: iter
REAL(SP), INTENT(IN) :: ftol
REAL(SP), INTENT(OUT) :: fret
REAL(SP), DIMENSION(:), INTENT(INOUT) :: p
INTERFACE
  FUNCTION func(p)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), DIMENSION(:), INTENT(IN) :: p
    REAL(SP) :: func
  END FUNCTION func

  FUNCTION dfunc(p)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), DIMENSION(:), INTENT(IN) :: p
    REAL(SP), DIMENSION(size(p)) :: dfunc
  END FUNCTION dfunc
END INTERFACE
INTEGER(I4B), PARAMETER :: ITMAX=200
REAL(SP), PARAMETER :: EPS=1.0e-10_sp
  Given a starting point p that is a vector of length N, Fletcher-Reeves-Polak-Ribiere
  minimization is performed on a function func, using its gradient as calculated by a routine
  dfunc. The convergence tolerance on the function value is input as ftol. Returned quan-
  tities are p (the location of the minimum), iter (the number of iterations that were
  performed), and fret (the minimum value of the function). The routine linmin is called
  to perform line minimizations.
  Parameters: ITMAX is the maximum allowed number of iterations; EPS is a small number
  to rectify the special case of converging to exactly zero function value.
INTEGER(I4B) :: its
REAL(SP) :: dgg,fp,gam,gg
REAL(SP), DIMENSION(size(p)) :: g,h,xi
fp=func(p)           Initializations.
xi=dfunc(p)
g=-xi
h=g
xi=h
do its=1,ITMAX      Loop over iterations.
  iter=its
  call linmin(p,xi,fret)  Next statement is the normal return:
  if (2.0_sp*abs(fret-fp) <= ftol*(abs(fret)+abs(fp)+EPS)) RETURN
  fp=fret
  xi=dfunc(p)
  gg=dot_product(g,g)
  dgg=dot_product(xi,xi)  This statement for Fletcher-Reeves.
  dgg=dot_product(xi+g,xi) This statement for Polak-Ribiere.
  if (gg == 0.0) RETURN  Unlikely. If gradient is exactly zero then we are al-
  gam=dgg/gg             ready done.
  g=-xi
  h=g+gam*h
  xi=h
end do
call nrerror('frprmn: maximum iterations exceeded')
END SUBROUTINE frprmn

```

\* \* \*

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```

SUBROUTINE dfpmin(p,gto1,iter,fret,func,dfunc)
USE nrtype; USE nrutil, ONLY : nrerror,outerprod,unit_matrix,vabs
USE nr, ONLY : lnsrch
IMPLICIT NONE
INTEGER(I4B), INTENT(OUT) :: iter
REAL(SP), INTENT(IN) :: gto1
REAL(SP), INTENT(OUT) :: fret
REAL(SP), DIMENSION(:), INTENT(INOUT) :: p
INTERFACE
  FUNCTION func(p)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), DIMENSION(:), INTENT(IN) :: p
    REAL(SP) :: func
  END FUNCTION func

  FUNCTION dfunc(p)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), DIMENSION(:), INTENT(IN) :: p
    REAL(SP), DIMENSION(size(p)) :: dfunc
  END FUNCTION dfunc
END INTERFACE
INTEGER(I4B), PARAMETER :: ITMAX=200
REAL(SP), PARAMETER :: STPMX=100.0_sp,EPS=epsilon(p),TOLX=4.0_sp*EPS
  Given a starting point  $p$  that is a vector of length  $N$ , the Broyden-Fletcher-Goldfarb-Shanno
  variant of Davidon-Fletcher-Powell minimization is performed on a function func, using its
  gradient as calculated by a routine dfunc. The convergence requirement on zeroing the
  gradient is input as gto1. Returned quantities are p (the location of the minimum), iter
  (the number of iterations that were performed), and fret (the minimum value of the
  function). The routine lnsrch is called to perform approximate line minimizations.
  Parameters: ITMAX is the maximum allowed number of iterations; STPMX is the scaled
  maximum step length allowed in line searches; EPS is the machine precision; TOLX is the
  convergence criterion on  $x$  values.
INTEGER(I4B) :: its
LOGICAL :: check
REAL(SP) :: den,fac,fad,fae,fp,stpmax,sumdg,sumxi
REAL(SP), DIMENSION(size(p)) :: dg,g,hdg,pnew,xi
REAL(SP), DIMENSION(size(p),size(p)) :: hessin
fp=func(p)           Calculate starting function value and gradi-
g=dfunc(p)           ent.
call unit_matrix(hessin)  Initialize inverse Hessian to the unit matrix.
xi=-g               Initial line direction.
stpmax=STPMX*max(vabs(p),real(size(p),sp))
do its=1,ITMAX       Main loop over the iterations.
  iter=its
  call lnsrch(p,fp,g,xi,pnew,fret,stpmax,check,func)
  The new function evaluation occurs in lnsrch; save the function value in fp for the next
  line search. It is usually safe to ignore the value of check.
  fp=fret
  xi=pnew-p           Update the line direction,
  p=pnew              and the current point.
  if (maxval(abs(xi)/max(abs(p),1.0_sp)) < TOLX) RETURN
  Test for convergence on  $\Delta x$ .
  dg=g                Save the old gradient,
  g=dfunc(p)          and get the new gradient.
  den=max(fret,1.0_sp)
  if (maxval(abs(g)*max(abs(p),1.0_sp)/den) < gto1) RETURN
  Test for convergence on zero gradient.
  dg=g-dg             Compute difference of gradients,
  hdg=matmul(hessin,dg) and difference times current matrix.
  fac=dot_product(dg,xi) Calculate dot products for the denominators.
  fae=dot_product(dg,hdg)
  sumdg=dot_product(dg,dg)

```

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```

sumxi=dot_product(xi,xi)
if (fac > sqrt(EPS*sumdg*sumxi)) then      Skip update if fac not sufficiently
    fac=1.0_sp/fac                          positive.
    fad=1.0_sp/fae
    dg=fac*xi-fad*hdg                       Vector that makes BFGS different from DFP.
    hessin=hessin+fac*outerprod(xi,xi)-&    The BFGS updating formula.
        fad*outerprod(hdg,hdg)+fae*outerprod(dg,dg)
end if
xi=-matmul(hessin,g)                       Now calculate the next direction to go,
end do                                       and go back for another iteration.
call nrerror('dfpmin: too many iterations')
END SUBROUTINE dfpmin

```

**f**<sub>90</sub> call `unit_matrix(hessin)` The `unit_matrix` routine in `nrutil` does exactly what its name suggests. The routine `dfpmin` makes use of `outerprod` from `nrutil`, as well as the matrix intrinsics `matmul` and `dot_product`, to simplify and parallelize the coding.

```

* * *
SUBROUTINE simplx(a,m1,m2,m3,icase,izrov,iposv)
USE nrtype; USE nrutil, ONLY : arth,assert_eq,ifirstloc,imaxloc,&
    nrerror,outerprod,swap
IMPLICIT NONE
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: a
INTEGER(I4B), INTENT(IN) :: m1,m2,m3
INTEGER(I4B), INTENT(OUT) :: icase
INTEGER(I4B), DIMENSION(:), INTENT(OUT) :: izrov,iposv
REAL(SP), PARAMETER :: EPS=1.0e-6_sp
    Simplex method for linear programming. Input parameters a, m1, m2, and m3, and output
    parameters a, icase, izrov, and iposv are described above the routine in Vol. 1. Dimen-
    sions are  $(M+2) \times (N+1)$  for a,  $M$  for iposv,  $N$  for izrov, with  $m1+m2+m3=M$ .
    Parameter: EPS is the absolute precision, which should be adjusted to the scale of your
    variables.
INTEGER(I4B) :: ip,k,kh,kp,nl1,m,n
INTEGER(I4B), DIMENSION(size(a,2)) :: l1
INTEGER(I4B), DIMENSION(m2) :: l3
REAL(SP) :: bmax
LOGICAL(LGT) :: init
m=assert_eq(size(a,1)-2,size(iposv),'simplx: m')
n=assert_eq(size(a,2)-1,size(izrov),'simplx: n')
if (m /= m1+m2+m3) call nrerror('simplx: bad input constraint counts')
if (any(a(2:m+1,1) < 0.0)) call nrerror('bad input tableau in simplx')
    Constants  $b_i$  must be nonnegative.
nl1=n
l1(1:n)=arth(1,1,n)
    Initialize index list of columns admissible for exchange.
izrov(:)=l1(1:n)                               Initially make all variables right-hand.
iposv(:)=n+arth(1,1,m)
    Initial left-hand variables. m1 type constraints are represented by having their slack variable
    initially left-hand, with no artificial variable. m2 type constraints have their slack variable
    initially left-hand, with a minus sign, and their artificial variable handled implicitly during
    their first exchange. m3 type constraints have their artificial variable initially left-hand.
init=.true.
phase1: do
    if (init) then                               Initial pass only.
        if (m2+m3 == 0) exit phase1             Origin is a feasible solution. Go to phase two.
        init=.false.
        l3(1:m2)=1
            Initialize list of m2 constraints whose slack variables have never been exchanged out
            of the initial basis.
        a(m+2,1:n+1)=-sum(a(m1+2:m+1,1:n+1),dim=1)    Compute the auxiliary objec-
    end if                                       tive function.

```

```

if (n11 > 0) then
  kp=l1(imaxloc(a(m+2,l1(1:n11)+1)))      Find the maximum coefficient of the
  bmax=a(m+2,kp+1)                      auxiliary objective function.
else
  bmax=0.0
end if
phase1a: do
  if (bmax <= EPS .and. a(m+2,1) < -EPS) then
    Auxiliary objective function is still negative and can't be improved, hence no
    feasible solution exists.
    icode=-1
    RETURN
  else if (bmax <= EPS .and. a(m+2,1) <= EPS) then
    Auxiliary objective function is zero and can't be improved. This signals that we
    have a feasible starting vector. Clean out the artificial variables corresponding
    to any remaining equality constraints and then eventually exit phase one.
    do ip=m1+m2+1,m
      if (iposv(ip) == ip+n) then          Found an artificial variable for an equal-
      if (n11 > 0) then                    ity constraint.
        kp=l1(imaxloc(abs(a(ip+1,l1(1:n11)+1))))
        bmax=a(ip+1,kp+1)
      else
        bmax=0.0
      end if
      if (bmax > EPS) exit phase1a        Exchange with column correspond-
      end if                               ing to maximum pivot ele-
      end do                               ment in row.
    where (spread(l3(1:m2),2,n+1) == 1) &
      a(m1+2:m1+m2+1,1:n+1)=-a(m1+2:m1+m2+1,1:n+1)
      Change sign of row for any m2 constraints still present from the initial basis.
    exit phase1                            Go to phase two.
  end if
  call simp1                               Locate a pivot element (phase one).
  if (ip == 0) then                         Maximum of auxiliary objective function is
  icode=-1                                  unbounded, so no feasible solution ex-
  RETURN                                    ists.
  end if
  exit phase1a
end do phase1a
call simp2(m+1,n)                          Exchange a left- and a right-hand variable.
if (iposv(ip) >= n+m1+m2+1) then           Exchanged out an artificial variable for an
k=ifirstloc(l1(1:n11) == kp)               equality constraint. Make sure it stays
n11=n11-1                                  out by removing it from the l1 list.
l1(k:n11)=l1(k+1:n11+1)
else
  kh=iposv(ip)-m1-n
  if (kh >= 1) then                         Exchanged out an m2 type constraint.
  if (l3(kh) /= 0) then                     If it's the first time, correct the pivot col-
  l3(kh)=0                                  umn for the minus sign and the implicit
  a(m+2,kp+1)=a(m+2,kp+1)+1.0_sp          artificial variable.
  a(1:m+2,kp+1)=-a(1:m+2,kp+1)
  end if
  end if
  end if
  call swap(izrov(kp),iposv(ip))           Update lists of left- and right-hand variables.
end do phase1                               If still in phase one, go back again.
phase2: do
  We have an initial feasible solution. Now optimize it.
  if (n11 > 0) then
    kp=l1(imaxloc(a(1,l1(1:n11)+1)))      Test the z-row for doneness.
    bmax=a(1,kp+1)
  else
    bmax=0.0
  end if

```

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```

    if (bmax <= EPS) then
        icode=0
        RETURN
    end if
    call simp1
    if (ip == 0) then
        icode=1
        RETURN
    end if
    call simp2(m,n)
    call swap(izrov(kp),iposv(ip))
end do phase2
CONTAINS
SUBROUTINE simp1
    Locate a pivot element, taking degeneracy into account.
    IMPLICIT NONE
    INTEGER(I4B) :: i,k
    REAL(SP) :: q,q0,q1,qp
    ip=0
    i=ifirstloc(a(2:m+1,kp+1) < -EPS)
    if (i > m) RETURN
    q1=-a(i+1,1)/a(i+1,kp+1)
    ip=i
    do i=ip+1,m
        if (a(i+1,kp+1) < -EPS) then
            q=-a(i+1,1)/a(i+1,kp+1)
            if (q < q1) then
                ip=i
                q1=q
            else if (q == q1) then
                We have a degeneracy.
                do k=1,n
                    qp=-a(ip+1,k+1)/a(ip+1,kp+1)
                    q0=-a(i+1,k+1)/a(i+1,kp+1)
                    if (q0 /= qp) exit
                end do
                if (q0 < qp) ip=i
            end if
        end if
    end do
END SUBROUTINE simp1
SUBROUTINE simp2(i1,k1)
    IMPLICIT NONE
    INTEGER(I4B), INTENT(IN) :: i1,k1
    Matrix operations to exchange a left-hand and right-hand variable (see text).
    INTEGER(I4B) :: ip1,kp1
    REAL(SP) :: piv
    INTEGER(I4B), DIMENSION(k1) :: icol
    INTEGER(I4B), DIMENSION(i1) :: irow
    INTEGER(I4B), DIMENSION(max(i1,k1)+1) :: itmp
    ip1=ip+1
    kp1=kp+1
    piv=1.0_sp/a(ip1,kp1)
    itmp(1:k1+1)=arth(1,1,k1+1)
    icol=pack(itmp(1:k1+1),itmp(1:k1+1) /= kp1)
    itmp(1:i1+1)=arth(1,1,i1+1)
    irow=pack(itmp(1:i1+1),itmp(1:i1+1) /= ip1)
    a(irow,kp1)=a(irow,kp1)*piv
    a(irow,icol)=a(irow,icol)-outerprod(a(irow,kp1),a(ip1,icol))
    a(ip1,icol)=-a(ip1,icol)*piv
    a(ip1,kp1)=piv
END SUBROUTINE simp2
END SUBROUTINE simplx

```

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**f90** `main_procedure: do` The routine `simplex` makes extensive use of named do-loops to control the program flow. The various `exit` statements have the names of the do-loops attached to them so we can easily tell where control is being transferred to. We believe that it is almost never necessary to use `goto` statements: Code will always be clearer with well-constructed block structures.

`phase1a: do...end do phase1a` This is not a real do-loop: It is executed only once, as you can see from the unconditional `exit` before the `end do`. We use this construction to define a block of code that is traversed once but that has several possible exit points.

```
where (spread(l3(1:m12-m1),2,n+1) == 1) &
a(m1+2:m12+1,1:n+1)=-a(m1+2:m12+1,1:n+1)
```

These lines are equivalent to

```
do i=m1+1,m12
  if (l3(i-m1) == 1) a(i+1,1:n+1)=-a(i+1,1:n+1)
end do
```

\* \* \*

```
SUBROUTINE anneal(x,y,iorder)
USE nrtype; USE nrutil, ONLY : arth,assert_eq,swap
USE nr, ONLY : ran1
IMPLICIT NONE
INTEGER(I4B), DIMENSION(:), INTENT(INOUT) :: iorder
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
  This algorithm finds the shortest round-trip path to N cities whose coordinates are in the
  length N arrays x, y. The length N array iorder specifies the order in which the cities are
  visited. On input, the elements of iorder may be set to any permutation of the numbers
  1...N. This routine will return the best alternative path it can find.
INTEGER(I4B), DIMENSION(6) :: n
INTEGER(I4B) :: i1,i2,j,k,nlimit,ncity,nn,nover,nsucc
REAL(SP) :: de,harvest,path,t,tfactr
LOGICAL(LGT) :: ans
ncity=assert_eq(size(x),size(y),size(iorder),'anneal')
nover=100*ncity           Maximum number of paths tried at any temperature,
nlimit=10*ncity          and of successful path changes before continuing.
tfactr=0.9_sp           Annealing schedule: t is reduced by this factor on
t=0.5_sp                 each step.
path=sum(alen_v(x(iorder(1:ncity-1)),x(iorder(2:ncity))),&
y(iorder(1:ncity-1)),y(iorder(2:ncity)))) Calculate initial path length.
i1=iorder(ncity)         Close the loop by tying path ends to-
i2=iorder(1)             gether.
path=path+alen(x(i1),x(i2),y(i1),y(i2))
do j=1,100               Try up to 100 temperature steps.
  nsucc=0
  do k=1,nover
    do
      call ran1(harvest)
      n(1)=1+int(ncity*harvest)           Choose beginning of segment...
      call ran1(harvest)
      n(2)=1+int((ncity-1)*harvest)       ... and end of segment.
      if (n(2) >= n(1)) n(2)=n(2)+1
      nn=1+mod((n(1)-n(2)+ncity-1),ncity) nn is the number of cities not on
      if (nn >= 3) exit                   the segment.
    end do
  end do
```

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```

call ran1(harvest)
  Decide whether to do a reversal or a transport.
if (harvest < 0.5_sp) then      Do a transport.
  call ran1(harvest)
  n(3)=n(2)+int(abs(mn-2)*harvest)+1
  n(3)=1+mod(n(3)-1,ncity)      Transport to a location not on the path.
  call trncst(x,y,iorder,n,de) Calculate cost.
  call metrop(de,t,ans)         Consult the oracle.
  if (ans) then
    nsucc=nsucc+1
    path=path+de
    call trnspt(iorder,n)       Carry out the transport.
  end if
else
  call revcst(x,y,iorder,n,de) Do a path reversal.
  call metrop(de,t,ans)         Calculate cost.
  if (ans) then                 Consult the oracle.
    nsucc=nsucc+1
    path=path+de
    call revers(iorder,n)       Carry out the reversal.
  end if
end if
  if (nsucc >= nlimit) exit      Finish early if we have enough successful
end do                          changes.
write(*,*)
write(*,*) 'T =',t,' Path Length =',path
write(*,*) 'Successful Moves: ',nsucc
t=t*tfactr                       Annealing schedule.
if (nsucc == 0) RETURN           If no success, we are done.
end do
CONTAINS
FUNCTION alen(x1,x2,y1,y2)
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x1,x2,y1,y2
REAL(SP) :: alen
  Computes distance between two cities.
alen=sqrt((x2-x1)**2+(y2-y1)**2)
END FUNCTION alen
FUNCTION alen_v(x1,x2,y1,y2)
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x1,x2,y1,y2
REAL(SP), DIMENSION(size(x1)) :: alen_v
  Computes distances between pairs of cities.
alen_v=sqrt((x2-x1)**2+(y2-y1)**2)
END FUNCTION alen_v
SUBROUTINE metrop(de,t,ans)
IMPLICIT NONE
REAL(SP), INTENT(IN) :: de,t
LOGICAL(LGT), INTENT(OUT) :: ans
  Metropolis algorithm. ans is a logical variable that issues a verdict on whether to accept a
  reconfiguration that leads to a change de in the objective function. If de<0, ans=.true.,
  while if de>0, ans is only .true. with probability exp(-de/t), where t is a temperature
  determined by the annealing schedule.
call ran1(harvest)
ans=(de < 0.0) .or. (harvest < exp(-de/t))
END SUBROUTINE metrop
SUBROUTINE revcst(x,y,iorder,n,de)
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: iorder
INTEGER(I4B), DIMENSION(:), INTENT(INOUT) :: n
REAL(SP), INTENT(OUT) :: de

```

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This subroutine returns the value of the cost function for a proposed path reversal. The arrays *x* and *y* give the coordinates of these cities. *iorder* holds the present itinerary. The first two values *n*(1) and *n*(2) of array *n* give the starting and ending cities along the path segment which is to be reversed. On output, *de* is the cost of making the reversal. The actual reversal is not performed by this routine.

```
INTEGER(I4B) :: ncity
REAL(SP), DIMENSION(4) :: xx,yy
ncity=size(x)
n(3)=1+mod((n(1)+ncity-2),ncity)
n(4)=1+mod(n(2),ncity)
xx(1:4)=x(iorder(n(1:4)))
yy(1:4)=y(iorder(n(1:4)))
de=-alen(xx(1),xx(3),yy(1),yy(3))&
  -alen(xx(2),xx(4),yy(2),yy(4))&
  +alen(xx(1),xx(4),yy(1),yy(4))&
  +alen(xx(2),xx(3),yy(2),yy(3))
END SUBROUTINE revcst
```

Find the city before *n*(1) ...  
... and the city after *n*(2).  
Find coordinates for the four cities involved.

Calculate cost of disconnecting the segment  
at both ends and reconnecting in the op-  
posite order.

```
SUBROUTINE revers(iorder,n)
IMPLICIT NONE
INTEGER(I4B), DIMENSION(:), INTENT(INOUT) :: iorder
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: n
```

This routine performs a path segment reversal. *iorder* is an input array giving the present itinerary. The vector *n* has as its first four elements the first and last cities *n*(1), *n*(2) of the path segment to be reversed, and the two cities *n*(3) and *n*(4) that immediately precede and follow this segment. *n*(3) and *n*(4) are found by subroutine *revcst*. On output, *iorder* contains the segment from *n*(1) to *n*(2) in reversed order.

```
INTEGER(I4B) :: j,k,l,nn,ncity
ncity=size(iorder)
nn=(1+mod(n(2)-n(1)+ncity,ncity))/2
do j=1,nn
  k=1+mod((n(1)+j-2),ncity)
  l=1+mod((n(2)-j+ncity),ncity)
  call swap(iorder(k),iorder(l))
end do
END SUBROUTINE revers
```

This many cities must be swapped to effect  
the reversal.

Start at the ends of the segment and swap  
pairs of cities, moving toward the cen-  
ter.

```
SUBROUTINE trncst(x,y,iorder,n,de)
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: iorder
INTEGER(I4B), DIMENSION(:), INTENT(INOUT) :: n
REAL(SP), INTENT(OUT) :: de
```

This subroutine returns the value of the cost function for a proposed path segment transport. Arrays *x* and *y* give the city coordinates. *iorder* is an array giving the present itinerary. The first three elements of array *n* give the starting and ending cities of the path to be transported, and the point among the remaining cities after which it is to be inserted. On output, *de* is the cost of the change. The actual transport is not performed by this routine.

```
INTEGER(I4B) :: ncity
REAL(SP), DIMENSION(6) :: xx,yy
ncity=size(x)
n(4)=1+mod(n(3),ncity)
n(5)=1+mod((n(1)+ncity-2),ncity)
n(6)=1+mod(n(2),ncity)
xx(1:6)=x(iorder(n(1:6)))
yy(1:6)=y(iorder(n(1:6)))
de=-alen(xx(2),xx(6),yy(2),yy(6))&
  -alen(xx(1),xx(5),yy(1),yy(5))&
  -alen(xx(3),xx(4),yy(3),yy(4))&
  +alen(xx(1),xx(3),yy(1),yy(3))&
  +alen(xx(2),xx(4),yy(2),yy(4))&
  +alen(xx(5),xx(6),yy(5),yy(6))
END SUBROUTINE trncst
```

Find the city following *n*(3) ...  
... and the one preceding *n*(1) ...  
... and the one following *n*(2).

Determine coordinates for the six cities in-  
volved.

Calculate the cost of disconnecting the path  
segment from *n*(1) to *n*(2), opening a  
space between *n*(3) and *n*(4), connect-  
ing the segment in the space, and connect-  
ing *n*(5) to *n*(6).

```
SUBROUTINE trnspt(iorder,n)
IMPLICIT NONE
```

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```

INTEGER(I4B), DIMENSION(:), INTENT(INOUT) :: iorder
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: n
  This routine does the actual path transport, once metrop has approved. iorder is an
  input array giving the present itinerary. The array n has as its six elements the beginning
  n(1) and end n(2) of the path to be transported, the adjacent cities n(3) and n(4)
  between which the path is to be placed, and the cities n(5) and n(6) that precede and
  follow the path. n(4), n(5), and n(6) are calculated by subroutine trncst. On output,
  iorder is modified to reflect the movement of the path segment.
INTEGER(I4B) :: m1,m2,m3,nn,ncity
INTEGER(I4B), DIMENSION(size(iorder)) :: jorder
ncity=size(iorder)
m1=1+mod((n(2)-n(1)+ncity),ncity)      Find number of cities from n(1) to n(2) ...
m2=1+mod((n(5)-n(4)+ncity),ncity)      ... and the number from n(4) to n(5)
m3=1+mod((n(3)-n(6)+ncity),ncity)      ... and the number from n(6) to n(3).
jorder(1:m1)=iorder(1+mod((arth(1,1,m1)+n(1)-2),ncity))  Copy the chosen segment.
nn=m1
jorder(nn+1:nn+m2)=iorder(1+mod((arth(1,1,m2)+n(4)-2),ncity))
  Then copy the segment from n(4) to n(5).
nn=nn+m2
jorder(nn+1:nn+m3)=iorder(1+mod((arth(1,1,m3)+n(6)-2),ncity))
  Finally, the segment from n(6) to n(3).
iorder(1:ncity)=jorder(1:ncity)        Copy jorder back into iorder.
END SUBROUTINE trnspt
END SUBROUTINE anneal

```

\* \* \*

```

SUBROUTINE amebasa(p,y,pb,yb,ftol,func,iter,temptr)
USE nrtype; USE nrutil, ONLY : assert_eq,imaxloc,iminloc,swap
USE nr, ONLY : ran1
IMPLICIT NONE
INTEGER(I4B), INTENT(INOUT) :: iter
REAL(SP), INTENT(INOUT) :: yb
REAL(SP), INTENT(IN) :: ftol,temptr
REAL(SP), DIMENSION(:), INTENT(INOUT) :: y,pb
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: p
INTERFACE
  FUNCTION func(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP) :: func
  END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: NMAX=200
  Minimization of the  $N$ -dimensional function func by simulated annealing combined with the
  downhill simplex method of Nelder and Mead. The  $(N+1) \times N$  matrix p is input. Its  $N+1$ 
  rows are  $N$ -dimensional vectors that are the vertices of the starting simplex. Also input is
  the vector y of length  $N+1$ , whose components must be preinitialized to the values of func
  evaluated at the  $N+1$  vertices (rows) of p; ftol, the fractional convergence tolerance to be
  achieved in the function value for an early return; iter, and temptr. The routine makes
  iter function evaluations at an annealing temperature temptr, then returns. You should
  then decrease temptr according to your annealing schedule, reset iter, and call the routine
  again (leaving other arguments unaltered between calls). If iter is returned with a positive
  value, then early convergence and return occurred. If you initialize yb to a very large value
  on the first call, then yb and pb (an array of length  $N$ ) will subsequently return the best
  function value and point ever encountered (even if it is no longer a point in the simplex).
INTEGER(I4B) :: ihi,ndim          Global variables.
REAL(SP) :: yhi
REAL(SP), DIMENSION(size(p,2)) :: psum
call amebasa_private

```

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CONTAINS

```

SUBROUTINE amebsa_private
INTEGER(I4B) :: i, ilo, inhi
REAL(SP) :: rtol, ylo, ynhi, ysave, ytry
REAL(SP), DIMENSION(size(y)) :: yt, harvest
ndim=assert_eq(size(p,2),size(p,1)-1,size(y)-1,size(pb),'amebsa')
psum(:)=sum(p(:,,:),dim=1)
do
    call ran1(harvest)
    yt(:)=y(:)-temptr*log(harvest)
    Whenever we "look at" a vertex, it gets a random thermal fluctuation.
    ilo=iminloc(yt(:))
    ylo=yt(ilo)
    ihi=imaxloc(yt(:))
    yhi=yt(ihi)
    yt(ihi)=ylo
    inhi=imaxloc(yt(:))
    ynhi=yt(inhi)
    rtol=2.0_sp*abs(yhi-ylo)/(abs(yhi)+abs(ylo))
    Compute the fractional range from highest to lowest and return if satisfactory.
    if (rtol < ftol .or. iter < 0) then
        call swap(y(1),y(ilo))
        call swap(p(1,:),p(ilo,:))
        RETURN
    end if
    Begin a new iteration. First extrapolate by a factor -1 through the face of the simplex
    across from the high point, i.e., reflect the simplex from the high point.
    ytry=amotsa(-1.0_sp)
    iter=iter-1
    if (ytry <= ylo) then
        ytry=amotsa(2.0_sp)
        iter=iter-1
        Gives a result better than the best point, so
        try an additional extrapolation by a factor
        of 2.
    else if (ytry >= ynhi) then
        ysave=yhi
        ytry=amotsa(0.5_sp)
        iter=iter-1
        The reflected point is worse than the second-
        highest, so look for an intermediate lower
        point, i.e., do a one-dimensional contraction.
        if (ytry >= ysave) then
            Can't seem to get rid of that high point. Better contract around the lowest
            (best) point.
            p(:, :)=0.5_sp*(p(:, :)+spread(p(ilo, :), 1, size(p, 1)))
            do i=1, ndim+1
                if (i /= ilo) y(i)=func(p(i, :))
            end do
            iter=iter-ndim
            psum(:)=sum(p(:, :), dim=1)
            Keep track of function evaluations.
        end if
    end if
end do
END SUBROUTINE amebsa_private

FUNCTION amotsa(fac)
IMPLICIT NONE
REAL(SP), INTENT(IN) :: fac
REAL(SP) :: amotsa
    Extrapolates by a factor fac through the face of the simplex across from the high point,
    tries it, and replaces the high point if the new point is better.
REAL(SP) :: fac1, fac2, yflu, ytry, harv
REAL(SP), DIMENSION(size(p, 2)) :: ptry
fac1=(1.0_sp-fac)/ndim
fac2=fac1-fac
ptry(:)=psum(:)*fac1-p(ihi, :)*fac2
ytry=func(ptry)
if (ytry <= yb) then
    pb(:)=ptry(:)
    Save the best-ever.
end if

```

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```

      yb=ytry
end if
call ran1(harv)
yflu=ytry+temptr*log(harv)
if (yflu < yhi) then
  y(ihi)=ytry
  yhi=yflu
  psum(:)=psum(:)-p(ihi,:)+ptry(:)
  p(ihi,:)=ptry(:)
end if
amotsa=yflu
END FUNCTION amotsa
END SUBROUTINE amebsa

```

We *added* a thermal fluctuation to all the current vertices, but we *subtract* it here, so as to give the simplex a thermal Brownian motion: It *likes* to accept any suggested change.



See the discussion of amoeba on p. 1209 for why the routine is coded this way.

## Chapter B11. Eigensystems

```

SUBROUTINE jacobi(a,d,v,nrot)
USE nrtype; USE nrutil, ONLY : assert_eq,get_diag,nrerror,unit_matrix,&
    upper_triangle
IMPLICIT NONE
INTEGER(I4B), INTENT(OUT) :: nrot
REAL(SP), DIMENSION(:), INTENT(OUT) :: d
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: a
REAL(SP), DIMENSION(:,:), INTENT(OUT) :: v
    Computes all eigenvalues and eigenvectors of a real symmetric  $N \times N$  matrix a. On output,
    elements of a above the diagonal are destroyed. d is a vector of length N that returns the
    eigenvalues of a. v is an  $N \times N$  matrix whose columns contain, on output, the normalized
    eigenvectors of a. nrot returns the number of Jacobi rotations that were required.
INTEGER(I4B) :: i,ip,iq,n
REAL(SP) :: c,g,h,s,sm,t,tau,theta,tresh
REAL(SP), DIMENSION(size(d)) :: b,z
n=assert_eq(/size(a,1),size(a,2),size(d),size(v,1),size(v,2)/),'jacobi')
call unit_matrix(v(:,:))           Initialize v to the identity matrix.
b(:)=get_diag(a(:,:))             Initialize b and d to the diagonal of
d(:)=b(:)                          a.
z(:)=0.0                            This vector will accumulate terms of
nrot=0                               the form  $ta_{pq}$  as in eq. (11.1.14).
do i=1,50
    sm=sum(abs(a),mask=upper_triangle(n,n))    Sum off-diagonal elements.
    if (sm == 0.0) RETURN
        The normal return, which relies on quadratic convergence to machine underflow.
    tresh=merge(0.2_sp*sm/n**2,0.0_sp, i < 4 )
        On the first three sweeps, we will rotate only if tresh exceeded.
    do ip=1,n-1
        do iq=ip+1,n
            g=100.0_sp*abs(a(ip,iq))
                After four sweeps, skip the rotation if the off-diagonal element is small.
            if ((i > 4) .and. (abs(d(ip))+g == abs(d(ip))) &
                .and. (abs(d(iq))+g == abs(d(iq)))) then
                a(ip,iq)=0.0
            else if (abs(a(ip,iq)) > tresh) then
                h=d(iq)-d(ip)
                if (abs(h)+g == abs(h)) then
                    t=a(ip,iq)/h                 $t = 1/(2\theta)$ 
                else
                    theta=0.5_sp*h/a(ip,iq)    Equation (11.1.10).
                    t=1.0_sp/(abs(theta)+sqrt(1.0_sp+theta**2))
                    if (theta < 0.0) t=-t
                end if
                c=1.0_sp/sqrt(1+t**2)
                s=t*c
                tau=s/(1.0_sp+c)
                h=t*a(ip,iq)
                z(ip)=z(ip)-h
                z(iq)=z(iq)+h
                d(ip)=d(ip)-h
                d(iq)=d(iq)+h
                a(ip,iq)=0.0

```


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```

      call jrotate(a(1:ip-1,ip),a(1:ip-1,iq))
        Case of rotations  $1 \leq j < p$ .
      call jrotate(a(ip,ip+1:iq-1),a(ip+1:iq-1,iq))
        Case of rotations  $p < j < q$ .
      call jrotate(a(ip,iq+1:n),a(iq,iq+1:n))
        Case of rotations  $q < j \leq n$ .
      call jrotate(v(:,ip),v(:,iq))
      nrot=nrot+1
    end if
  end do
end do
b(:)=b(:)+z(:)
d(:)=b(:)
z(:)=0.0
call nrerror('too many iterations in jacobi')
CONTAINS
SUBROUTINE jrotate(a1,a2)
REAL(SP), DIMENSION(:), INTENT(INOUT) :: a1,a2
REAL(SP), DIMENSION(size(a1)) :: wk1
wk1(:)=a1(:)
a1(:)=a1(:)-s*(a2(:)+a1(:)*tau)
a2(:)=a2(:)+s*(wk1(:)-a2(:)*tau)
END SUBROUTINE jrotate
END SUBROUTINE jacobi

```

Update d with the sum of  $ta_{pq}$ ,  
and reinitialize z.

 As discussed in Volume 1, `jacobi` is generally not competitive with `tqli` in terms of efficiency. However, `jacobi` can be parallelized whereas `tqli` uses an intrinsically serial algorithm. The version of `jacobi` implemented here is likely to be adequate for a small-scale parallel (SSP) machine, but is probably still not competitive with `tqli`. For a massively multiprocessor (MMP) machine, the order of the rotations needs to be chosen in a more complicated pattern than here so that the rotations can be executed in parallel. In this case the Jacobi algorithm may well turn out to be the method of choice. Parallel replacements for `tqli` based on a divide and conquer algorithm have also been proposed. See the discussion after `tqli` on p. 1229.

 `call unit_matrix...b(:)=get_diag...` These routines in `nrutil` both require access to the diagonal of a matrix, an operation that is not conveniently provided for in Fortran 90. We have split them off into `nrutil` in case your compiler provides parallel library routines so you can replace our standard versions.

`sm=sum(abs(a),mask=upper_triangle(n,n))` The `upper_triangle` function in `nrutil` returns an upper triangular logical mask. As used here, the mask is true everywhere in the upper triangle of an  $n \times n$  matrix, excluding the diagonal. An optional integer argument `extra` allows additional diagonals to be set to true. With `extra=1` the upper triangle including the diagonal would be true. By using the mask, we can conveniently sum over the desired matrix elements in parallel.

`SUBROUTINE jrotate(a1,a2)` This internal subroutine also uses the values of `s` and `tau` from the calling subroutine `jacobi`. Variables in the calling routine are visible to an internal subprogram, but you should be circumspect in making use of this fact. It is easy to overwrite a value in the calling program inadvertently, and it is



often difficult to figure out the logic of an internal routine if not all its variables are declared explicitly. However, `jrotate` is so simple that there is no danger here.

\* \* \*

```

SUBROUTINE eigsrt(d,v)
USE nrtype; USE nrutil, ONLY : assert_eq,imaxloc,swap
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: d
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: v
    Given the eigenvalues d and eigenvectors v as output from jacobi (§11.1) or tqli (§11.3),
    this routine sorts the eigenvalues into descending order, and rearranges the columns of v
    correspondingly. The method is straight insertion.
INTEGER(I4B) :: i,j,n
n=assert_eq(size(d),size(v,1),size(v,2),'eigsrt')
do i=1,n-1
    j=imaxloc(d(i:n))+i-1
    if (j /= i) then
        call swap(d(i),d(j))
        call swap(v(:,i),v(:,j))
    end if
end do
END SUBROUTINE eigsrt

```



`j=imaxloc...` See discussion of `imaxloc` on p. 1017.

`call swap...` See discussion of overloaded versions of `swap` after `amoeba` on p. 1210.

\* \* \*

```

SUBROUTINE tred2(a,d,e,novectors)
USE nrtype; USE nrutil, ONLY : assert_eq,outerprod
IMPLICIT NONE
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: a
REAL(SP), DIMENSION(:), INTENT(OUT) :: d,e
LOGICAL(LGT), OPTIONAL, INTENT(IN) :: novectors
    Householder reduction of a real, symmetric,  $N \times N$  matrix a. On output, a is replaced
    by the orthogonal matrix Q effecting the transformation. d returns the diagonal elements
    of the tridiagonal matrix, and e the off-diagonal elements, with e(1)=0. If the optional
    argument novectors is present, only eigenvalues are to be found subsequently, in which
    case a contains no useful information on output.
INTEGER(I4B) :: i,j,l,n
REAL(SP) :: f,g,h,hh,scale
REAL(SP), DIMENSION(size(a,1)) :: gg
LOGICAL(LGT), SAVE :: yesvec=.true.
n=assert_eq(size(a,1),size(a,2),size(d),size(e),'tred2')
if (present(novectors)) yesvec=.not. novectors
do i=n,2,-1
    l=i-1
    h=0.0
    if (l > 1) then
        scale=sum(abs(a(i,1:l)))
        if (scale == 0.0) then
            Skip transformation.
            e(i)=a(i,1)
        else
            a(i,1:l)=a(i,1:l)/scale
            Use scaled a's for transformation.
            h=sum(a(i,1:l)**2)
            Form  $\sigma$  in h.
        end if
    end if
end do

```

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```

      f=a(i,1)
      g=-sign(sqrt(h),f)
      e(i)=scale*g
      h=h-f*g
      a(i,1)=f-g
      if (yesvec) a(1:1,i)=a(i,1:1)/h
      do j=1,1
         e(j)=(dot_product(a(j,1:j),a(i,1:j)) &
               +dot_product(a(j+1:1,j),a(i,j+1:1)))/h
      end do
      f=dot_product(e(1:1),a(i,1:1))
      hh=f/(h+h)
      e(1:1)=e(1:1)-hh*a(i,1:1)
      do j=1,1
         a(j,1:j)=a(j,1:j)-a(i,j)*e(1:1)-e(j)*a(i,1:j)
      end do
    end if
  else
    e(i)=a(i,1)
  end if
  d(i)=h
end do
if (yesvec) d(1)=0.0
e(1)=0.0
do i=1,n
  if (yesvec) then
    l=i-1
    if (d(i) /= 0.0) then
      gg(1:1)=matmul(a(i,1:1),a(1:1,1:1))
      a(1:1,1:1)=a(1:1,1:1)-outerprod(a(1:1,i),gg(1:1))
    end if
    d(i)=a(i,i)
    a(i,i)=1.0
    a(i,1:1)=0.0
    a(1:1,i)=0.0
  else
    d(i)=a(i,i)
  end if
end do
END SUBROUTINE tred2

```

Now  $h$  is equation (11.2.4).  
 Store  $u$  in the  $i$ th row of  $a$ .  
 Store  $u/H$  in  $i$ th column of  $a$ .  
 Store elements of  $p$  in temporarily unused elements of  $e$ .  
 Form  $K$ , equation (11.2.11).  
 Form  $q$  and store in  $e$  overwriting  $p$ .  
 Reduce  $a$ , equation (11.2.13).  
 Begin accumulation of transformation matrices.  
 This block skipped when  $i=1$ . Use  $u$  and  $u/H$  stored in  $a$  to form  $P \cdot Q$ .  
 Reset row and column of  $a$  to identity matrix for next iteration.

**f90** This routine gives a nice example of the usefulness of optional arguments. The routine is written under the assumption that usually you will want to find both eigenvalues and eigenvectors. In this case you just supply the arguments  $a$ ,  $d$ , and  $e$ . If, however, you want only eigenvalues, you supply the additional logical argument `novectors` with the value `.true.`. The routine then skips the unnecessary computations. Supplying `novectors` with the value `.false.` has the same effect as omitting it.

\* \* \*

```

SUBROUTINE tqli(d,e,z)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
USE nr, ONLY : pythag
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: d,e
REAL(SP), DIMENSION(:,:), OPTIONAL, INTENT(INOUT) :: z
  QL algorithm with implicit shifts, to determine the eigenvalues and eigenvectors of a real,
  symmetric, tridiagonal matrix, or of a real, symmetric matrix previously reduced by tred2

```

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§11.2.  $d$  is a vector of length  $N$ . On input, its elements are the diagonal elements of the tridiagonal matrix. On output, it returns the eigenvalues. The vector  $e$  inputs the subdiagonal elements of the tridiagonal matrix, with  $e(1)$  arbitrary. On output  $e$  is destroyed. When finding only the eigenvalues, the optional argument  $z$  is omitted. If the eigenvectors of a tridiagonal matrix are desired, the  $N \times N$  matrix  $z$  is input as the identity matrix. If the eigenvectors of a matrix that has been reduced by `tred2` are required, then  $z$  is input as the matrix output by `tred2`. In either case, the  $k$ th column of  $z$  returns the normalized eigenvector corresponding to  $d(k)$ .

```

INTEGER(I4B) :: i,iter,l,m,n,ndum
REAL(SP) :: b,c,dd,f,g,p,r,s
REAL(SP), DIMENSION(size(e)) :: ff
n=assert_eq(size(d),size(e),'tqli: n')
if (present(z)) ndum=assert_eq(n,size(z,1),size(z,2),'tqli: ndum')
e(:)=eoshift(e(:),1)           Convenient to renumber the elements of
do l=1,n                       e.
  iter=0
  iterate: do
    do m=l,n-1
      dd=abs(d(m))+abs(d(m+1))   Look for a single small subdiagonal ele-
      if (abs(e(m))+dd == dd) exit ment to split the matrix.
    end do
    if (m == 1) exit iterate
    if (iter == 30) call nrerror('too many iterations in tqli')
    iter=iter+1
    g=(d(l+1)-d(l))/(2.0_sp*e(l))   Form shift.
    r=pythag(g,1.0_sp)
    g=d(m)-d(l)+e(l)/(g+sign(r,g))  This is  $d_m - k_s$ .
    s=1.0
    c=1.0
    p=0.0
    do i=m-1,l,-1
      f=s*e(i)                   A plane rotation as in the original  $QL$ ,
      b=c*e(i)                   followed by Givens rotations to re-
      r=pythag(f,g)              store tridiagonal form.
      e(i+1)=r
      if (r == 0.0) then          Recover from underflow.
        d(i+1)=d(i+1)-p
        e(m)=0.0
        cycle iterate
      end if
      s=f/r
      c=g/r
      g=d(i+1)-p
      r=(d(i)-g)*s+2.0_sp*c*b
      p=s*r
      d(i+1)=g+p
      g=c*r-b
      if (present(z)) then       Form eigenvectors.
        ff(1:n)=z(1:n,i+1)
        z(1:n,i+1)=s*z(1:n,i)+c*ff(1:n)
        z(1:n,i)=c*z(1:n,i)-s*ff(1:n)
      end if
    end do
    d(l)=d(l)-p
    e(l)=g
    e(m)=0.0
  end do iterate
end do
END SUBROUTINE tqli

```



The routine `tqli` is intrinsically serial. A parallel replacement based on a divide and conquer algorithm has been proposed [1,2]. The idea is to split the tridiagonal matrix recursively into two tridiagonal matrices of

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half the size plus a correction. Given the eigensystems of the two smaller tridiagonal matrices, it is possible to join them together and add in the effect of the correction. When some small size of tridiagonal matrix is reached during the recursive splitting, its eigensystem is found directly with a routine like `tqli`. Each of these small problems is independent and can be assigned to an independent processor. The procedures for sewing together can also be done independently. For very large matrices, this algorithm can be an order of magnitude faster than `tqli` even on a serial machine, and no worse than a factor of 2 or 3 slower, depending on the matrix. Unfortunately the parallelism is not well expressed in Fortran 90. Also, the sewing together requires quite involved coding. For an implementation see the LAPACK routine `SSTEDC`. Another parallel strategy for eigensystems uses inverse iteration, where each eigenvalue and eigenvector can be found independently [3].



This routine uses `z` as an optional argument that is required only if eigenvectors are being found as well as eigenvalues.

`iterate:` do See discussion of named do loops after `simplx` on p. 1219.

\* \* \*

```

SUBROUTINE balanc(a)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:, :), INTENT(INOUT) :: a
REAL(SP), PARAMETER :: RADX=radix(a),SQRADX=RADX**2
    Given an  $N \times N$  matrix a, this routine replaces it by a balanced matrix with identical
    eigenvalues. A symmetric matrix is already balanced and is unaffected by this procedure.
    The parameter RADX is the machine's floating-point radix.
INTEGER(I4B) :: i,last,ndum
REAL(SP) :: c,f,g,r,s
ndum=assert_eq(size(a,1),size(a,2),'balanc')
do
  last=1
  do i=1,size(a,1)
    c=sum(abs(a(:,i)))-a(i,i)
    r=sum(abs(a(i,:)))-a(i,i)
    if (c /= 0.0 .and. r /= 0.0) then
      g=r/RADX
      f=1.0
      s=c+r
      do
        if (c >= g) exit
        f=f*RADX
        c=c*SQRADX
      end do
      g=r*RADX
      do
        if (c <= g) exit
        f=f/RADX
        c=c/SQRADX
      end do
      if ((c+r)/f < 0.95_sp*s) then
        last=0
        g=1.0_sp/f
        a(i,:)=a(i,:)*g
        a(:,i)=a(:,i)*f
      end if
    end if
  end do
end if

```

Calculate row and column norms.

If both are nonzero,

find the integer power of the machine radix that comes closest to balancing the matrix.

Apply similarity transformation.

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```

    end do
    if (last /= 0) exit
end do
END SUBROUTINE balanc

```

**f90** REAL(SP), PARAMETER :: RADX=radix(a)... Fortran 90 provides a nice collection of numeric inquiry intrinsic functions. Here we find the machine's floating-point radix. Note that only the type of the argument *a* affects the returned function value.

\* \* \*

```

SUBROUTINE elmhes(a)
USE nrtype; USE nrutil, ONLY : assert_eq,imaxloc,outerprod,swap
IMPLICIT NONE
REAL(SP), DIMENSION(:, :) , INTENT(INOUT) :: a
  Reduction to Hessenberg form by the elimination method. The real, nonsymmetric,  $N \times N$ 
  matrix a is replaced by an upper Hessenberg matrix with identical eigenvalues. Recommended,
  but not required, is that this routine be preceded by balanc. On output, the
  Hessenberg matrix is in elements a(i, j) with  $i \leq j + 1$ . Elements with  $i > j + 1$  are to be
  thought of as zero, but are returned with random values.
INTEGER(I4B) :: i,m,n
REAL(SP) :: x
REAL(SP), DIMENSION(size(a,1)) :: y
n=assert_eq(size(a,1),size(a,2),'elmhes')
do m=2,n-1
  i=imaxloc(abs(a(m:n,m-1)))+m-1
  x=a(i,m-1)
  if (i /= m) then
    call swap(a(i,m-1:n),a(m,m-1:n))
    call swap(a(:,i),a(:,m))
  end if
  if (x /= 0.0) then
    y(m+1:n)=a(m+1:n,m-1)/x
    a(m+1:n,m-1)=y(m+1:n)
    a(m+1:n,m:n)=a(m+1:n,m:n)-outerprod(y(m+1:n),a(m,m:n))
    a(:,m)=a(:,m)+matmul(a(:,m+1:n),y(m+1:n))
  end if
end do
END SUBROUTINE elmhes

```

*m* is called *r* + 1 in the text.  
Find the pivot.  
Interchange rows and columns.  
Carry out the elimination.

**f90** *y*(*m*+1:*n*)=... If the four lines of code starting here were all coded for a serial machine in a single do-loop starting with `do i=m+1,n` (see Volume 1), it would pay to test whether *y* was zero because the next three lines could then be skipped for that value of *i*. There is no convenient way to do this here, even with a `where`, since the shape of the arrays on each of the three lines is different. For a parallel machine it is probably best just to do a few unnecessary multiplies and skip the test for zero values of *y*.

\* \* \*

```

SUBROUTINE hqr(a,wr,wi)
USE nrtype; USE nrutil, ONLY : assert_eq,diagadd,nrerror,upper_triangle
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(OUT) :: wr,wi
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: a
  Finds all eigenvalues of an  $N \times N$  upper Hessenberg matrix a. On input a can be exactly
  as output from elmhes §11.5; on output it is destroyed. The real and imaginary parts of
  the  $N$  eigenvalues are returned in wr and wi, respectively.
INTEGER(I4B) :: i,its,k,l,m,n,nn,mnk
REAL(SP) :: anorm,p,q,r,s,t,u,v,w,x,y,z
REAL(SP), DIMENSION(size(a,1)) :: pp
n=assert_eq(size(a,1),size(a,2),size(wr),size(wi),'hqr')
anorm=sum(abs(a),mask=upper_triangle(n,n,extra=2))
  Compute matrix norm for possible use in locating single small subdiagonal element.
nn=n
t=0.0
do
  Gets changed only by an exceptional shift.
  Begin search for next eigenvalue: "Do while
  nn >= 1".
  if (nn < 1) exit
  its=0
  iterate: do
    Begin iteration.
    do l=nn,2,-1
      Look for single small subdiagonal element.
      s=abs(a(l-1,l-1))+abs(a(l,l))
      if (s == 0.0) s=anorm
      if (abs(a(l,l-1))+s == s) exit
    end do
    x=a(nn,nn)
    if (l == nn) then
      One root found.
      wr(nn)=x+t
      wi(nn)=0.0
      nn=nn-1
      exit iterate
    Go back for next eigenvalue.
    end if
    y=a(nn-1,nn-1)
    w=a(nn,nn-1)*a(nn-1,nn)
    if (l == nn-1) then
      Two roots found ...
      p=0.5_sp*(y-x)
      q=p**2+w
      z=sqrt(abs(q))
      x=x+t
      if (q >= 0.0) then
        ... a real pair ...
        z=p+sign(z,p)
        wr(nn)=x+z
        wr(nn-1)=wr(nn)
        if (z /= 0.0) wr(nn)=x-w/z
        wi(nn)=0.0
        wi(nn-1)=0.0
      else
        ... a complex pair.
        wr(nn)=x+p
        wr(nn-1)=wr(nn)
        wi(nn)=z
        wi(nn-1)=-z
      end if
      nn=nn-2
      exit iterate
    Go back for next eigenvalue.
    end if
    No roots found. Continue iteration.
  if (its == 30) call nrerror('too many iterations in hqr')
  if (its == 10 .or. its == 20) then
    Form exceptional shift.
    t=t+x
    call diagadd(a(1:nn,1:nn),-x)
    s=abs(a(nn,nn-1))+abs(a(nn-1,nn-2))
    x=0.75_sp*s
    y=x
    w=-0.4375_sp*s**2

```

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```

end if
its=its+1
do m=nn-2,1,-1
    z=a(m,m)
    r=x-z
    s=y-z
    p=(r*s-w)/a(m+1,m)+a(m,m+1)
    q=a(m+1,m+1)-z-r-s
    r=a(m+2,m+1)
    s=abs(p)+abs(q)+abs(r)
    p=p/s
    q=q/s
    r=r/s
    if (m == 1) exit
    u=abs(a(m,m-1))*(abs(q)+abs(r))
    v=abs(p)*(abs(a(m-1,m-1))+abs(z)+abs(a(m+1,m+1)))
    if (u+v == v) exit
end do
do i=m+2,nn
    a(i,i-2)=0.0
    if (i /= m+2) a(i,i-3)=0.0
end do
do k=m,nn-1
    if (k /= m) then
        p=a(k,k-1)
        q=a(k+1,k-1)
        r=0.0
        if (k /= nn-1) r=a(k+2,k-1)
        x=abs(p)+abs(q)+abs(r)
        if (x /= 0.0) then
            p=p/x
            q=q/x
            r=r/x
        end if
    end if
    s=sign(sqrt(p**2+q**2+r**2),p)
    if (s /= 0.0) then
        if (k == m) then
            if (1 /= m) a(k,k-1)=-a(k,k-1)
        else
            a(k,k-1)=-s*x
        end if
        p=p+s
        x=p/s
        y=q/s
        z=r/s
        q=q/p
        r=r/p
        pp(k:nn)=a(k,k:nn)+q*a(k+1,k:nn)
        if (k /= nn-1) then
            pp(k:nn)=pp(k:nn)+r*a(k+2,k:nn)
            a(k+2,k:nn)=a(k+2,k:nn)-pp(k:nn)*z
        end if
        a(k+1,k:nn)=a(k+1,k:nn)-pp(k:nn)*y
        a(k,k:nn)=a(k,k:nn)-pp(k:nn)*x
        mnnk=min(nn,k+3)
        pp(1:mnnk)=x*a(1:mnnk,k)+y*a(1:mnnk,k+1)
        if (k /= nn-1) then
            pp(1:mnnk)=pp(1:mnnk)+z*a(1:mnnk,k+2)
            a(1:mnnk,k+2)=a(1:mnnk,k+2)-pp(1:mnnk)*r
        end if
        a(1:mnnk,k+1)=a(1:mnnk,k+1)-pp(1:mnnk)*q
        a(1:mnnk,k)=a(1:mnnk,k)-pp(1:mnnk)
    end if
end if

```

Form shift and then look for 2 consecutive small subdiagonal elements.

Equation (11.6.23).

Scale to prevent overflow or underflow.

Equation (11.6.26).

Double QR step on rows 1 to nn and columns m to nn.  
Begin setup of Householder vector.

Scale to prevent overflow or underflow.

Equations (11.6.24).

Ready for row modification.

Column modification.

```

      end do
    end do iterate
  end do
END SUBROUTINE hqr

```

Go back for next iteration on current eigenvalue.

**f90** `anorm=sum(abs(a),mask=upper_triangle(n,n,extra=2)` See the discussion of `upper_triangle` after `jacobi` on p. 1226. Setting `extra=2` here picks out the upper Hessenberg part of the matrix.

`iterate: do` We use a named loop to improve the readability and structuring of the routine. The if-blocks that test for one or two roots end with `exit iterate`, transferring control back to the outermost loop and thus starting a search for the next root.

`call diagadd...` The routines that operate on the diagonal of a matrix are collected in `nrutil` partly so you can write clear code and partly in the hope that compiler writers will provide parallel library routines. Fortran 90 does not provide convenient parallel access to the diagonal of a matrix.

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- Lo, S.-S., Philippe, B., and Sameh, A. 1987, *SIAM Journal on Scientific and Statistical Computing*, vol. 8, pp. s155–s165. [3]



## Chapter B12. Fast Fourier Transform

The algorithms underlying the parallel routines in this chapter are described in §22.4. As described there, the basic building block is a routine for simultaneously taking the FFT of each row of a two-dimensional matrix:

```

SUBROUTINE fourrow_sp(data,isign)
USE nrtype; USE nrutil, ONLY : assert,swap
IMPLICIT NONE
COMPLEX(SPC), DIMENSION(:,,:), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign
    Replaces each row (constant first index) of data(1:M,1:N) by its discrete Fourier trans-
    form (transform on second index), if isign is input as 1; or replaces each row of data
    by N times its inverse discrete Fourier transform, if isign is input as -1. N must be an
    integer power of 2. Parallelism is M-fold on the first index of data.
INTEGER(I4B) :: n,i,istep,j,m,mmax,n2
REAL(DP) :: theta
COMPLEX(SPC), DIMENSION(size(data,1)) :: temp
COMPLEX(DPC) :: w,wp           Double precision for the trigonometric recurrences.
COMPLEX(SPC) :: ws
n=size(data,2)
call assert(iand(n,n-1)==0, 'n must be a power of 2 in fourrow_sp')
n2=n/2
j=n2
    This is the bit-reversal section of the routine.
do i=1,n-2
    if (j > i) call swap(data(:,j+1),data(:,i+1))
    m=n2
    do
        if (m < 2 .or. j < m) exit
        j=j-m
        m=m/2
    end do
    j=j+m
end do
mmax=1
    Here begins the Danielson-Lanczos section of the routine.
do                                     Outer loop executed log2 N times.
    if (n <= mmax) exit
    istep=2*mmax
    theta=PI_D/(isign*mmax)           Initialize for the trigonometric recurrence.
    wp=cplx(-2.0_dp*sin(0.5_dp*theta)**2,sin(theta),kind=dpc)
    w=cplx(1.0_dp,0.0_dp,kind=dpc)
    do m=1,mmax                         Here are the two nested inner loops.
        ws=w
        do i=m,n,istep
            j=i+mmax
            temp=ws*data(:,j)           This is the Danielson-Lanczos formula.
            data(:,j)=data(:,i)-temp
            data(:,i)=data(:,i)+temp
        end do
        w=w*wp+w                         Trigonometric recurrence.
    end do
    mmax=istep

```

```
end do
END SUBROUTINE fourrow_sp
```

**f90** call assert(iand(n,n-1)==0 ... All the Fourier routines in this chapter require the dimension  $N$  of the data to be a power of 2. This is easily tested for by AND'ing  $N$  and  $N - 1$ :  $N$  should have the binary representation 10000..., in which case  $N - 1 = 01111...$

```
SUBROUTINE fourrow_dp(data, isign)
USE nrtype; USE nrutil, ONLY : assert, swap
IMPLICIT NONE
COMPLEX(DPC), DIMENSION(:, :), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign
INTEGER(I4B) :: n, i, istep, j, m, mmax, n2
REAL(DP) :: theta
COMPLEX(DPC), DIMENSION(size(data,1)) :: temp
COMPLEX(DPC) :: w, wp
COMPLEX(DPC) :: ws
n=size(data,2)
call assert(iand(n,n-1)==0, 'n must be a power of 2 in fourrow_dp')
n2=n/2
j=n2
do i=1,n-2
  if (j > i) call swap(data(:,j+1),data(:,i+1))
  m=n2
  do
    if (m < 2 .or. j < m) exit
    j=j-m
    m=m/2
  end do
  j=j+m
end do
mmax=1
do
  if (n <= mmax) exit
  istep=2*mmax
  theta=PI_D/(isign*mmax)
  wp=cplx(-2.0_dp*sin(0.5_dp*theta)**2, sin(theta), kind=dpc)
  w=cplx(1.0_dp, 0.0_dp, kind=dpc)
  do m=1, mmax
    ws=w
    do i=m, n, istep
      j=i+mmax
      temp=ws*data(:,j)
      data(:,j)=data(:,i)-temp
      data(:,i)=data(:,i)+temp
    end do
    w=w*wp+w
  end do
  mmax=istep
end do
END SUBROUTINE fourrow_dp
```

```
SUBROUTINE fourrow_3d(data, isign)
USE nrtype; USE nrutil, ONLY : assert, swap
IMPLICIT NONE
COMPLEX(SPC), DIMENSION(:, :, :), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign
  If isign is input as 1, replaces each third-index section (constant first and second indices)
  of data(1:L, 1:M, 1:N) by its discrete Fourier transform (transform on third index); or
```

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replaces each third-index section of data by  $N$  times its inverse discrete Fourier transform, if *isign* is input as  $-1$ .  $N$  must be an integer power of 2. Parallelism is  $L \times M$ -fold on the first and second indices of data.

```

INTEGER(I4B) :: n,i,istep,j,m,mmax,n2
REAL(DP) :: theta
COMPLEX(SPC), DIMENSION(size(data,1),size(data,2)) :: temp
COMPLEX(DPC) :: w,wp                               Double precision for the trigonometric recurrences.
COMPLEX(SPC) :: ws
n=size(data,3)
call assert(iand(n,n-1)==0, 'n must be a power of 2 in fourrow_3d')
n2=n/2
j=n2
This is the bit-reversal section of the routine.
do i=1,n-2
  if (j > i) call swap(data(:, :, j+1), data(:, :, i+1))
  m=n2
  do
    if (m < 2 .or. j < m) exit
    j=j-m
    m=m/2
  end do
  j=j+m
end do
mmax=1
Here begins the Danielson-Lanczos section of the routine.
do
  if (n <= mmax) exit                               Outer loop executed  $\log_2 N$  times.
  istep=2*mmax
  theta=PI_D/(isign*mmax)                           Initialize for the trigonometric recurrence.
  wp=cplx(-2.0_dp*sin(0.5_dp*theta)**2, sin(theta), kind=dpc)
  w=cplx(1.0_dp, 0.0_dp, kind=dpc)
  do m=1,mmax                                       Here are the two nested inner loops.
    ws=w
    do i=m,n,istep
      j=i+mmax
      temp=ws*data(:, :, j)                         This is the Danielson-Lanczos formula.
      data(:, :, j)=data(:, :, i)-temp
      data(:, :, i)=data(:, :, i)+temp
    end do
    w=w*wp+w                                         Trigonometric recurrence.
  end do
  mmax=istep
end do
END SUBROUTINE fourrow_3d

```

\* \* \*



Exactly as in the preceding routines, we can take the FFT of each *column* of a two-dimensional matrix, and for each *first-index* section of a three-dimensional array.

```

SUBROUTINE fourcol(data, isign)
USE nrtype; USE nrutil, ONLY : assert, swap
IMPLICIT NONE
COMPLEX(SPC), DIMENSION(:, :), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign
Replaces each column (constant second index) of data(1:N, 1:M) by its discrete Fourier
transform (transform on first index), if isign is input as 1; or replaces each row of data

```

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```

    by  $N$  times its inverse discrete Fourier transform, if isign is input as  $-1$ .  $N$  must be an
    integer power of 2. Parallelism is  $M$ -fold on the second index of data.
INTEGER(I4B) :: n,i,istep,j,m,mmax,n2
REAL(DP) :: theta
COMPLEX(SPC), DIMENSION(size(data,2)) :: temp
COMPLEX(DPC) :: w,wp           Double precision for the trigonometric recurrences.
COMPLEX(SPC) :: ws
n=size(data,1)
call assert(iand(n,n-1)==0, 'n must be a power of 2 in fourcol')
n2=n/2
j=n2
    This is the bit-reversal section of the routine.
do i=1,n-2
    if (j > i) call swap(data(j+1,:),data(i+1,:))
    m=n2
    do
        if (m < 2 .or. j < m) exit
        j=j-m
        m=m/2
    end do
    j=j+m
end do
mmax=1
    Here begins the Danielson-Lanczos section of the routine.
do                                     Outer loop executed  $\log_2 N$  times.
    if (n <= mmax) exit
    istep=2*mmax
    theta=PI_D/(isign*mmax)           Initialize for the trigonometric recurrence.
    wp=cplx(-2.0_dp*sin(0.5_dp*theta)**2, sin(theta), kind=dpc)
    w=cplx(1.0_dp,0.0_dp, kind=dpc)
    do m=1,mmax                         Here are the two nested inner loops.
        ws=w
        do i=m,n,istep
            j=i+mmax
            temp=ws*data(j,:)           This is the Danielson-Lanczos formula.
            data(j,:)=data(i,)-temp
            data(i,:)=data(i,)+temp
        end do
        w=w*wp+w                       Trigonometric recurrence.
    end do
    mmax=istep
end do
END SUBROUTINE fourcol

```

```

SUBROUTINE fourcol_3d(data,isign)
USE nrtype; USE nrutil, ONLY : assert,swap
IMPLICIT NONE
COMPLEX(SPC), DIMENSION(:,:,:), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign
    If isign is input as 1, replaces each first-index section (constant second and third indices)
    of data(1:N,1:M,1:L) by its discrete Fourier transform (transform on first index); or
    replaces each first-index section of data by  $N$  times its inverse discrete Fourier transform,
    if isign is input as  $-1$ .  $N$  must be an integer power of 2. Parallelism is  $M \times L$ -fold on
    the second and third indices of data.
INTEGER(I4B) :: n,i,istep,j,m,mmax,n2
REAL(DP) :: theta
COMPLEX(SPC), DIMENSION(size(data,2),size(data,3)) :: temp
COMPLEX(DPC) :: w,wp           Double precision for the trigonometric recurrences.
COMPLEX(SPC) :: ws
n=size(data,1)
call assert(iand(n,n-1)==0, 'n must be a power of 2 in fourcol_3d')
n2=n/2

```

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```

j=n2
This is the bit-reversal section of the routine.
do i=1,n-2
  if (j > i) call swap(data(j+1,,:),data(i+1,,:))
  m=n2
  do
    if (m < 2 .or. j < m) exit
    j=j-m
    m=m/2
  end do
  j=j+m
end do
mmax=1
Here begins the Danielson-Lanczos section of the routine.
do
  Outer loop executed log2 N times.
  if (n <= mmax) exit
  istep=2*mmax
  theta=PI_D/(isign*mmax)      Initialize for the trigonometric recurrence.
  wp=cplx(-2.0_dp*sin(0.5_dp*theta)**2, sin(theta), kind=dpc)
  w=cplx(1.0_dp, 0.0_dp, kind=dpc)
  do m=1, mmax                Here are the two nested inner loops.
    ws=w
    do i=m, n, istep
      j=i+mmax
      temp=ws*data(j,,:)      This is the Danielson-Lanczos formula.
      data(j,,:)=data(i,,:)-temp
      data(i,,:)=data(i,,:)+temp
    end do
    w=w*wp+w                  Trigonometric recurrence.
  end do
  mmax=istep
end do
END SUBROUTINE fourcol_3d

```

\* \* \*

Here now are implementations of the method of §22.4 for the FFT of one-dimensional single- and double-precision complex arrays:

```

SUBROUTINE four1_sp(data, isign)
USE nrtype; USE nrutil, ONLY : arth, assert
USE nr, ONLY : fourrow
IMPLICIT NONE
COMPLEX(SPC), DIMENSION(:), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign
  Replaces a complex array data by its discrete Fourier transform, if isign is input as 1;
  or replaces data by its inverse discrete Fourier transform times the size of data, if isign
  is input as -1. The size of data must be an integer power of 2. Parallelism is achieved
  by internally reshaping the input array to two dimensions. (Use this version if fourrow is
  faster than fourcol on your machine.)
COMPLEX(SPC), DIMENSION(:, :), ALLOCATABLE :: dat, temp
COMPLEX(DPC), DIMENSION(:), ALLOCATABLE :: w, wp
REAL(DP), DIMENSION(:), ALLOCATABLE :: theta
INTEGER(I4B) :: n, m1, m2, j
n=size(data)
call assert(iand(n,n-1)==0, 'n must be a power of 2 in four1_sp')
  Find dimensions as close to square as possible, allocate space, and reshape the input array.
m1=2**ceiling(0.5_sp*log(real(n,sp))/0.693147_sp)
m2=n/m1
allocate(dat(m1,m2), theta(m1), w(m1), wp(m1), temp(m2,m1))
dat=reshape(data, shape(dat))
call fourrow(dat, isign)      Transform on second index.

```

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```

theta=arth(0, isign, m1)*TWOPI_D/n      Set up recurrence.
wp=cmplx(-2.0_dp*sin(0.5_dp*theta)**2, sin(theta), kind=dpc)
w=cmplx(1.0_dp, 0.0_dp, kind=dpc)
do j=2, m2                               Multiply by the extra phase factor.
    w=w*wp+w
    dat(:, j)=dat(:, j)*w
end do
temp=transpose(dat)                       Transpose, and transform on (original) first in-
call fourrow(temp, isign)                  dex.
data=reshape(temp, shape(data))           Reshape the result back to one dimension.
deallocate(dat, w, wp, theta, temp)
END SUBROUTINE four1_sp

```

```

SUBROUTINE four1_dp(data, isign)
USE nrtype; USE nrutil, ONLY : arth, assert
USE nr, ONLY : fourrow
IMPLICIT NONE
COMPLEX(DPC), DIMENSION(:), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign
COMPLEX(DPC), DIMENSION(:,:), ALLOCATABLE :: dat, temp
COMPLEX(DPC), DIMENSION(:), ALLOCATABLE :: w, wp
REAL(DP), DIMENSION(:), ALLOCATABLE :: theta
INTEGER(I4B) :: n, m1, m2, j
n=size(data)
call assert(iand(n, n-1)==0, 'n must be a power of 2 in four1_dp')
m1=2**ceiling(0.5_sp*log(real(n, sp))/0.693147_sp)
m2=n/m1
allocate(dat(m1, m2), theta(m1), w(m1), wp(m1), temp(m2, m1))
dat=reshape(data, shape(dat))
call fourrow(dat, isign)
theta=arth(0, isign, m1)*TWOPI_D/n
wp=cmplx(-2.0_dp*sin(0.5_dp*theta)**2, sin(theta), kind=dpc)
w=cmplx(1.0_dp, 0.0_dp, kind=dpc)
do j=2, m2
    w=w*wp+w
    dat(:, j)=dat(:, j)*w
end do
temp=transpose(dat)
call fourrow(temp, isign)
data=reshape(temp, shape(data))
deallocate(dat, w, wp, theta, temp)
END SUBROUTINE four1_dp

```

The above routines use `fourrow` exclusively, on the assumption that it is faster than its sibling `fourcol`. When that is the case (as we typically find), it is likely that `four1_sp` is also faster than Volume 1's scalar `four1`. The reason, on scalar machines, is that `fourrow`'s parallelism is taking better advantage of cache memory locality.

If `fourrow` is *not* faster than `fourcol` on your machine, then you should instead try the following alternative FFT version that uses `fourcol` only.

```

SUBROUTINE four1_alt(data, isign)
USE nrtype; USE nrutil, ONLY : arth, assert
USE nr, ONLY : fourcol
IMPLICIT NONE
COMPLEX(SPC), DIMENSION(:), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign

```

Replaces a complex array `data` by its discrete Fourier transform, if `isign` is input as 1; or replaces `data` by its inverse discrete Fourier transform times the size of `data`, if `isign` is

```

input as -1. The size of data must be an integer power of 2. Parallelism is achieved by
internally reshaping the input array to two dimensions. (Use this version only if fourcol
is faster than fourrow on your machine.)
COMPLEX(SPC), DIMENSION(:, :), ALLOCATABLE :: dat,temp
COMPLEX(DPC), DIMENSION(:), ALLOCATABLE :: w,wp
REAL(DP), DIMENSION(:), ALLOCATABLE :: theta
INTEGER(I4B) :: n,m1,m2,j
n=size(data)
call assert(iand(n,n-1)==0, 'n must be a power of 2 in four1_alt')
  Find dimensions as close to square as possible, allocate space, and reshape the input array.
m1=2**ceiling(0.5_sp*log(real(n,sp))/0.693147_sp)
m2=n/m1
allocate(dat(m1,m2),theta(m1),w(m1),wp(m1),temp(m2,m1))
dat=reshape(data,shape(dat))
temp=transpose(dat)           Transpose and transform on (original) second in-
                              dex.
call fourcol(temp,isign)      Set up recurrence.
theta=arth(0,isign,m1)*TWOPI_D/n
wp=cmplx(-2.0_dp*sin(0.5_dp*theta)**2,sin(theta),kind=dpc)
w=cmplx(1.0_dp,0.0_dp,kind=dpc)
do j=2,m2                     Multiply by the extra phase factor.
  w=w*wp+w
  temp(j,:)=temp(j,:)*w
end do
dat=transpose(temp)          Transpose, and transform on (original) first in-
call fourcol(dat,isign)      dex.
temp=transpose(dat)         Transpose and then reshape the result back to
data=reshape(temp,shape(data) one dimension.
deallocate(dat,w,wp,theta,temp)
END SUBROUTINE four1_alt

```

\* \* \*

With all the machinery of `fourrow` and `fourcol`, two-dimensional FFTs are extremely straightforward. Again there is an alternative version provided in case your hardware favors `fourcol` (which would be, we think, unusual).

```

SUBROUTINE four2(data,isign)
USE nrtype
USE nr, ONLY : fourrow
IMPLICIT NONE
COMPLEX(SPC), DIMENSION(:, :), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign
  Replaces a 2-d complex array data by its discrete 2-d Fourier transform, if isign is input
  as 1; or replaces data by its inverse 2-d discrete Fourier transform times the product of its
  two sizes, if isign is input as -1. Both of data's sizes must be integer powers of 2 (this
  is checked for in fourrow). Parallelism is by use of fourrow.
COMPLEX(SPC), DIMENSION(size(data,2),size(data,1)) :: temp
call fourrow(data,isign)     Transform in second dimension.
temp=transpose(data)        Tranpose.
call fourrow(temp,isign)    Transform in (original) first dimension.
data=transpose(temp)        Transpose into data.
END SUBROUTINE four2

```

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```

SUBROUTINE four2_alt(data, isign)
USE nrtype
USE nr, ONLY : fourcol
IMPLICIT NONE
COMPLEX(SPC), DIMENSION(:, :), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign
    Replaces a 2-d complex array data by its discrete 2-d Fourier transform, if isign is input
    as 1; or replaces data by its inverse 2-d discrete Fourier transform times the product of
    its two sizes, if isign is input as -1. Both of data's sizes must be integer powers of 2
    (this is checked for in fourcol). Parallelism is by use of fourcol. (Use this version only
    if fourcol is faster than fourrow on your machine.)
COMPLEX(SPC), DIMENSION(size(data,2), size(data,1)) :: temp
temp=transpose(data)           Tranpose.
call fourcol(temp, isign)      Transform in (original) second dimension.
data=transpose(temp)          Transpose.
call fourcol(data, isign)      Transform in (original) first dimension.
END SUBROUTINE four2_alt

```

\* \* \*

Most of the remaining routines in this chapter simply call one or another of the above FFT routines, with a small amount of auxiliary computation, so they are fairly straightforward conversions from their Volume 1 counterparts.

```

SUBROUTINE twofft(data1, data2, fft1, fft2)
USE nrtype; USE nrutil, ONLY : assert, assert_eq
USE nr, ONLY : four1
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: data1, data2
COMPLEX(SPC), DIMENSION(:), INTENT(OUT) :: fft1, fft2
    Given two real input arrays data1 and data2 of length N, this routine calls four1 and
    returns two complex output arrays, fft1 and fft2, each of complex length N, that contain
    the discrete Fourier transforms of the respective data arrays. N must be an integer power
    of 2.
INTEGER(I4B) :: n, n2
COMPLEX(SPC), PARAMETER :: C1=(0.5_sp, 0.0_sp), C2=(0.0_sp, -0.5_sp)
COMPLEX, DIMENSION(size(data1)/2+1) :: h1, h2
n=assert_eq(size(data1), size(data2), size(fft1), size(fft2), 'twofft')
call assert(iand(n, n-1) == 0, 'n must be a power of 2 in twofft')
fft1=cplx(data1, data2, kind=spc)    Pack the two real arrays into one complex array.
call four1(fft1, 1)                  Transform the complex array.
fft2(1)=cplx(aimag(fft1(1)), 0.0_sp, kind=spc)
fft1(1)=cplx(real(fft1(1)), 0.0_sp, kind=spc)
n2=n/2+1
h1(2:n2)=C1*(fft1(2:n2)+conjg(fft1(n:n2:-1)))    Use symmetries to separate the
h2(2:n2)=C2*(fft1(2:n2)-conjg(fft1(n:n2:-1)))    two transforms.
fft1(2:n2)=h1(2:n2)                            Ship them out in two complex arrays.
fft1(n:n2:-1)=conjg(h1(2:n2))
fft2(2:n2)=h2(2:n2)
fft2(n:n2:-1)=conjg(h2(2:n2))
END SUBROUTINE twofft

```

\* \* \*

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```

SUBROUTINE realft_sp(data, isign, zdata)
USE nrtype; USE nrutil, ONLY : assert, assert_eq, zroots_unity
USE nr, ONLY : four1
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign
COMPLEX(SPC), DIMENSION(:), OPTIONAL, TARGET :: zdata
  When isign = 1, calculates the Fourier transform of a set of  $N$  real-valued data points,
  input in the array data. If the optional argument zdata is not present, the data are replaced
  by the positive frequency half of its complex Fourier transform. The real-valued first and
  last components of the complex transform are returned as elements data(1) and data(2),
  respectively. If the complex array zdata of length  $N/2$  is present, data is unchanged and
  the transform is returned in zdata.  $N$  must be a power of 2. If isign = -1, this routine
  calculates the inverse transform of a complex data array if it is the transform of real data.
  (Result in this case must be multiplied by  $2/N$ .) The data can be supplied either in data,
  with zdata absent, or in zdata.
INTEGER(I4B) :: n, ndum, nh, nq
COMPLEX(SPC), DIMENSION(size(data)/4) :: w
COMPLEX(SPC), DIMENSION(size(data)/4-1) :: h1, h2
COMPLEX(SPC), DIMENSION(:), POINTER :: cdata    Used for internal complex computa-
COMPLEX(SPC) :: z                                tions.
REAL(SP) :: c1=0.5_sp, c2
n=size(data)
call assert(iand(n,n-1)==0, 'n must be a power of 2 in realft_sp')
nh=n/2
nq=n/4
if (present(zdata)) then
  ndum=assert_eq(n/2, size(zdata), 'realft_sp')
  cdata=>zdata                                Use zdata as cdata.
  if (isign == 1) cdata=cmplx(data(1:n-1:2), data(2:n:2), kind=spc)
else
  allocate(cdata(n/2))                        Have to allocate storage ourselves.
  cdata=cmplx(data(1:n-1:2), data(2:n:2), kind=spc)
end if
if (isign == 1) then
  c2=-0.5_sp
  call four1(cdata, +1)                        The forward transform is here.
else
  c2=0.5_sp                                    Otherwise set up for an inverse trans-
                                              form.
end if
w=zroots_unity(sign(n, isign), n/4)
w=cmplx(-aimag(w), real(w), kind=spc)
h1=c1*(cdata(2:nq)+conjg(cdata(nh:nq+2:-1)))  The two separate transforms are sep-
h2=c2*(cdata(2:nq)-conjg(cdata(nh:nq+2:-1)))  arated out of cdata.
  Next they are recombined to form the true transform of the original real data:
cdata(2:nq)=h1+w(2:nq)*h2
cdata(nh:nq+2:-1)=conjg(h1-w(2:nq)*h2)
z=cdata(1)                                    Squeeze the first and last data to-
if (isign == 1) then                            gether to get them all within the
  cdata(1)=cmplx(real(z)+aimag(z), real(z)-aimag(z), kind=spc)  original array.
else
  cdata(1)=cmplx(c1*(real(z)+aimag(z)), c1*(real(z)-aimag(z)), kind=spc)
  call four1(cdata, -1)                        This is the inverse transform for the
  case isign=-1.
end if
if (present(zdata)) then
  if (isign /= 1) then
    data(1:n-1:2)=real(cdata)
    data(2:n:2)=aimag(cdata)
  end if
  Ship out answer in data if required.
else
  data(1:n-1:2)=real(cdata)
  data(2:n:2)=aimag(cdata)
  deallocate(cdata)
end if

```

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```

END SUBROUTINE realft_sp

SUBROUTINE realft_dp(data, isign, zdata)
USE nrtype; USE nrutil, ONLY : assert, assert_eq, roots_unity
USE nr, ONLY : four1
IMPLICIT NONE
REAL(DP), DIMENSION(:), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign
COMPLEX(DPC), DIMENSION(:), OPTIONAL, TARGET :: zdata
INTEGER(I4B) :: n, ndum, nh, nq
COMPLEX(DPC), DIMENSION(size(data)/4) :: w
COMPLEX(DPC), DIMENSION(size(data)/4-1) :: h1, h2
COMPLEX(DPC), DIMENSION(:), POINTER :: cdata
COMPLEX(DPC) :: z
REAL(DP) :: c1=0.5_dp, c2
n=size(data)
call assert(iand(n,n-1)==0, 'n must be a power of 2 in realft_dp')
nh=n/2
nq=n/4
if (present(zdata)) then
    ndum=assert_eq(n/2, size(zdata), 'realft_dp')
    cdata=>zdata
    if (isign == 1) cdata=cmplx(data(1:n-1:2), data(2:n:2), kind=spc)
else
    allocate(cdata(n/2))
    cdata=cmplx(data(1:n-1:2), data(2:n:2), kind=spc)
end if
if (isign == 1) then
    c2=-0.5_dp
    call four1(cdata, +1)
else
    c2=0.5_dp
end if
w=roots_unity(sign(n, isign), n/4)
w=cmplx(-aimag(w), real(w), kind=dpc)
h1=c1*(cdata(2:nq)+conjg(cdata(nh:nq+2:-1)))
h2=c2*(cdata(2:nq)-conjg(cdata(nh:nq+2:-1)))
cdata(2:nq)=h1+w(2:nq)*h2
cdata(nh:nq+2:-1)=conjg(h1-w(2:nq)*h2)
z=cdata(1)
if (isign == 1) then
    cdata(1)=cmplx(real(z)+aimag(z), real(z)-aimag(z), kind=dpc)
else
    cdata(1)=cmplx(c1*(real(z)+aimag(z)), c1*(real(z)-aimag(z)), kind=dpc)
    call four1(cdata, -1)
end if
if (present(zdata)) then
    if (isign /= 1) then
        data(1:n-1:2)=real(cdata)
        data(2:n:2)=aimag(cdata)
    end if
else
    data(1:n-1:2)=real(cdata)
    data(2:n:2)=aimag(cdata)
    deallocate(cdata)
end if
END SUBROUTINE realft_dp

```

\* \* \*

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```

SUBROUTINE sinft(y)
USE nrtype; USE nrutil, ONLY : assert,cumsum,zroots_unity
USE nr, ONLY : realft
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
  Calculates the sine transform of a set of  $N$  real-valued data points stored in array  $y$ . The
  number  $N$  must be a power of 2. On exit  $y$  is replaced by its transform. This program,
  without changes, also calculates the inverse sine transform, but in this case the output array
  should be multiplied by  $2/N$ .
REAL(SP), DIMENSION(size(y)/2+1) :: w1
REAL(SP), DIMENSION(size(y)/2) :: y1,y2
INTEGER(I4B) :: n,nh
n=size(y)
call assert(iand(n,n-1)==0, 'n must be a power of 2 in sinft')
nh=n/2
w1=aimag(zroots_unity(n+n,nh+1))      Calculate the sine for the auxiliary array.
y(1)=0.0
y1=w1(2:nh+1)*(y(2:nh+1)+y(n:nh+1:-1))
  Construct the two pieces of the auxiliary array.
y2=0.5_sp*(y(2:nh+1)-y(n:nh+1:-1))    Put them together to make the auxiliary array.
y(2:nh+1)=y1+y2
y(n:nh+1:-1)=y1-y2
call realft(y,+1)                      Transform the auxiliary array.
y(1)=0.5_sp*y(1)                       Initialize the sum used for odd terms.
y(2)=0.0
y1=cumsum(y(1:n-1:2))                  Odd terms are determined by this running sum.
y(1:n-1:2)=y(2:n:2)                   Even terms in the transform are determined di-
y(2:n:2)=y1                             rectly.
END SUBROUTINE sinft

```

```

SUBROUTINE cosft1(y)
USE nrtype; USE nrutil, ONLY : assert,cumsum,zroots_unity
USE nr, ONLY : realft
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
  Calculates the cosine transform of a set of  $N+1$  real-valued data points  $y$ . The transformed
  data replace the original data in array  $y$ .  $N$  must be a power of 2. This program, without
  changes, also calculates the inverse cosine transform, but in this case the output array
  should be multiplied by  $2/N$ .
COMPLEX(SPC), DIMENSION((size(y)-1)/2) :: w
REAL(SP), DIMENSION((size(y)-1)/2-1) :: y1,y2
REAL(SP) :: summ
INTEGER(I4B) :: n,nh
n=size(y)-1
call assert(iand(n,n-1)==0, 'n must be a power of 2 in cosft1')
nh=n/2
w=zroots_unity(n+n,nh)
summ=0.5_sp*(y(1)-y(n+1))
y(1)=0.5_sp*(y(1)+y(n+1))
y1=0.5_sp*(y(2:nh)+y(n:nh+2:-1))      Construct the two pieces of the auxiliary array.
y2=y(2:nh)-y(n:nh+2:-1)
summ=summ+sum(real(w(2:nh))*y2)       Carry along this sum for later use in unfolding
y2=y2*aimag(w(2:nh))                  the transform.
y(2:nh)=y1-y2                          Calculate the auxiliary function.
y(n:nh+2:-1)=y1+y2
call realft(y(1:n),1)                  Calculate the transform of the auxiliary function.
y(n+1)=y(2)
y(2)=summ
y(2:n:2)=cumsum(y(2:n:2))              summ is the value of  $F_1$  in equation (12.3.21).
END SUBROUTINE cosft1                  Equation (12.3.20).

```

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```

SUBROUTINE cosft2(y, isign)
USE nrtype; USE nrutil, ONLY : assert, cumsum, zroots_unity
USE nr, ONLY : realft
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
INTEGER(I4B), INTENT(IN) :: isign
    Calculates the "staggered" cosine transform of a set of  $N$  real-valued data points  $y$ . The
    transformed data replace the original data in array  $y$ .  $N$  must be a power of 2. Set  $isign$ 
    to +1 for a transform, and to -1 for an inverse transform. For an inverse transform, the
    output array should be multiplied by  $2/N$ .
COMPLEX(SPC), DIMENSION(size(y)) :: w
REAL(SP), DIMENSION(size(y)/2) :: y1, y2
REAL(SP) :: ytemp
INTEGER(I4B) :: n, nh
n=size(y)
call assert(iand(n,n-1)==0, 'n must be a power of 2 in cosft2')
nh=n/2
w=zroots_unity(4*n,n)
if (isign == 1) then
    Forward transform.
    y1=0.5_sp*(y(1:nh)+y(n:nh+1:-1))    Calculate the auxiliary function.
    y2=aimag(w(2:n:2))*(y(1:nh)-y(n:nh+1:-1))
    y(1:nh)=y1+y2
    y(n:nh+1:-1)=y1-y2
    call realft(y,1)                    Calculate transform of the auxiliary function.
    y1(1:nh-1)=y(3:n-1:2)*real(w(3:n-1:2)) &    Even terms.
    -y(4:n:2)*aimag(w(3:n-1:2))
    y2(1:nh-1)=y(4:n:2)*real(w(3:n-1:2)) &
    +y(3:n-1:2)*aimag(w(3:n-1:2))
    y(3:n-1:2)=y1(1:nh-1)
    y(4:n:2)=y2(1:nh-1)
    ytemp=0.5_sp*y(2)                    Initialize recurrence for odd terms with  $\frac{1}{2}R_{N/2}$ .
    y(n-2:2:-2)=cumsum(y(n:4:-2), ytemp)    Recurrence for odd terms.
    y(n)=ytemp
else if (isign == -1) then
    Inverse transform.
    ytemp=y(n)
    y(4:n:2)=y(2:n-2:2)-y(4:n:2)        Form difference of odd terms.
    y(2)=2.0_sp*ytemp
    y1(1:nh-1)=y(3:n-1:2)*real(w(3:n-1:2)) &    Calculate  $R_k$  and  $I_k$ .
    +y(4:n:2)*aimag(w(3:n-1:2))
    y2(1:nh-1)=y(4:n:2)*real(w(3:n-1:2)) &
    -y(3:n-1:2)*aimag(w(3:n-1:2))
    y(3:n-1:2)=y1(1:nh-1)
    y(4:n:2)=y2(1:nh-1)
    call realft(y,-1)
    y1=y(1:nh)+y(n:nh+1:-1)            Invert auxiliary array.
    y2=(0.5_sp/aimag(w(2:n:2)))*(y(1:nh)-y(n:nh+1:-1))
    y(1:nh)=0.5_sp*(y1+y2)
    y(n:nh+1:-1)=0.5_sp*(y1-y2)
end if
END SUBROUTINE cosft2

```

\* \* \*

```

SUBROUTINE four3(data, isign)
USE nrtype
USE nr, ONLY : fourrow_3d
IMPLICIT NONE
COMPLEX(SPC), DIMENSION(:,:,:), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign
    Replaces a 3-d complex array  $data$  by its discrete 3-d Fourier transform, if  $isign$  is input
    as 1; or replaces  $data$  by its inverse 3-d discrete Fourier transform times the product of its

```

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```

three sizes, if isign is input as -1. All three of data's sizes must be integer powers of 2
(this is checked for in fourrow_3d). Parallelism is by use of fourrow_3d.
COMPLEX(SPC), DIMENSION(:,:,:), ALLOCATABLE :: dat2,dat3
call fourrow_3d(data,isign)          Transform in third dimension.
allocate(dat2(size(data,2),size(data,3),size(data,1)))
dat2=reshape(data,shape=shape(dat2),order=(/3,1,2/))  Transpose.
call fourrow_3d(dat2,isign)         Transform in (original) first dimension.
allocate(dat3(size(data,3),size(data,1),size(data,2)))
dat3=reshape(dat2,shape=shape(dat3),order=(/3,1,2/))  Transpose.
deallocate(dat2)
call fourrow_3d(dat3,isign)         Transform in (original) second dimension.
data=reshape(dat3,shape=shape(data),order=(/3,1,2/))  Transpose back to output order.
deallocate(dat3)
END SUBROUTINE four3

```



The `reshape` intrinsic, used with an `order=` parameter, is the multidimensional generalization of the two-dimensional transpose operation. The line

```
dat2=reshape(data,shape=shape(dat2),order=(/3,1,2/))
```

is equivalent to the do-loop

```

do j=1,size(data,1)
  dat2(:,j)=data(j,:,:)
end do

```

Incidentally, we have found some Fortran 90 compilers that (for scalar machines) are significantly *slower* executing the `reshape` than executing the equivalent do-loop. This, of course, shouldn't happen, since the `reshape` basically *is* an implicit do-loop. If you find such inefficient behavior on your compiler, you should report it as a bug to your compiler vendor! (Only thus will Fortran 90 compilers be brought to mature states of efficiency.)

```

SUBROUTINE four3_alt(data,isign)
USE nrtype
USE nr, ONLY : fourcol_3d
IMPLICIT NONE
COMPLEX(SPC), DIMENSION(:,:,:), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign
  Replaces a 3-d complex array data by its discrete 2-d Fourier transform, if isign is input
  as 1; or replaces data by its inverse 3-d discrete Fourier transform times the product of
  its three sizes, if isign is input as -1. All three of data's sizes must be integer powers
  of 2 (this is checked for in fourcol_3d). Parallelism is by use of fourcol_3d. (Use this
  version only if fourcol_3d is faster than fourrow_3d on your machine.)
COMPLEX(SPC), DIMENSION(:,:,:), ALLOCATABLE :: dat2,dat3
call fourcol_3d(data,isign)          Transform in first dimension.
allocate(dat2(size(data,2),size(data,3),size(data,1)))
dat2=reshape(data,shape=shape(dat2),order=(/3,1,2/))  Transpose.
call fourcol_3d(dat2,isign)         Transform in (original) second dimension.
allocate(dat3(size(data,3),size(data,1),size(data,2)))
dat3=reshape(dat2,shape=shape(dat3),order=(/3,1,2/))  Transpose.
deallocate(dat2)
call fourcol_3d(dat3,isign)         Transform in (original) third dimension.
data=reshape(dat3,shape=shape(data),order=(/3,1,2/))  Transpose back to output order.
deallocate(dat3)
END SUBROUTINE four3_alt

```

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Note that `four3` uses `fourrow_3d`, the three-dimensional counterpart of `fourrow`, while `four3_alt` uses `fourcol_3d`, the three-dimensional counterpart of `fourcol`. You may want to time these programs to see which is faster on your machine.

\* \* \*

**f90** In Volume 1, a single routine named `rlft3` was able to serve both as a three-dimensional real FFT, and as a two-dimensional real FFT. The trick is that the Fortran 77 version doesn't care whether the input array data is dimensioned as two- or three-dimensional. Fortran 90 is not so indifferent, and better programming practice is to have two separate versions of the algorithm:

```

SUBROUTINE rlft2(data,spec,specq,sign)
USE nrtype; USE nrutil, ONLY : assert,assert_eq
USE nr, ONLY : four2
REAL(SP), DIMENSION(:,), INTENT(INOUT) :: data
COMPLEX(SPC), DIMENSION(:,), INTENT(INOUT) :: spec
COMPLEX(SPC), DIMENSION(:,), INTENT(INOUT) :: specq
INTEGER(I4B), INTENT(IN) :: sign
    Given a two-dimensional real array data(1:M,1:N), this routine returns (for sign=1)
    the complex fast Fourier transform as two complex arrays: On output, spec(1:M/2,1:N)
    contains the zero and positive frequency values of the first frequency component, while
    specq(1:N) contains the Nyquist critical frequency values of the first frequency component.
    The second frequency components are stored for zero, positive, and negative frequencies,
    in standard wrap-around order. For sign=-1, the inverse transform (times  $M \times N/2$  as
    a constant multiplicative factor) is performed, with output data deriving from input spec
    and specq. For inverse transforms on data not generated first by a forward transform, make
    sure the complex input data array satisfies property (12.5.2). The size of all arrays must
    always be integer powers of 2.
INTEGER :: i1,j1,nn1,nn2
REAL(DP) :: theta
COMPLEX(SPC) :: c1=(0.5_sp,0.0_sp),c2,h1,h2,w
COMPLEX(SPC), DIMENSION(size(data,2)-1) :: h1a,h2a
COMPLEX(DPC) :: ww,wp
nn1=assert_eq(size(data,1),2*size(spec,1),'rlft2: nn1')
nn2=assert_eq(size(data,2),size(spec,2),size(specq),'rlft2: nn2')
call assert(iand((/nn1,nn2/),(/nn1,nn2/)-1)==0, &
'dimensions must be powers of 2 in rlft2')
c2=cmplx(0.0_sp,-0.5_sp*sign,kind=spc)
theta=TWOPI_D/(sign*nn1)
wp=cmplx(-2.0_dp*sin(0.5_dp*theta)**2,sin(theta),kind=spc)
if (sign == 1) then
    Case of forward transform.
    spec(:,)=cmplx(data(1:nn1:2,:),data(2:nn1:2,:),kind=spc)
    call four2(spec,sign)
    Here is where most all of the compute time
    specq=spec(1,:)
    is spent.
end if
h1=c1*(spec(1,1)+conjg(specq(1)))
h1a=c1*(spec(1,2:nn2)+conjg(specq(nn2:2:-1)))
h2=c2*(spec(1,1)-conjg(specq(1)))
h2a=c2*(spec(1,2:nn2)-conjg(specq(nn2:2:-1)))
spec(1,1)=h1+h2
spec(1,2:nn2)=h1a+h2a
specq(1)=conjg(h1-h2)
specq(nn2:2:-1)=conjg(h1a-h2a)
ww=cmplx(1.0_dp,0.0_dp,kind=dpc)
Initialize trigonometric recurrence.
do i1=2,nn1/4+1
    j1=nn1/2-i1+2
    Corresponding negative frequency.
    ww=ww*wp+ww
    Do the trig recurrence.
    w=ww
    h1=c1*(spec(i1,1)+conjg(spec(j1,1)))
    Equation (12.3.5).
    h1a=c1*(spec(i1,2:nn2)+conjg(spec(j1,nn2:2:-1)))

```

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```

    h2=c2*(spec(i1,1)-conjg(spec(j1,1)))
    h2a=c2*(spec(i1,2:nn2)-conjg(spec(j1,nn2:2:-1)))
    spec(i1,1)=h1+w*h2
    spec(i1,2:nn2)=h1a+w*h2a
    spec(j1,1)=conjg(h1-w*h2)
    spec(j1,nn2:2:-1)=conjg(h1a-w*h2a)
end do
if (isign == -1) then                Case of reverse transform.
    call four2(spec,isign)
    data(1:nn1:2,:)=real(spec)
    data(2:nn1:2,:)=aimag(spec)
end if
END SUBROUTINE rlft2

```

**f**<sub>90</sub> call `assert(iand((/nn1,nn2/),(/nn1,nn2/)-1))==0 ...` Here an overloaded version of `assert` that takes vector arguments is used to check that each dimension is a power of 2. Note that `iand` acts element-by-element on an array.

```

SUBROUTINE rlft3(data,spec,speq,isign)
USE nrtype; USE nrutil, ONLY : assert,assert_eq
USE nr, ONLY : four3
REAL(SP), DIMENSION(:,:,:), INTENT(INOUT) :: data
COMPLEX(SPC), DIMENSION(:,:,:), INTENT(INOUT) :: spec
COMPLEX(SPC), DIMENSION(:,:), INTENT(INOUT) :: speq
INTEGER(I4B), INTENT(IN) :: isign

```

Given a three-dimensional real array `data(1:L,1:M,1:N)`, this routine returns (for `isign=1`) the complex Fourier transform as two complex arrays: On output, the zero and positive frequency values of the first frequency component are in `spec(1:L/2,1:M,1:N)`, while `speq(1:M,1:N)` contains the Nyquist critical frequency values of the first frequency component. The second and third frequency components are stored for zero, positive, and negative frequencies, in standard wrap-around order. For `isign=-1`, the inverse transform (times  $L \times M \times N/2$  as a constant multiplicative factor) is performed, with output `data` deriving from input `spec` and `speq`. For inverse transforms on data not generated first by a forward transform, make sure the complex input data array satisfies property (12.5.2). The size of all arrays must always be integer powers of 2.

```

INTEGER :: i1,i3,j1,j3,nn1,nn2,nn3
REAL(DP) :: theta
COMPLEX(SPC) :: c1=(0.5_sp,0.0_sp),c2,h1,h2,w
COMPLEX(SPC), DIMENSION(size(data,2)-1) :: h1a,h2a
COMPLEX(DPC) :: ww,wp
c2=cmplx(0.0_sp,-0.5_sp*isign,kind=spc)
nn1=assert_eq(size(data,1),2*size(spec,1),'rlft2: nn1')
nn2=assert_eq(size(data,2),size(spec,2),size(speq,1),'rlft2: nn2')
nn3=assert_eq(size(data,3),size(spec,3),size(speq,2),'rlft2: nn3')
call assert(iand((/nn1,nn2,nn3/),(/nn1,nn2,nn3/)-1))==0, &
'dimensions must be powers of 2 in rlft3')
theta=TWOPI_D/(isign*nn1)
wp=cmplx(-2.0_dp*sin(0.5_dp*theta)**2,sin(theta),kind=dpc)
if (isign == 1) then                Case of forward transform.
    spec(:,:)=cmplx(data(1:nn1:2,:,:),data(2:nn1:2,:,:),kind=spc)
    call four3(spec,isign)          Here is where most all of the compute time
    speq=spec(1,:,:)              is spent.
end if
do i3=1,nn3
    j3=1
    if (i3 /= 1) j3=nn3-i3+2
    h1=c1*(spec(1,1,i3)+conjg(speq(1,j3)))
    h1a=c1*(spec(1,2:nn2,i3)+conjg(speq(nn2:2:-1,j3)))
    h2=c2*(spec(1,1,i3)-conjg(speq(1,j3)))
    h2a=c2*(spec(1,2:nn2,i3)-conjg(speq(nn2:2:-1,j3)))
    spec(1,1,i3)=h1+h2
    spec(1,2:nn2,i3)=h1a+h2a

```

```

speq(1, j3)=conjg(h1-h2)
speq(nn2:2:-1, j3)=conjg(h1a-h2a)
ww=cplx(1.0_dp, 0.0_dp, kind=dpc)      Initialize trigonometric recurrence.
do i1=2, nn1/4+1
  j1=nn1/2-i1+2                       Corresponding negative frequency.
  ww=ww*wp+ww                          Do the trig recurrence.
  w=ww
  h1=c1*(spec(i1, 1, i3)+conjg(spec(j1, 1, j3)))      Equation (12.3.5).
  h1a=c1*(spec(i1, 2:nn2, i3)+conjg(spec(j1, nn2:2:-1, j3)))
  h2=c2*(spec(i1, 1, i3)-conjg(spec(j1, 1, j3)))
  h2a=c2*(spec(i1, 2:nn2, i3)-conjg(spec(j1, nn2:2:-1, j3)))
  spec(i1, 1, i3)=h1+w*h2
  spec(i1, 2:nn2, i3)=h1a+w*h2a
  spec(j1, 1, j3)=conjg(h1-w*h2)
  spec(j1, nn2:2:-1, j3)=conjg(h1a-w*h2a)
end do
end do
if (isign == -1) then                  Case of reverse transform.
  call four3(spec, isign)
  data(1:nn1:2, :, :) = real(spec)
  data(2:nn1:2, :, :) = aimag(spec)
end if
END SUBROUTINE r1ft3

```

\* \* \*

Referring back to the discussion of parallelism, §22.4, that led to four1's implementation with  $\sqrt{N}$  parallelism, you might wonder whether Fortran 90 provides sufficiently powerful high-level constructs to enable an FFT routine with  $N$ -fold parallelism. The answer is, "*It does*, but you wouldn't want to use them!" Access to arbitrary interprocessor communication in Fortran 90 is through the mechanism of the "vector subscript" (one-dimensional array of indices in arbitrary order). When a vector subscript is on the right-hand side of an assignment statement, the operation performed is effectively a "gather"; when it is on the left-hand side, the operation is effectively a "scatter."

It is quite possible to write the classic FFT algorithm in terms of gather and scatter operations. In fact, we do so now. The problem is efficiency: The computations involved in constructing the vector subscripts for the scatter/gather operations, and the actual scatter/gather operations themselves, tend to swamp the underlying very lean FFT algorithm. The result is very slow, though theoretically perfectly parallelizable, code. Since small-scale parallel (SSP) machines can saturate their processors with  $\sqrt{N}$  parallelism, while massively multiprocessor (MMP) machines inevitably come with architecture-optimized FFT library calls, there is really no niche for these routines, except as pedagogical demonstrations. We give here a one-dimensional routine, and also an arbitrary-dimensional routine modeled on Volume 1's fourn. Note the complete absence of do-loops of size  $N$ ; the loops that remain are over  $N$  stages, or over the number of dimensions.

```

SUBROUTINE four1_gather(data, isign)
USE nrtype; USE nrutil, ONLY : arth, assert
IMPLICIT NONE
COMPLEX(SPC), DIMENSION(:), INTENT(INOUT) :: data
INTEGER(I4B), INTENT(IN) :: isign

```

Replaces a complex array `data` by its discrete Fourier transform, if `isign` is input as 1; or replaces `data` by `size(data)` times its inverse discrete Fourier transform, if `isign` is input as -1. The size of `data` must be an integer power of 2. This routine demonstrates coding the FFT algorithm in high-level Fortran 90 constructs. Generally the result is *very*

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*much slower* than library routines coded for specific architectures, and also *significantly slower* than the parallelization-by-rows method used in the routine `four1`.

```

INTEGER(I4B) :: n,n2,m,mm
REAL(DP) :: theta
COMPLEX(SPC) :: wp
INTEGER(I4B), DIMENSION(size(data)) :: jarr
INTEGER(I4B), DIMENSION(:), ALLOCATABLE :: jrev
COMPLEX(SPC), DIMENSION(:), ALLOCATABLE :: wtab,dtemp
n=size(data)
call assert(iand(n,n-1)==0, 'n must be a power of 2 in four1_gather')
if (n <= 1) RETURN
allocate(jrev(n))
jarr=arith(0,1,n)
jrev=0
n2=n/2
m=n2
do
    where (iand(jarr,1) /= 0) jrev=jrev+m
    jarr=jarr/2
    m=m/2
    if (m == 0) exit
end do
data=data(jrev+1)
deallocate(jrev)
allocate(dtemp(n), wtab(n2))
jarr=arith(0,1,n)
m=1
mm=n2
wtab(1)=(1.0_sp,0.0_sp)
do
    where (iand(jarr,m) /= 0)
        dtemp=data*wtab(mm*iand(jarr,m-1)+1)
        data=eoshift(data,-m)-dtemp
    elsewhere
        data=data+eoshift(dtemp,m)
    end where
    m=m*2
    if (m >= n) exit
    mm=mm/2
    theta=PI_D/(isign*m)
    wp=cplx(-2.0_dp*sin(0.5_dp*theta)**2, sin(theta),kind=spc)
    wtab(mm+1:n2:2*mm)=wtab(1:n2-mm:2*mm)*wp+wtab(1:n2-mm:2*mm)
end do
deallocate(dtemp, wtab)
END SUBROUTINE four1_gather

```

Begin bit-reversal section of the routine.

Construct an array of pointers from an index to its bit-reverse.

Move all data to bit-reversed location by a single gather/scatter.

Begin Danielson-Lanczos section of the routine.

Seed the roots-of-unity table.

Outer loop executed  $\log_2 N$  times.

The basic idea is to address the correct root-of-unity for each Danielson-Lanczos multiplication by tricky bit manipulations.

This is half of Danielson-Lanczos.

This is the other half. The referenced elements of `dtemp` will have been set in the `where` clause.

Ready for trigonometry?

Add entries to the table for the next iteration.

```

SUBROUTINE fourn_gather(data,nn,isign)
USE nrtype; USE nrutil, ONLY : arth,assert
IMPLICIT NONE
COMPLEX(SPC), DIMENSION(:), INTENT(INOUT) :: data
INTEGER(I4B), DIMENSION(:) :: nn
INTEGER(I4B), INTENT(IN) :: isign

```

For `data` a one-dimensional complex array containing the values (in Fortran normal ordering) of an  $M$ -dimensional complex array, this routine replaces `data` by its  $M$ -dimensional discrete Fourier transform, if `isign` is input as 1. `nn(1:M)` is an integer array containing the lengths of each dimension (number of complex values), each of which must be a power of 2. If `isign` is input as  $-1$ , `data` is replaced by its inverse transform times the product of the lengths of all dimensions. This routine demonstrates coding the multidimensional FFT algorithm in high-level Fortran 90 constructs. Generally the result is *very much slower* than

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```

library routines coded for specific architectures, and significantly slower than routines four2
and four3 for the two- and three-dimensional cases.
INTEGER(I4B), DIMENSION(:), ALLOCATABLE :: jarr
INTEGER(I4B) :: ndim, idim, ntot, nprev, n, n2, msk0, msk1, msk2, m, mm, mn
REAL(DP) :: theta
COMPLEX(SPC) :: wp
COMPLEX(SPC), DIMENSION(:), ALLOCATABLE :: wtab, dtemp
call assert(iand(nn,nn-1)==0, &
'each dimension must be a power of 2 in fourn_gather')
ndim=size(nn)
ntot=product(nn)
nprev=1
allocate(jarr(ntot))
do idim=1,ndim
jarr=arth(0,1,ntot)
n=nn(idim)
n2=n/2
msk0=nprev
msk1=nprev*n2
msk2=msk0+msk1
do
if (msk1 <= msk0) exit
where (iand(jarr,msk0) == 0 .neqv. iand(jarr,msk1) == 0) &
jarr=ieor(jarr,msk2)
msk0=msk0*2
msk1=msk1/2
msk2=msk0+msk1
end do
data=data(jarr+1)
allocate(dtemp(ntot),wtab(n2))
We begin the Danielson-Lanczos section of the routine.
jarr=iand(n-1,arth(0,1,ntot)/nprev)
m=1
mm=n2
mn=m*nprev
wtab(1)=(1.0_sp,0.0_sp)
do
if (mm == 0) exit
where (iand(jarr,m) /= 0)
The basic idea is to address the correct root-of-unity for each Danielson-Lanczos
multiplication by tricky bit manipulations.
dtemp=data*wtab(mm*iand(jarr,m-1)+1)
data=eoshift(data,-mn)-dtemp
elsewhere
data=data+eoshift(dtemp,mn)
end where
m=m*2
if (m >= n) exit
mn=m*nprev
mm=mm/2
theta=PI_D/(isign*m)
wp=cplx(-2.0_dp*sin(0.5_dp*theta)**2,sin(theta),kind=dpc)
Add entries to the table for the next iteration.
wtab(mm+1:n2:2*mm)=wtab(1:n2-mm:2*mm)*wp &
+wtab(1:n2-mm:2*mm)
end do
deallocate(dtemp,wtab)
nprev=n*nprev
end do
deallocate(jarr)
END SUBROUTINE fourn_gather

```



call assert(iand(nn,nn-1)==0 ... Once again the vector version of assert is used to test all the dimensions stored in nn simultaneously.

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## Chapter B13. Fourier and Spectral Applications

```

FUNCTION convlv(data,respns,isign)
USE nrtype; USE nrutil, ONLY : assert,nrerror
USE nr, ONLY : realft
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: data
REAL(SP), DIMENSION(:), INTENT(IN) :: respns
INTEGER(I4B), INTENT(IN) :: isign
REAL(SP), DIMENSION(size(data)) :: convlv
    Convolves or deconvolves a real data set data (of length N, including any user-supplied
    zero padding) with a response function respns, stored in wrap-around order in a real array
    of length  $M \leq N$ . (M should be an odd integer, N a power of 2.) Wrap-around order
    means that the first half of the array respns contains the impulse response function at
    positive times, while the second half of the array contains the impulse response function at
    negative times, counting down from the highest element respns(M). On input isign is
    +1 for convolution, -1 for deconvolution. The answer is returned as the function convlv,
    an array of length N. data has INTENT(INOUT) for consistency with realft, but is
    actually unchanged.
INTEGER(I4B) :: no2,n,m
COMPLEX(SPC), DIMENSION(size(data)/2) :: tmpd,tmpr
n=size(data)
m=size(respns)
call assert(iand(n,n-1)==0, 'n must be a power of 2 in convlv')
call assert(mod(m,2)==1, 'm must be odd in convlv')
convlv(1:m)=respns(:)           Put respns in array of length n.
convlv(n-(m-3)/2:n)=convlv((m+3)/2:m)
convlv((m+3)/2:n-(m-1)/2)=0.0   Pad with zeros.
no2=n/2
call realft(data,1,tmpd)         FFT both arrays.
call realft(convlv,1,tmpd)
if (isign == 1) then             Multiply FFTs to convolve.
    tmpr(1)=cmplx(real(tmpd(1))*real(tmpd(1))/no2, &
        aimag(tmpd(1))*aimag(tmpd(1))/no2, kind=spc)
    tmpr(2:)=tmpd(2:)*tmpd(2:)/no2
else if (isign == -1) then      Divide FFTs to deconvolve.
    if (any(abs(tmpd(2:)) == 0.0) .or. real(tmpd(1)) == 0.0 &
        .or. aimag(tmpd(1)) == 0.0) call nrerror &
        ('deconvolving at response zero in convlv')
    tmpr(1)=cmplx(real(tmpd(1))/real(tmpd(1))/no2, &
        aimag(tmpd(1))/aimag(tmpd(1))/no2, kind=spc)
    tmpr(2:)=tmpd(2:)/tmpd(2:)/no2
else
    call nrerror('no meaning for isign in convlv')
end if
call realft(convlv,-1,tmpd)     Inverse transform back to time domain.
END FUNCTION convlv

```

**f90** `tmpr(1)=cplx(...kind=spc)` The intrinsic function `cplx` returns a quantity of type default complex unless the `kind` argument is present. It is therefore a good idea always to include this argument. The intrinsic functions `real` and `aimag`, on the other hand, when called with a complex argument, return the same kind as their argument. So it is a good idea *not* to put in a `kind` argument for these. (In fact, `aimag` doesn't allow one.) Don't confuse these situations, regarding complex variables, with the completely unrelated use of `real` to convert a real or integer variable to a real value of specified kind. In this latter case, `kind` should be specified.

\* \* \*

```
FUNCTION correl(data1,data2)
USE nrtype; USE nrutil, ONLY : assert,assert_eq
USE nr, ONLY : realft
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: data1,data2
REAL(SP), DIMENSION(size(data1)) :: correl
  Computes the correlation of two real data sets data1 and data2 of length  $N$  (including any user-supplied zero padding).  $N$  must be an integer power of 2. The answer is returned as the function correl, an array of length  $N$ . The answer is stored in wrap-around order, i.e., correlations at increasingly negative lags are in correl(N) on down to correl(N/2+1), while correlations at increasingly positive lags are in correl(1) (zero lag) on up to correl(N/2). Sign convention of this routine: if data1 lags data2, i.e., is shifted to the right of it, then correl will show a peak at positive lags.
COMPLEX(SPC), DIMENSION(size(data1)/2) :: cdat1,cdat2
INTEGER(I4B) :: no2,n           Normalization for inverse FFT.
n=assert_eq(size(data1),size(data2),'correl')
call assert(iand(n,n-1)==0, 'n must be a power of 2 in correl')
no2=n/2
call realft(data1,1,cdat1)      Transform both data vectors.
call realft(data2,1,cdat2)
cdat1(1)=cplx(real(cdat1(1))*real(cdat2(1))/no2, &    Multiply to find FFT of their
  aimag(cdat1(1))*aimag(cdat2(1))/no2, kind=spc)    correlation.
cdat1(2:)=cdat1(2:)*conjg(cdat2(2:))/no2
call realft(correl,-1,cdat1)   Inverse transform gives correlation.
END FUNCTION correl
```

**f90** `cdat1(1)=cplx(...kind=spc)` See just above for why we use the explicit `kind` type parameter `spc` for `cplx`, but omit `sp` for `real`.

\* \* \*

```
SUBROUTINE spectrm(p,k,ovrlap,unit,n_window)
USE nrtype; USE nrutil, ONLY : arth,nrerror
USE nr, ONLY : four1
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(OUT) :: p
INTEGER(I4B), INTENT(IN) :: k
LOGICAL(LGT), INTENT(IN) :: ovrlap      True for overlapping segments, false otherwise.
INTEGER(I4B), OPTIONAL, INTENT(IN) :: n_window,unit
  Reads data from input unit 9, or if the optional argument unit is present, from that input unit. The output is an array p of length  $M$  that contains the data's power (mean square amplitude) at frequency  $(j-1)/2M$  cycles per grid point, for  $j = 1, 2, \dots, M$ , based on  $(2*k+1)*M$  data points (if ovrlap is set .true.) or  $4*k*M$  data points (if ovrlap is set .false.). The number of segments of the data is  $2*k$  in both cases: The routine calls four1 k times, each call with 2 partitions each of  $2M$  real data points. If the optional argument n_window is present, the routine uses the Bartlett window, the square window,
```

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```

    or the Welch window for n_window = 1, 2, 3 respectively. If n_window is not present, the
    Bartlett window is used.
INTEGER(I4B) :: j, joff, joffn, kk, m, m4, m43, m44, mm, iunit, nn_window
REAL(SP) :: den, facm, facp, sumw
REAL(SP), DIMENSION(2*size(p)) :: w
REAL(SP), DIMENSION(4*size(p)) :: w1
REAL(SP), DIMENSION(size(p)) :: w2
COMPLEX(SPC), DIMENSION(2*size(p)) :: cw1
m=size(p)
if (present(n_window)) then
    nn_window=n_window
else
    nn_window=1
end if
if (present(unit)) then
    iunit=unit
else
    iunit=9
end if
mm=m+m
m4=mm+mm
m44=m4+4
m43=m4+3
den=0.0
facm=m
facp=1.0_sp/m
w1(1:mm)=window(arth(1,1,mm), facm, facp, nn_window)
sumw=dot_product(w1(1:mm), w1(1:mm))
p(:)=0.0
if (ovrlap) read (iunit,*) (w2(j), j=1,m)
do kk=1,k
    do joff=-1,0,1
        if (ovrlap) then
            w1(joff+2:joff+mm:2)=w2(1:m)
            read (iunit,*) (w2(j), j=1,m)
            joffn=joff+mm
            w1(joffn+2:joffn+mm:2)=w2(1:m)
        else
            read (iunit,*) (w1(j), j=joff+2,m4,2)
        end if
    end do
    w=window(arth(1,1,mm), facm, facp, nn_window)
    w1(2:m4:2)=w1(2:m4:2)*w
    w1(1:m4:2)=w1(1:m4:2)*w
    cw1(1:mm)=cplx(w1(1:m4:2), w1(2:m4:2), kind=spc)
    call four1(cw1(1:mm), 1)
    w1(1:m4:2)=real(cw1(1:mm))
    w1(2:m4:2)=aimag(cw1(1:mm))
    p(1)=p(1)+w1(1)**2+w1(2)**2
    p(2:m)=p(2:m)+w1(4:2*m:2)**2+w1(3:2*m-1:2)**2+
        w1(m44-4:m44-2*m:-2)**2+w1(m43-4:m43-2*m:-2)**2
    den=den+sumw
end do
p(:)=p(:)/(m4*den)
CONTAINS

FUNCTION window(j, facm, facp, nn_window)
IMPLICIT NONE
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: j
INTEGER(I4B), INTENT(IN) :: nn_window
REAL(SP), INTENT(IN) :: facm, facp
REAL(SP), DIMENSION(size(j)) :: window
select case(nn_window)
    case(1)

```

Useful factors.

Factors used by the window function.

Accumulate the squared sum of the weights.

Initialize the spectrum to zero.

Initialize the "save" half-buffer.

Loop over data segments in groups of two.

Get two complete segments into workspace.

Apply the window to the data.

Fourier transform the windowed data.

Sum results into previous segments.

Normalize the output.

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```

        window(j)=(1.0_sp-abs(((j-1)-facm)*facp))      Bartlett window.
    case(2)
        window(j)=1.0                                  Square window.
    case(3)
        window(j)=(1.0_sp-(((j-1)-facm)*facp)**2)     Welch window.
    case default
        call nrerror('unimplemented window function in spctrm')
end select
END FUNCTION window
END SUBROUTINE spctrm

```

**f**<sub>90</sub> The Fortran 90 optional argument feature allows us to make unit 9 the default output unit in this routine, but leave the user the option of specifying a different output unit by supplying an actual argument for unit. We also use an optional argument to allow the user the option of overriding the default selection of the Bartlett window function.

FUNCTION window(j,facm,facp,nn\_window) In Fortran 77 we coded this as a statement function. Here the internal function is equivalent, but allows full specification of the interface and so is preferred.

```

                *   *   *

SUBROUTINE memcof(data,xms,d)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: xms
REAL(SP), DIMENSION(:), INTENT(IN) :: data
REAL(SP), DIMENSION(:), INTENT(OUT) :: d
    Given a real vector data of length N, this routine returns M linear prediction coefficients
    in a vector d of length M, and returns the mean square discrepancy as xms.
INTEGER(I4B) :: k,m,n
REAL(SP) :: denom,pneum
REAL(SP), DIMENSION(size(data)) :: wk1,wk2,wktmp
REAL(SP), DIMENSION(size(d)) :: wkm
m=size(d)
n=size(data)
xms=dot_product(data,data)/n
wk1(1:n-1)=data(1:n-1)
wk2(1:n-1)=data(2:n)
do k=1,m
    pneum=dot_product(wk1(1:n-k),wk2(1:n-k))
    denom=dot_product(wk1(1:n-k),wk1(1:n-k))+ &
        dot_product(wk2(1:n-k),wk2(1:n-k))
    d(k)=2.0_sp*pneum/denom
    xms=xms*(1.0_sp-d(k)**2)
    d(1:k-1)=wkm(1:k-1)-d(k)*wkm(k-1:1:-1)
    The algorithm is recursive, although it is implemented as an iteration. It builds up the
    answer for larger and larger values of m until the desired value is reached. At this point
    in the algorithm, one could return the vector d and scalar xms for a set of LP coefficients
    with k (rather than m) terms.
    if (k == m) RETURN
    wkm(1:k)=d(1:k)
    wktmp(2:n-k)=wk1(2:n-k)
    wk1(1:n-k-1)=wk1(1:n-k-1)-wkm(k)*wk2(1:n-k-1)
    wk2(1:n-k-1)=wk2(2:n-k)-wkm(k)*wktmp(2:n-k)
end do
call nrerror('never get here in memcof')
END SUBROUTINE memcof

```

\* \* \*

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```

SUBROUTINE fixrts(d)
USE nrtype
USE nr, ONLY : zroots
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: d
    Given the LP coefficients d, this routine finds all roots of the characteristic polynomial
    (13.6.14), reflects any roots that are outside the unit circle back inside, and then returns
    a modified set of coefficients in d.
INTEGER(I4B) :: i,m
LOGICAL(LGT) :: polish
COMPLEX(SPC), DIMENSION(size(d)+1) :: a
COMPLEX(SPC), DIMENSION(size(d)) :: roots
m=size(d)
a(m+1)=cmplx(1.0_sp,kind=spc)          Set up complex coefficients for polynomial
a(m:1:-1)=cmplx(-d(1:m),kind=spc)     root finder.
polish=.true.
call zroots(a(1:m+1),roots,polish)     Find all the roots.
where (abs(roots) > 1.0) roots=1.0_sp/conjg(roots)
    Reflect all roots outside the unit circle back inside.
a(1)=-roots(1)                         Now reconstruct the polynomial coefficients,
a(2:m+1)=cmplx(1.0_sp,kind=spc)        by looping over the roots
do i=2,m                                 and synthetically multiplying.
    a(2:i)=a(1:i-1)-roots(i)*a(2:i)
    a(1)=-roots(i)*a(1)
end do
d(m:1:-1)=-real(a(1:m))                 The polynomial coefficients are guaranteed
END SUBROUTINE fixrts                    to be real, so we need only return the
                                         real part as new LP coefficients.

```



**90** `a(m+1)=cmplx(1.0_sp,kind=spc)` See after `convlv` on p. 1254 to review why we use the explicit kind type parameter `spc` for `cmplx`.

\* \* \*

```

FUNCTION predic(data,d,nfut)
USE nrtype
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: data,d
INTEGER(I4B), INTENT(IN) :: nfut
REAL(SP), DIMENSION(nfut) :: predic
    Given an array data, and given the data's LP coefficients d in an array of length M, this
    routine applies equation (13.6.11) to predict the next nfut data points, which it returns in
    an array as the function value predic. Note that the routine references only the last M
    values of data, as initial values for the prediction.
INTEGER(I4B) :: j,ndata,m
REAL(SP) :: discrpsm
REAL(SP), DIMENSION(size(d)) :: reg
m=size(d)
ndata=size(data)
reg(1:m)=data(ndata:ndata+1-m:-1)
do j=1,nfut
    discrpsm=0.0
    This is where you would put in a known discrepancy if you were reconstructing a function
    by linear predictive coding rather than extrapolating a function by linear prediction. See
    text.
    sm=discrpsm+dot_product(d,reg)
    reg=eoshift(reg,-1,sm)          [If you want to implement circular arrays, you can
    predic(j)=sm                    avoid this shifting of coefficients!]
end do
END FUNCTION predic

```

\* \* \*

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```

FUNCTION evlmem(fdt,d,xms)
USE nrtype; USE nrutil, ONLY : poly
IMPLICIT NONE
REAL(SP), INTENT(IN) :: fdt,xms
REAL(SP), DIMENSION(:), INTENT(IN) :: d
REAL(SP) :: evlmem
    Given d and xms as returned by memcof, this function returns the power spectrum estimate
     $P(f)$  as a function of  $fdt = f\Delta$ .
COMPLEX(SPC) :: z,zz
REAL(DP) :: theta           Trigonometric recurrences in double precision.
theta=TWOPI_D*fdt
z=cplx(cos(theta),sin(theta),kind=spc)
zz=1.0_sp-z*poly(z,d)
evlmem=xms/abs(zz)**2       Equation (13.7.4).
END FUNCTION evlmem

```

**f<sub>90</sub>** `zz=...poly(z,d)` The `poly` function in `nrutil` returns the value of the polynomial with coefficients `d(:)` at `z`. Here a version that takes real coefficients and a complex argument is actually invoked, but all the different versions have been overloaded onto the same name `poly`.

\* \* \*

```

SUBROUTINE period(x,y,ofac,hifac,px,py,jmax,prob)
USE nrtype; USE nrutil, ONLY : assert_eq,imaxloc
USE nr, ONLY : avevar
IMPLICIT NONE
INTEGER(I4B), INTENT(OUT) :: jmax
REAL(SP), INTENT(IN) :: ofac,hifac
REAL(SP), INTENT(OUT) :: prob
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
REAL(SP), DIMENSION(:), POINTER :: px,py
    Input is a set of  $N$  data points with abscissas  $x$  (which need not be equally spaced) and
    ordinates  $y$ , and a desired oversampling factor ofac (a typical value being 4 or larger).
    The routine returns pointers to internally allocated arrays px and py. px is filled with
    an increasing sequence of frequencies (not angular frequencies) up to hifac times the
    "average" Nyquist frequency, and py is filled with the values of the Lomb normalized
    periodogram at those frequencies. The length of these arrays is  $0.5*ofac*hifac*N$ .
    The arrays x and y are not altered. The routine also returns jmax such that py(jmax) is
    the maximum element in py, and prob, an estimate of the significance of that maximum
    against the hypothesis of random noise. A small value of prob indicates that a significant
    periodic signal is present.
INTEGER(I4B) :: i,n,nout
REAL(SP) :: ave,cwtau,effm,expy,pnow,sumc,sumcy,&
    sums,sumsh,sumsy,swtau,var,wtau,xave,xdif,xmax,xmin
REAL(DP), DIMENSION(size(x)) :: tmp1,tmp2,wi,wpi,wpr,wr
LOGICAL(LGT), SAVE :: init=.true.
n=assert_eq(size(x),size(y),'period')
if (init) then
    init=.false.
    nullify(px,py)
else
    if (associated(px)) deallocate(px)
    if (associated(py)) deallocate(py)
end if
nout=0.5_sp*ofac*hifac*n
allocate(px(nout),py(nout))
call avevar(y(:),ave,var)
xmax=maxval(x(:))
xmin=minval(x(:))
xdif=xmax-xmin
    Get mean and variance of the input data.
    Go through data to get the range of abscis-
    sas.

```

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```

xave=0.5_sp*(xmax+xmin)
pnow=1.0_sp/(xdif*ofac)
tmp1(:)=TWOPI_D*((x(:)-xave)*pnow)
wpr(:)=-2.0_dp*sin(0.5_dp*tmp1)**2
wpi(:)=sin(tmp1(:))
wr(:)=cos(tmp1(:))
wi(:)=wpi(:)
do i=1,nout
  px(i)=pnow
  sumsh=dot_product(wi,wr)
  sumc=dot_product(wr(:)-wi(:),wr(:)+wi(:))
  wtau=0.5_sp*atan2(2.0_sp*sumsh,sumc)
  swtau=sin(wtau)
  cwtau=cos(wtau)
  tmp1(:)=wi(:)*cwtau-wr(:)*swtau
  tmp2(:)=wr(:)*cwtau+wi(:)*swtau
  sums=dot_product(tmp1,tmp1)
  sumc=dot_product(tmp2,tmp2)
  sumsy=dot_product(y(:)-ave,tmp1)
  sumcy=dot_product(y(:)-ave,tmp2)
  tmp1(:)=wr(:)
  wr(:)=(wr(:)*wpr(:)-wi(:)*wpi(:))+wr(:)
  wi(:)=(wi(:)*wpr(:)+tmp1(:)*wpi(:))+wi(:)
  py(i)=0.5_sp*(sumcy**2/sumc+sumsy**2/sums)/var
  pnow=pnow+1.0_sp/(ofac*xdif)
end do
jmax=imaxloc(py(1:nout))
expy=exp(-py(jmax))
effm=2.0_sp*nout/ofac
prob=effm*expy
if (prob > 0.01_sp) prob=1.0_sp-(1.0_sp-expy)**effm
END SUBROUTINE period

```

Starting frequency.  
Initialize values for the trigonometric recurrences at each data point. The recurrences are done in double precision.

Main loop over the frequencies to be evaluated.  
First, loop over the data to get  $\tau$  and related quantities.  
Then, loop over the data again to get the periodogram value.

Update the trigonometric recurrences.  
The next frequency.

Evaluate statistical significance of the maximum.

**f90** This routine shows another example of how to return arrays whose size is not known in advance (cf. `zbrac` in Chapter B9). The coding is explained in the subsection on pointers in §21.5. The size of the output arrays, `nout` in the code, is available as `size(px)`.

`jmax=imaxloc...` See discussion of `imaxloc` on p. 1017.

```

SUBROUTINE fasper(x,y,ofac,hifac,px,py,jmax,prob)
USE nrtype; USE nrutil, ONLY : arth,assert_eq,imaxloc,nrerror
USE nr, ONLY : avevar,realft
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
REAL(SP), INTENT(IN) :: ofac,hifac
INTEGER(I4B), INTENT(OUT) :: jmax
REAL(SP), INTENT(OUT) :: prob
REAL(SP), DIMENSION(:), POINTER :: px,py
INTEGER(I4B), PARAMETER :: MACC=4

```

Input is a set of  $N$  data points with abscissas  $x$  (which need not be equally spaced) and ordinates  $y$ , and a desired oversampling factor `ofac` (a typical value being 4 or larger). The routine returns pointers to internally allocated arrays `px` and `py`. `px` is filled with an increasing sequence of frequencies (not angular frequencies) up to `hifac` times the “average” Nyquist frequency, and `py` is filled with the values of the Lomb normalized periodogram at those frequencies. The length of these arrays is  $0.5 \cdot \text{ofac} \cdot \text{hifac} \cdot N$ . The arrays  $x$  and  $y$  are not altered. The routine also returns `jmax` such that `py(jmax)` is the maximum element in `py`, and `prob`, an estimate of the significance of that maximum against the hypothesis of random noise. A small value of `prob` indicates that a significant

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```

periodic signal is present.
Parameter: MACC is the number of interpolation points per 1/4 cycle of highest frequency.
INTEGER(I4B) :: j,k,n,ndim,nfreq,nfreqt,nout
REAL(SP) :: ave,ck,ckk,cterm,cwt,den,df,effm,expy,fac,fndim,hc2wt,&
    hs2wt,hypo,sterm,swt,var,xdif,xmax,xmin
REAL(SP), DIMENSION(:), ALLOCATABLE :: wk1,wk2
LOGICAL(LGT), SAVE :: init=.true.
n=assert_eq(size(x),size(y),'fasper')
if (init) then
    init=.false.
    nullify(px,py)
else
    if (associated(px)) deallocate(px)
    if (associated(py)) deallocate(py)
end if
nfreqt=ofac*hifac*n*MACC
nfreq=64
do
    if (nfreq >= nfreqt) exit
    nfreq=nfreq*2
end do
ndim=2*nfreq
allocate(wk1(ndim),wk2(ndim))
call avevar(y(1:n),ave,var)
xmax=maxval(x(:))
xmin=minval(x(:))
xdif=xmax-xmin
wk1(1:ndim)=0.0
wk2(1:ndim)=0.0
fac=ndim/(xdif*ofac)
fndim=ndim
do j=1,n
    ck=1.0_sp+mod((x(j)-xmin)*fac,fndim)
    ckk=1.0_sp+mod(2.0_sp*(ck-1.0_sp),fndim)
    call spreadval(y(j)-ave,wk1,ck,MACC)
    call spreadval(1.0_sp,wk2,ckk,MACC)
end do
call realft(wk1(1:ndim),1)
call realft(wk2(1:ndim),1)
df=1.0_sp/(xdif*ofac)
nout=0.5_sp*ofac*hifac*n
allocate(px(nout),py(nout))
k=3
do j=1,nout
    hypo=sqrt(wk2(k)**2+wk2(k+1)**2)
    hc2wt=0.5_sp*wk2(k)/hypo
    hs2wt=0.5_sp*wk2(k+1)/hypo
    cwt=sqrt(0.5_sp+hc2wt)
    swt=sign(sqrt(0.5_sp-hc2wt),hs2wt)
    den=0.5_sp*n+hc2wt*wk2(k)+hs2wt*wk2(k+1)
    cterm=(cwt*wk1(k)+swt*wk1(k+1))**2/den
    sterm=(cwt*wk1(k+1)-swt*wk1(k))**2/(n-den)
    px(j)=j*df
    py(j)=(cterm+sterm)/(2.0_sp*var)
    k=k+2
end do
deallocate(wk1,wk2)
jmax=imaxloc(py(1:nout))
expy=exp(-py(jmax))
effm=2.0_sp*nout/ofac
prob=effm*expy
if (prob > 0.01_sp) prob=1.0_sp-(1.0_sp-expy)**effm
CONTAINS

```

Size the FFT as next power of 2 above nfreqt.

Compute the mean, variance, and range of the data.

Zero the workspaces.

Extirpolate the data into the workspaces.

Take the fast Fourier transforms.

Compute the Lomb value for each frequency.

Estimate significance of largest peak value.

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```

SUBROUTINE spreadval(y,yy,x,m)
IMPLICIT NONE
REAL(SP), INTENT(IN) :: y,x
REAL(SP), DIMENSION(:), INTENT(INOUT) :: yy
INTEGER(I4B), INTENT(IN) :: m
    Given an array yy of length N, extirpolate (spread) a value y into m actual array elements
    that best approximate the "fictional" (i.e., possibly noninteger) array element number x.
    The weights used are coefficients of the Lagrange interpolating polynomial.
INTEGER(I4B) :: ihi,ilo,ix,j,nden,n
REAL(SP) :: fac
INTEGER(I4B), DIMENSION(10) :: nfac = (/ &
    1,1,2,6,24,120,720,5040,40320,362880 /)
if (m > 10) call nrerror('factorial table too small in spreadval')
n=size(yy)
ix=x
if (x == real(ix,sp)) then
    yy(ix)=yy(ix)+y
else
    ilo=min(max(int(x-0.5_sp*m+1.0_sp),1),n-m+1)
    ihi=ilo+m-1
    nden=nfac(m)
    fac=product(x-arth(ilo,1,m))
    yy(ihi)=yy(ihi)+y*fac/(nden*(x-ihl))
    do j=ihl-1,ilo,-1
        nden=(nden/(j+1-ilo))*(j-ihl)
        yy(j)=yy(j)+y*fac/(nden*(x-j))
    end do
end if
END SUBROUTINE spreadval
END SUBROUTINE fasper

```

**f**<sub>90</sub> This routine shows another example of how to return arrays whose size is not known in advance (cf. `zbrac` in Chapter B9). The coding is explained in the subsection on pointers in §21.5. The size of the output arrays, `nout` in the code, is available as `size(px)`.

`jmax=imaxloc...` See discussion of `imaxloc` on p. 1017.

`if (x == real(ix,sp)) then` Without the explicit kind type parameter `sp`, `real` returns a value of type default real for an integer argument. This prevents automatic conversion of the routine from single to double precision. Here all you have to do is redefine `sp` in `nrtype` to get double precision.

\* \* \*

```

SUBROUTINE dftcor(w,delta,a,b,endpts,corre,corim,corfac)
USE nrtype; USE nrutil, ONLY : assert
IMPLICIT NONE
REAL(SP), INTENT(IN) :: w,delta,a,b
REAL(SP), INTENT(OUT) :: corre,corim,corfac
REAL(SP), DIMENSION(:), INTENT(IN) :: endpts

```

For an integral approximated by a discrete Fourier transform, this routine computes the correction factor that multiplies the DFT and the endpoint correction to be added. Input is the angular frequency `w`, stepsize `delta`, lower and upper limits of the integral `a` and `b`, while the array `endpts` of length 8 contains the first 4 and last 4 function values. The

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```

correction factor  $W(\theta)$  is returned as corfac, while the real and imaginary parts of the
endpoint correction are returned as corre and corim.
REAL(SP) :: a0i,a0r,a1i,a1r,a2i,a2r,a3i,a3r,arg,c,cl,cr,s,sl,sr,t,&
t2,t4,t6
REAL(DP) :: cth,ctth,spth2,sth,sth4i,stth,th,th2,th4,&
tmth2,tth4i
th=w*delta
call assert(a < b, th >= 0.0, th <= PI_D, 'dftcor args')
if (abs(th) < 5.0e-2_dp) then          Use series.
  t=th
  t2=t*t
  t4=t2*t2
  t6=t4*t2
  corfac=1.0_sp-(11.0_sp/720.0_sp)*t4+(23.0_sp/15120.0_sp)*t6
  a0r=(-2.0_sp/3.0_sp)+t2/45.0_sp+(103.0_sp/15120.0_sp)*t4-&
    (169.0_sp/226800.0_sp)*t6
  a1r=(7.0_sp/24.0_sp)-(7.0_sp/180.0_sp)*t2+(5.0_sp/3456.0_sp)*t4&
    -(7.0_sp/259200.0_sp)*t6
  a2r=(-1.0_sp/6.0_sp)+t2/45.0_sp-(5.0_sp/6048.0_sp)*t4+t6/64800.0_sp
  a3r=(1.0_sp/24.0_sp)-t2/180.0_sp+(5.0_sp/24192.0_sp)*t4-t6/259200.0_sp
  a0i=t*(2.0_sp/45.0_sp+(2.0_sp/105.0_sp)*t2-&
    (8.0_sp/2835.0_sp)*t4+(86.0_sp/467775.0_sp)*t6)
  a1i=t*(7.0_sp/72.0_sp-t2/168.0_sp+(11.0_sp/72576.0_sp)*t4-&
    (13.0_sp/5987520.0_sp)*t6)
  a2i=t*(-7.0_sp/90.0_sp+t2/210.0_sp-(11.0_sp/90720.0_sp)*t4+&
    (13.0_sp/7484400.0_sp)*t6)
  a3i=t*(7.0_sp/360.0_sp-t2/840.0_sp+(11.0_sp/362880.0_sp)*t4-&
    (13.0_sp/29937600.0_sp)*t6)
else          Use trigonometric formulas in double precision.
  cth=cos(th)
  sth=sin(th)
  ctth=cth**2-sth**2
  stth=2.0_dp*sth*cth
  th2=th*th
  th4=th2*th2
  tmth2=3.0_dp-th2
  spth2=6.0_dp+th2
  sth4i=1.0_sp/(6.0_dp*th4)
  tth4i=2.0_dp*sth4i
  corfac=tth4i*spth2*(3.0_sp-4.0_dp*cth+ctth)
  a0r=sth4i*(-42.0_dp+5.0_dp*th2+spth2*(8.0_dp*cth-ctth))
  a0i=sth4i*(th*(-12.0_dp+6.0_dp*th2)+spth2*stth)
  a1r=sth4i*(14.0_dp*tmth2-7.0_dp*spth2*cth)
  a1i=sth4i*(30.0_dp*th-5.0_dp*spth2*sth)
  a2r=tth4i*(-4.0_dp*tmth2+2.0_dp*spth2*cth)
  a2i=tth4i*(-12.0_dp*th+2.0_dp*spth2*sth)
  a3r=sth4i*(2.0_dp*tmth2-spth2*cth)
  a3i=sth4i*(6.0_dp*th-spth2*sth)
end if
cl=a0r*endpts(1)+a1r*endpts(2)+a2r*endpts(3)+a3r*endpts(4)
sl=a0i*endpts(1)+a1i*endpts(2)+a2i*endpts(3)+a3i*endpts(4)
cr=a0r*endpts(8)+a1r*endpts(7)+a2r*endpts(6)+a3r*endpts(5)
sr=-a0i*endpts(8)-a1i*endpts(7)-a2i*endpts(6)-a3i*endpts(5)
arg=w*(b-a)
c=cos(arg)
s=sin(arg)
corre=cl+c*cr-s*sr
corim=sl+s*cr+c*sr
END SUBROUTINE dftcor

```

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```

SUBROUTINE dftint(func,a,b,w,cosint,sinint)
USE nrtype; USE nrutil, ONLY : arth
USE nr, ONLY : dftcor,polint,realft
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b,w
REAL(SP), INTENT(OUT) :: cosint,sinint
INTERFACE
  FUNCTION func(x)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: func
  END FUNCTION func
END INTERFACE
INTEGER(I4B), PARAMETER :: M=64,NDFT=1024,MPOL=6
Example subroutine illustrating how to use the routine dftcor. The user supplies an external function func that returns the quantity  $h(t)$ . The routine then returns  $\int_a^b \cos(\omega t)h(t) dt$  as cosint and  $\int_a^b \sin(\omega t)h(t) dt$  as sinint.
Parameters: The values of M, NDFT, and MPOL are merely illustrative and should be optimized for your particular application. M is the number of subintervals, NDFT is the length of the FFT (a power of 2), and MPOL is the degree of polynomial interpolation used to obtain the desired frequency from the FFT.
INTEGER(I4B) :: nn
INTEGER(I4B), SAVE :: init=0
INTEGER(I4B), DIMENSION(MPOL) :: nmpol
REAL(SP) :: c,cdft,cerr,corfac,corim,corre,en,s,sdft,serr
REAL(SP), SAVE :: delta
REAL(SP), DIMENSION(MPOL) :: cpol,spol,xpol
REAL(SP), DIMENSION(NDFT), SAVE :: data
REAL(SP), DIMENSION(8), SAVE :: endpts
REAL(SP), SAVE :: aold=-1.0e30_sp,bold=-1.0e30_sp
if (init /= 1 .or. a /= aold .or. b /= bold) then
  init=1
  aold=a
  bold=b
  delta=(b-a)/M
  data(1:M+1)=func(a+arth(0,1,M+1)*delta)
  Load the function values into the data array.
  data(M+2:NDFT)=0.0
  Zero pad the rest of the data array.
  endpts(1:4)=data(1:4)
  Load the endpoints.
  endpts(5:8)=data(M-2:M+1)
  call realft(data(1:NDFT),1)
  realft returns the unused value corresponding to  $\omega_{N/2}$  in data(2). We actually want this element to contain the imaginary part corresponding to  $\omega_0$ , which is zero.
  data(2)=0.0
end if
Now interpolate on the DFT result for the desired frequency. If the frequency is an  $\omega_n$ , i.e., the quantity en is an integer, then cdft=data(2*en-1), sdft=data(2*en), and you could omit the interpolation.
en=w*delta*NDFT/TWOPI+1.0_sp
nn=min(max(int(en-0.5_sp*MPOL+1.0_sp),1),NDFT/2-MPOL+1)
Leftmost point for the interpolation.
nmpol=arth(nn,1,MPOL)
cpol(1:MPOL)=data(2*nmpol:)-1)
spol(1:MPOL)=data(2*nmpol:))
xpol(1:MPOL)=nmpol(:)
call polint(xpol,cpol,en,cdft,cerr)
call polint(xpol,spol,en,sdft,serr)
call dftcor(w,delta,a,b,endpts,corre,corim,corfac)
Now get the endpoint correction and the multiplicative factor  $W(\theta)$ .
cdft=cdft*corfac+corre
sdft=sdft*corfac+corim
c=delta*cos(w*a)
s=delta*sin(w*a)
Finally multiply by  $\Delta$  and  $\exp(i\omega a)$ .
cosint=c*cdft-s*sdft

```

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```
sinint=s*cdft+c*sdf
END SUBROUTINE dftint
```

\* \* \*

```
SUBROUTINE wt1(a,isign,wstep)
USE nrtype; USE nrutil, ONLY : assert
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
INTEGER(I4B), INTENT(IN) :: isign
INTERFACE
  SUBROUTINE wstep(a,isign)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
    INTEGER(I4B), INTENT(IN) :: isign
  END SUBROUTINE wstep
END INTERFACE
```

One-dimensional discrete wavelet transform. This routine implements the pyramid algorithm, replacing  $a$  by its wavelet transform (for  $isign=1$ ), or performing the inverse operation (for  $isign=-1$ ). The length of  $a$  is  $N$ , which must be an integer power of 2. The subroutine  $wstep$ , whose actual name must be supplied in calling this routine, is the underlying wavelet filter. Examples of  $wstep$  are  $daub4$  and (preceded by  $pwtset$ )  $pwt$ .

```
INTEGER(I4B) :: n,nn
n=size(a)
call assert(iand(n,n-1)==0, 'n must be a power of 2 in wt1')
if (n < 4) RETURN
if (isign >= 0) then      Wavelet transform.
  nn=n                   Start at largest hierarchy,
  do
    if (nn < 4) exit
    call wstep(a(1:nn),isign)
    nn=nn/2              and work towards smallest.
  end do
else                      Inverse wavelet transform.
  nn=4                   Start at smallest hierarchy,
  do
    if (nn > n) exit
    call wstep(a(1:nn),isign)
    nn=nn*2              and work towards largest.
  end do
end if
END SUBROUTINE wt1
```

```
SUBROUTINE daub4(a,isign)
USE nrtype
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
INTEGER(I4B), INTENT(IN) :: isign
  Applies the Daubechies 4-coefficient wavelet filter to data vector  $a$  (for  $isign=1$ ) or applies
  its transpose (for  $isign=-1$ ). Used hierarchically by routines  $wt1$  and  $wtn$ .
REAL(SP), DIMENSION(size(a)) :: wksp
REAL(SP), PARAMETER :: C0=0.4829629131445341_sp,&
  C1=0.8365163037378079_sp,C2=0.2241438680420134_sp,&
  C3=-0.1294095225512604_sp
INTEGER(I4B) :: n,nh,nhp,nhm
n=size(a)
if (n < 4) RETURN
nh=n/2
nhp=nh+1
nhm=nh-1
```

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```

if (isign >= 0) then      Apply filter.
  wksp(1:nhm) = C0*a(1:n-3:2)+C1*a(2:n-2:2) &
    +C2*a(3:n-1:2)+C3*a(4:n:2)
  wksp(nh)=C0*a(n-1)+C1*a(n)+C2*a(1)+C3*a(2)
  wksp(nhp:n-1) = C3*a(1:n-3:2)-C2*a(2:n-2:2) &
    +C1*a(3:n-1:2)-C0*a(4:n:2)
  wksp(n)=C3*a(n-1)-C2*a(n)+C1*a(1)-C0*a(2)
else                      Apply transpose filter.
  wksp(1)=C2*a(nh)+C1*a(n)+C0*a(1)+C3*a(nhp)
  wksp(2)=C3*a(nh)-C0*a(n)+C1*a(1)-C2*a(nhp)
  wksp(3:n-1:2) = C2*a(1:nhm)+C1*a(nhp:n-1) &
    +C0*a(2:nh)+C3*a(nh+2:n)
  wksp(4:n:2) = C3*a(1:nhm)-C0*a(nhp:n-1) &
    +C1*a(2:nh)-C2*a(nh+2:n)
end if
a(1:n)=wksp(1:n)
END SUBROUTINE daub4

```

**MODULE pwtcom**

```

USE nrtype
INTEGER(I4B), SAVE :: ncof=0,ioff,joff      These module variables communicate the
REAL(SP), DIMENSION(:), ALLOCATABLE, SAVE :: cc,cr      filter to pwt.
END MODULE pwtcom

```

**SUBROUTINE pwtset(n)**

```

USE nrtype; USE nrutil, ONLY : nrerror
USE pwtcom
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
  Initializing routine for pwt, here implementing the Daubechies wavelet filters with 4, 12,
  and 20 coefficients, as selected by the input value n. Further wavelet filters can be included
  in the obvious manner. This routine must be called (once) before the first use of pwt. (For
  the case n=4, the specific routine daub4 is considerably faster than pwt.)
REAL(SP) :: sig
REAL(SP), PARAMETER :: &
  c4(4)=(/ &
  0.4829629131445341_sp, 0.8365163037378079_sp, &
  0.2241438680420134_sp,-0.1294095225512604_sp /), &
  c12(12)=(/ &
  0.111540743350_sp, 0.494623890398_sp, 0.751133908021_sp, &
  0.315250351709_sp,-0.226264693965_sp,-0.129766867567_sp, &
  0.097501605587_sp, 0.027522865530_sp,-0.031582039318_sp, &
  0.000553842201_sp, 0.004777257511_sp,-0.001077301085_sp /), &
  c20(20)=(/ &
  0.026670057901_sp, 0.188176800078_sp, 0.527201188932_sp, &
  0.688459039454_sp, 0.281172343661_sp,-0.249846424327_sp, &
  -0.195946274377_sp, 0.127369340336_sp, 0.093057364604_sp, &
  -0.071394147166_sp,-0.029457536822_sp, 0.033212674059_sp, &
  0.003606553567_sp,-0.010733175483_sp, 0.001395351747_sp, &
  0.001992405295_sp,-0.000685856695_sp,-0.000116466855_sp, &
  0.000093588670_sp,-0.000013264203_sp /)
if (allocated(cc)) deallocate(cc)
if (allocated(cr)) deallocate(cr)
allocate(cc(n),cr(n))
ncof=n
ioff=-n/2      These values center the "support" of the wavelets at each
joff=-n/2      level. Alternatively, the "peaks" of the wavelets can
sig=-1.0       be approximately centered by the choices ioff=-2
select case(n) and joff=-n+2. Note that daub4 and pwtset with
  case(4)      n=4 use different default centerings.

```

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```

        cc=c4
    case(12)
        cc=c12
    case(20)
        cc=c20
    case default
        call nrerror('unimplemented value n in pwtset')
end select
cr(n:1:-1) = cc
cr(n:1:-2) = -cr(n:1:-2)
END SUBROUTINE pwtset

```

**f90** Here we need to have as global variables arrays whose dimensions are known only at run time. At first sight the situation is the same as with the module `fminln` in `newt` on p. 1197. If you review the discussion there and in §21.5, you will recall that there are two good ways to implement this: with allocatable arrays (“Method 1”) or with pointers (“Method 2”). There is a difference here that makes allocatable arrays simpler. We do not wish to deallocate the arrays on exiting `pwtset`. On the contrary, the values in `cc` and `cr` need to be preserved for use in `pwt`. Since allocatable arrays are born in the well-defined state of “not currently allocated,” we can declare the arrays here as

```
REAL(SP), DIMENSION(:), ALLOCATABLE, SAVE :: cc, cr
```

and test whether they were used on a previous call with

```
if (allocated(cc)) deallocate(cc)
if (allocated(cr)) deallocate(cr)
```

We are then ready to allocate the new storage:

```
allocate(cc(n), cr(n))
```

With pointers, we would need the additional machinery of nullifying the pointers on the initial call, since pointers are born in an undefined state (see §21.5).

There is an additional important point in this example. The module variables need to be used by a “sibling” routine, `pwt`. We need to be sure that they do not become undefined when we exit `pwtset`. We could ensure this by putting a `USE pwtcom` in the main program that calls both `pwtset` and `pwt`, but it’s easy to forget to do this. It is preferable to put explicit `SAVEs` on all the module variables.

```

SUBROUTINE pwt(a, isign)
USE nrtype; USE nrutil, ONLY : arth, nrerror
USE pwtcom
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
INTEGER(I4B), INTENT(IN) :: isign
    Partial wavelet transform: applies an arbitrary wavelet filter to data vector a (for isign=1)
    or applies its transpose (for isign=-1). Used hierarchically by routines wt1 and wtn. The
    actual filter is determined by a preceding (and required) call to pwtset, which initializes
    the module pwtcom.
REAL(SP), DIMENSION(size(a)) :: wksp
INTEGER(I4B), DIMENSION(size(a)/2) :: jf, jr
INTEGER(I4B) :: k, n, nh, nmod
n=size(a)
if (n < 4) RETURN
if (ncof == 0) call nrerror('pwt: must call pwtset before pwt')
nmod=ncof*n

```

A positive constant equal to zero mod n.



```

nh=n/2
wksp(:)=0.0
jf=iand(n-1,arth(2+nmod+ioff,2,nh))
jr=iand(n-1,arth(2+nmod+joff,2,nh))
do k=1,ncof
  if (isign >= 0) then
    wksp(1:nh)=wksp(1:nh)+cc(k)*a(jf+1)
    wksp(nh+1:n)=wksp(nh+1:n)+cr(k)*a(jr+1)
  else
    wksp(jf+1)=wksp(jf+1)+cc(k)*a(1:nh)
    wksp(jr+1)=wksp(jr+1)+cr(k)*a(nh+1:n)
  end if
  if (k == ncof) exit
  jf=iand(n-1,jf+1)
  jr=iand(n-1,jr+1)
end do
a(:)=wksp(:)
END SUBROUTINE pwt

```

Use bitwise AND to wrap-around the pointers.  $n-1$  is a mask of all bits, since  $n$  is a power of 2.

Apply filter.

Apply transpose filter.

Copy the results back from workspace.

\* \* \*

```

SUBROUTINE wtn(a,nn,isign,wtstep)
USE nrtype; USE nrutil, ONLY : arth,assert
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: nn
INTEGER(I4B), INTENT(IN) :: isign
INTERFACE
  SUBROUTINE wtstep(a,isign)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
    INTEGER(I4B), INTENT(IN) :: isign
  END SUBROUTINE wtstep
END INTERFACE

```

Replaces  $a$  by its  $N$ -dimensional discrete wavelet transform, if  $isign$  is input as 1.  $nn$  is an integer array of length  $N$ , containing the lengths of each dimension (number of real values), which must all be powers of 2.  $a$  is a real array of length equal to the product of these lengths, in which the data are stored as in a multidimensional real FORTRAN array. If  $isign$  is input as  $-1$ ,  $a$  is replaced by its inverse wavelet transform. The subroutine  $wtstep$ , whose actual name must be supplied in calling this routine, is the underlying wavelet filter. Examples of  $wtstep$  are `daub4` and (preceded by `pwtset`) `pwt`.

```

INTEGER(I4B) :: i1,i2,i3,idim,n,ndim,nnew,nprev,nt,ntot
REAL(SP), DIMENSION(:), ALLOCATABLE :: wksp
call assert(iand(nn,nn-1)==0, 'each dimension must be a power of 2 in wtn')
allocate(wksp(maxval(nn)))
ndim=size(nn)
ntot=product(nn(:))
nprev=1
do idim=1,ndim
  n=nn(idim)
  nnew=n*nprev
  if (n > 4) then
    do i2=0,ntot-1,nnew
      do i1=1,nprev
        i3=i1+i2
        wksp(1:n)=a(arth(i3,nprev,n))
        i3=i3+n*nprev
        if (isign >= 0) then
          nt=n
          do

```

Main loop over the dimensions.

Copy the relevant row or column or etc. into workspace.

Do one-dimensional wavelet transform.

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```

        if (nt < 4) exit
        call wtstep(wksp(1:nt),isign)
        nt=nt/2
    end do
else
    Or inverse transform.
    nt=4
    do
        if (nt > n) exit
        call wtstep(wksp(1:nt),isign)
        nt=nt*2
    end do
end if
i3=i1+i2
a(arth(i3,nprev,n))=wksp(1:n)
i3=i3+n*nprev
    end do
end do
end if
nprev=nnew
end do
deallocate(wksp)
END SUBROUTINE wtn
Copy back from workspace.

```

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## Chapter B14. Statistical Description of Data

```

SUBROUTINE moment(data,ave,adev,sdev,var,skew,curt)
USE nrtype; USE nrutil, ONLY : nrerror
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: ave,adev,sdev,var,skew,curt
REAL(SP), DIMENSION(:), INTENT(IN) :: data
    Given an array of data, this routine returns its mean ave, average deviation adev, standard
    deviation sdev, variance var, skewness skew, and kurtosis curt.
INTEGER(I4B) :: n
REAL(SP) :: ep
REAL(SP), DIMENSION(size(data)) :: p,s
n=size(data)
if (n <= 1) call nrerror('moment: n must be at least 2')
ave=sum(data(:))/n           First pass to get the mean.
s(:)=data(:)-ave           Second pass to get the first (absolute), second, third, and
ep=sum(s(:))                fourth moments of the deviation from the mean.
adev=sum(abs(s(:)))/n
p(:)=s(:)*s(:)
var=sum(p(:))
p(:)=p(:)*s(:)
skew=sum(p(:))
p(:)=p(:)*s(:)
curt=sum(p(:))
var=(var-ep**2/n)/(n-1)     Corrected two-pass formula.
sdev=sqrt(var)
if (var /= 0.0) then
    skew=skew/(n*sdev**3)
    curt=curt/(n*var**2)-3.0_sp
else
    call nrerror('moment: no skew or kurtosis when zero variance')
end if
END SUBROUTINE moment

```

\* \* \*

```

SUBROUTINE ttest(data1,data2,t,prob)
USE nrtype
USE nr, ONLY : avevar,betai
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2
REAL(SP), INTENT(OUT) :: t,prob
    Given the arrays data1 and data2, which need not have the same length, this routine
    returns Student's t as t, and its significance as prob, small values of prob indicating that

```

the arrays have significantly different means. The data arrays are assumed to be drawn from populations with the same true variance.

```

INTEGER(I4B) :: n1,n2
REAL(SP) :: ave1,ave2,df,var,var1,var2
n1=size(data1)
n2=size(data2)
call avevar(data1,ave1,var1)
call avevar(data2,ave2,var2)
df=n1+n2-2
var=((n1-1)*var1+(n2-1)*var2)/df
t=(ave1-ave2)/sqrt(var*(1.0_sp/n1+1.0_sp/n2))
prob=betai(0.5_sp*df,0.5_sp,df/(df+t**2))
END SUBROUTINE ttest

```

Degrees of freedom.  
Pooled variance.  
See equation (6.4.9).

\* \* \*

```

SUBROUTINE avevar(data,ave,var)
USE nrtype
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: data
REAL(SP), INTENT(OUT) :: ave,var
    Given array data, returns its mean as ave and its variance as var.
INTEGER(I4B) :: n
REAL(SP), DIMENSION(size(data)) :: s
n=size(data)
ave=sum(data(:))/n
s(:)=data(:)-ave
var=dot_product(s,s)
var=(var-sum(s)**2/n)/(n-1)
END SUBROUTINE avevar

```

Corrected two-pass formula (14.1.8).

\* \* \*

```

SUBROUTINE tutest(data1,data2,t,prob)
USE nrtype
USE nr, ONLY : avevar,betai
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2
REAL(SP), INTENT(OUT) :: t,prob
    Given the arrays data1 and data2, which need not have the same length, this routine
    returns Student's t as t, and its significance as prob, small values of prob indicating that
    the arrays have significantly different means. The data arrays are allowed to be drawn from
    populations with unequal variances.
INTEGER(I4B) :: n1,n2
REAL(SP) :: ave1,ave2,df,var1,var2
n1=size(data1)
n2=size(data2)
call avevar(data1,ave1,var1)
call avevar(data2,ave2,var2)
t=(ave1-ave2)/sqrt(var1/n1+var2/n2)
df=(var1/n1+var2/n2)**2/((var1/n1)**2/(n1-1)+(var2/n2)**2/(n2-1))
prob=betai(0.5_sp*df,0.5_sp,df/(df+t**2))
END SUBROUTINE tutest

```

\* \* \*

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```

SUBROUTINE tptest(data1,data2,t,prob)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : avevar,betai
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2
REAL(SP), INTENT(OUT) :: t,prob
  Given the paired arrays data1 and data2 of the same length, this routine returns Student's
  t for paired data as t, and its significance as prob, small values of prob indicating a
  significant difference of means.
INTEGER(I4B) :: n
REAL(SP) :: ave1,ave2,cov,df,sd,var1,var2
n=assert_eq(size(data1),size(data2),'tptest')
call avevar(data1,ave1,var1)
call avevar(data2,ave2,var2)
cov=dot_product(data1(:)-ave1,data2(:)-ave2)
df=n-1
cov=cov/df
sd=sqrt((var1+var2-2.0_sp*cov)/n)
t=(ave1-ave2)/sd
prob=betai(0.5_sp*df,0.5_sp,df/(df+t**2))
END SUBROUTINE tptest

```

\* \* \*

```

SUBROUTINE ftest(data1,data2,f,prob)
USE nrtype
USE nr, ONLY : avevar,betai
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: f,prob
REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2
  Given the arrays data1 and data2, which need not have the same length, this routine
  returns the value of f, and its significance as prob. Small values of prob indicate that the
  two arrays have significantly different variances.
INTEGER(I4B) :: n1,n2
REAL(SP) :: ave1,ave2,df1,df2,var1,var2
n1=size(data1)
n2=size(data2)
call avevar(data1,ave1,var1)
call avevar(data2,ave2,var2)
if (var1 > var2) then      Make F the ratio of the larger variance to the smaller one.
  f=var1/var2
  df1=n1-1
  df2=n2-1
else
  f=var2/var1
  df1=n2-1
  df2=n1-1
end if
prob=2.0_sp*betai(0.5_sp*df2,0.5_sp*df1,df2/(df2+df1*f))
if (prob > 1.0) prob=2.0_sp-prob
END SUBROUTINE ftest

```

\* \* \*

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```

SUBROUTINE chsone(bins,ebins,knstrn,df,chs,prob)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
USE nr, ONLY : gammq
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: knstrn
REAL(SP), INTENT(OUT) :: df,chs,prob
REAL(SP), DIMENSION(:), INTENT(IN) :: bins,ebins
  Given the same-size arrays bins containing the observed numbers of events, and ebins
  containing the expected numbers of events, and given the number of constraints knstrn
  (normally one), this routine returns (trivially) the number of degrees of freedom df, and
  (nontrivially) the chi-square chsq and the significance prob. A small value of prob indi-
  cates a significant difference between the distributions bins and ebins. Note that bins
  and ebins are both real arrays, although bins will normally contain integer values.
INTEGER(I4B) :: ndum
ndum=assert_eq(size(bins),size(ebins),'chsone')
if (any(ebins(:) <= 0.0)) call nrerror('bad expected number in chsone')
df=size(bins)-knstrn
chs=sum((bins(:)-ebins(:))**2/ebins(:))
prob=gammq(0.5_sp*df,0.5_sp*chs)      Chi-square probability function. See §6.2.
END SUBROUTINE chsone

```

```

SUBROUTINE chstwo(bins1,bins2,knstrn,df,chs,prob)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : gammq
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: knstrn
REAL(SP), INTENT(OUT) :: df,chs,prob
REAL(SP), DIMENSION(:), INTENT(IN) :: bins1,bins2
  Given the same-size arrays bins1 and bins2, containing two sets of binned data, and given
  the number of constraints knstrn (normally 1 or 0), this routine returns the number of
  degrees of freedom df, the chi-square chsq, and the significance prob. A small value of
  prob indicates a significant difference between the distributions bins1 and bins2. Note
  that bins1 and bins2 are both real arrays, although they will normally contain integer
  values.
INTEGER(I4B) :: ndum
LOGICAL(LGT), DIMENSION(size(bins1)) :: nzeromask
ndum=assert_eq(size(bins1),size(bins2),'chstwo')
nzeromask = bins1(:) /= 0.0 .or. bins2(:) /= 0.0
chs=sum((bins1(:)-bins2(:))**2/(bins1(:)+bins2(:)),mask=nzeromask)
df=count(nzeromask)-knstrn      No data means one less degree of freedom.
prob=gammq(0.5_sp*df,0.5_sp*chs)      Chi-square probability function. See §6.2.
END SUBROUTINE chstwo

```

**f90** `nzeromask=...chsq=sum(...mask=nzeromask)` We use the optional argument mask in sum to select out the elements to be summed over. In this case, at least one of the elements of bins1 or bins2 is not zero for each term in the sum.

\* \* \*

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```

SUBROUTINE ksone(data,func,d,prob)
USE nrtype; USE nrutil, ONLY : arth
USE nr, ONLY : probks,sort
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: d,prob
REAL(SP), DIMENSION(:), INTENT(INOUT) :: data
INTERFACE
  FUNCTION func(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: func
  END FUNCTION func
END INTERFACE

```

Given an array `data`, and given a user-supplied function of a single variable `func` which is a cumulative distribution function ranging from 0 (for smallest values of its argument) to 1 (for largest values of its argument), this routine returns the K–S statistic `d`, and the significance level `prob`. Small values of `prob` show that the cumulative distribution function of `data` is significantly different from `func`. The array `data` is modified by being sorted into ascending order.

```

INTEGER(I4B) :: n
REAL(SP) :: en
REAL(SP), DIMENSION(size(data)) :: fvals
REAL(SP), DIMENSION(size(data)+1) :: temp
call sort(data)
n=size(data)
en=n
fvals(:)=func(data(:))
temp=arth(0,1,n+1)/en
d=maxval(max(abs(temp(1:n)-fvals(:)), &
  abs(temp(2:n+1)-fvals(:))))
en=sqrt(en)
prob=probks((en+0.12_sp+0.11_sp/en)*d)
END SUBROUTINE ksone

```

If the data are already sorted into ascending order, then this call can be omitted.

Compute the maximum distance between the data's c.d.f. and the user-supplied function.

Compute significance.

**f**<sub>90</sub> `d=maxval(max...` Note the difference between `max` and `maxval`: `max` takes two or more arguments and returns the maximum. If the arguments are two arrays, it returns an array each of whose elements is the maximum of the corresponding elements in the two arrays. `maxval` takes a single array argument and returns its maximum value.

```

SUBROUTINE kstwo(data1,data2,d,prob)
USE nrtype; USE nrutil, ONLY : cumsum
USE nr, ONLY : probks,sort2
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: d,prob
REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2

```

Given arrays `data1` and `data2`, which can be of different length, this routine returns the K–S statistic `d`, and the significance level `prob` for the null hypothesis that the data sets are drawn from the same distribution. Small values of `prob` show that the cumulative distribution function of `data1` is significantly different from that of `data2`. The arrays `data1` and `data2` are not modified.

```

INTEGER(I4B) :: n1,n2
REAL(SP) :: en1,en2,en
REAL(SP), DIMENSION(size(data1)+size(data2)) :: dat,org
n1=size(data1)
n2=size(data2)
en1=n1
en2=n2
dat(1:n1)=data1
dat(n1+1:)=data2

```

Copy the two data sets into a single array.

```

org(1:n1)=0.0          Define an array that contains 0 when the
org(n1+1:)=1.0        corresponding element comes from
call sort2(dat,org)    data1, 1 from data2.
Sort the array of 1's and 0's into the order of the merged data sets.
d=maxval(abs(cumsum(org)/en2-cumsum(1.0_sp-org)/en1))
Now use cumsum to get the c.d.f. corresponding to each set of data.
en=sqrt(en1*en2/(en1+en2))
prob=probks((en+0.12_sp+0.11_sp/en)*d)    Compute significance.
END SUBROUTINE kstwo

```



The problem here is how to compute the cumulative distribution function (c.d.f.) corresponding to each set of data, and then find the corresponding KS statistic, without a serial loop over the data. The trick is to define an array that contains 0 when the corresponding element comes from the first data set and 1 when it's from the second data set. Sort the array of 1's and 0's into the same order as the merged data sets. Now tabulate the partial sums of the array. Every time you encounter a 1, the partial sum increases by 1. So if you normalize the partial sums by dividing by the number of elements in the second data set, you have the c.d.f. of the second data set.

If you subtract the array of 1's and 0's from an array of all 1's, you get an array where 1 corresponds to an element in the first data set, 0 the second data set. So tabulating its partial sums and normalizing gives the c.d.f. of the first data set. As we've seen before, tabulating partial sums can be done with a parallel algorithm (cumsum in `nrutil`). The KS statistic is just the maximum absolute difference of the c.d.f.'s, computed in parallel with Fortran 90's `maxval` function.

```

FUNCTION probks(alam)
USE nrtype
IMPLICIT NONE
REAL(SP), INTENT(IN) :: alam
REAL(SP) :: probks
REAL(SP), PARAMETER :: EPS1=0.001_sp, EPS2=1.0e-8_sp
INTEGER(I4B), PARAMETER :: NITER=100
Kolmogorov-Smirnov probability function.
INTEGER(I4B) :: j
REAL(SP) :: a2, fac, term, termbf
a2=-2.0_sp*alam**2
fac=2.0
probks=0.0
termbf=0.0          Previous term in sum.
do j=1, NITER
term=fac*exp(a2*j**2)
probks=probks+term
if (abs(term) <= EPS1*termbf .or. abs(term) <= EPS2*probks) RETURN
fac=-fac          Alternating signs in sum.
termbf=abs(term)
end do
probks=1.0          Get here only by failing to converge, which implies the func-
END FUNCTION probks          tion is very close to 1.

```

\* \* \*

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```

SUBROUTINE cntab1(nn,chisq,df,prob,cramrv,ccc)
USE nrtype; USE nrutil, ONLY : outerprod
USE nr, ONLY : gammq
IMPLICIT NONE
INTEGER(I4B), DIMENSION(:,:), INTENT(IN) :: nn
REAL(SP), INTENT(OUT) :: chisq,df,prob,cramrv,ccc
REAL(SP), PARAMETER :: TINY=1.0e-30_sp
    Given a two-dimensional contingency table in the form of a rectangular integer array nn,
    this routine returns the chi-square chisq, the number of degrees of freedom df, the signifi-
    cance level prob (small values indicating a significant association), and two measures of
    association, Cramer's V (cramrv), and the contingency coefficient C (ccc).
INTEGER(I4B) :: nni,nnj
REAL(SP) :: sumn
REAL(SP), DIMENSION(size(nn,1)) :: sumi
REAL(SP), DIMENSION(size(nn,2)) :: sumj
REAL(SP), DIMENSION(size(nn,1),size(nn,2)) :: expctd
sumi(:)=sum(nn(:,,:),dim=2)           Get the row totals.
sumj(:)=sum(nn(:,,:),dim=1)           Get the column totals.
sumn=sum(sumi(:))                     Get the grand total.
nni=size(sumi)-count(sumi(:) == 0.0)
    Eliminate any zero rows by reducing the number of rows.
nnj=size(sumj)-count(sumj(:) == 0.0)  Eliminate any zero columns.
df=nni*nnj-nni-nnj+1                 Corrected number of degrees of freedom.
expctd(:,:)=outerprod(sumi(:),sumj(:))/sumn
chisq=sum((nn(:,:)-expctd(:,:))**2/(expctd(:,:)+TINY))
    Do the chi-square sum. Here TINY guarantees that any eliminated row or column will not
    contribute to the sum.
prob=gammq(0.5_sp*df,0.5_sp*chisq)    Chi-square probability function.
cramrv=sqrt(chisq/(sumn*min(nni-1,nnj-1)))
ccc=sqrt(chisq/(chisq+sumn))
END SUBROUTINE cntab1

```

**f90**

`sumi(:)=sum(...dim=2)...sumj(:)=sum(...dim=1)` We use the optional argument `dim` of `sum` to sum first over the columns (`dim=2`) to get the row totals, and then to sum over the rows (`dim=1`) to get the column totals.

`expctd(:,:)=...` This is a direct implementation of equation (14.4.2) using `outerprod` from `nrutil`.

`chisq=...` And here is a direct implementation of equation (14.4.3).

```

SUBROUTINE cntab2(nn,h,hx,hy,hygx,hxgy,uygx,uxgy,uxy)
USE nrtype
IMPLICIT NONE
INTEGER(I4B), DIMENSION(:,:), INTENT(IN) :: nn
REAL(SP), INTENT(OUT) :: h,hx,hy,hygx,hxgy,uygx,uxgy,uxy
REAL(SP), PARAMETER :: TINY=1.0e-30_sp
    Given a two-dimensional contingency table in the form of a rectangular integer array nn,
    where the first index labels the x-variable and the second index labels the y variable, this
    routine returns the entropy h of the whole table, the entropy hx of the x-distribution, the
    entropy hy of the y-distribution, the entropy hygx of y given x, the entropy hxgy of x
    given y, the dependency uygx of y on x (eq. 14.4.15), the dependency uxgy of x on y
    (eq. 14.4.16), and the symmetrical dependency uxy (eq. 14.4.17).
REAL(SP) :: sumn
REAL(SP), DIMENSION(size(nn,1)) :: sumi
REAL(SP), DIMENSION(size(nn,2)) :: sumj
sumi(:)=sum(nn(:,,:),dim=2)           Get the row totals.
sumj(:)=sum(nn(:,,:),dim=1)           Get the column totals.
sumn=sum(sumi(:))
hx=-sum(sumi(:)*log(sumi(:)/sumn), mask=(sumi(:) /= 0.0) )/sumn
    Entropy of the x distribution,
hy=-sum(sumj(:)*log(sumj(:)/sumn), mask=(sumj(:) /= 0.0) )/sumn

```

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```

and of the  $y$  distribution.
h=-sum(nn(:, :)*log(nn(:, :)/sumn), mask=(nn(:, :)/= 0) )/sumn
  Total entropy: loop over both  $x$  and  $y$ .
hygx=h-hx           Uses equation (14.4.18),
hxyg=h-hy           as does this.
uygx=(hy-hygx)/(hy+TINY) Equation (14.4.15).
uxgy=(hx-hxgy)/(hx+TINY) Equation (14.4.16).
uxy=2.0_sp*(hx+hy-h)/(hx+hy+TINY) Equation (14.4.17).
END SUBROUTINE cntab2

```



This code exploits both the `dim` feature of `sum` (see discussion after `cntab1`) and the `mask` feature to restrict the elements to be summed over.

\* \* \*

```

SUBROUTINE pearsn(x,y,r,prob,z)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : betai
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: r,prob,z
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
REAL(SP), PARAMETER :: TINY=1.0e-20_sp
  Given two arrays  $x$  and  $y$  of the same size, this routine computes their correlation coefficient
   $r$  (returned as  $r$ ), the significance level at which the null hypothesis of zero correlation
  is disproved (prob whose small value indicates a significant correlation), and Fisher's  $z$ 
  (returned as  $z$ ), whose value can be used in further statistical tests as described above the
  routine in Volume 1.
  Parameter: TINY will regularize the unusual case of complete correlation.
REAL(SP), DIMENSION(size(x)) :: xt,yt
REAL(SP) :: ax,ay,df,sxx,sxy,syy,t
INTEGER(I4B) :: n
n=assert_eq(size(x),size(y),'pearsn')
ax=sum(x)/n           Find the means.
ay=sum(y)/n
xt(:)=x(:)-ax
yt(:)=y(:)-ay       Compute the correlation co-
                    efficient.
sxx=dot_product(xt,xt)
syy=dot_product(yt,yt)
sxy=dot_product(xt,yt)
r=sxy/(sqrt(sxx*syy)+TINY)
z=0.5_sp*log(((1.0_sp+r)+TINY)/((1.0_sp-r)+TINY))  Fisher's  $z$  transformation.
df=n-2
t=r*sqrt(df/(((1.0_sp-r)+TINY)*((1.0_sp+r)+TINY))) Equation (14.5.5).
prob=betai(0.5_sp*df,0.5_sp,df/(df+t**2))         Student's  $t$  probability.
! prob=erfcc(abs(z*sqrt(n-1.0_sp)))/SQRT2)
  For large  $n$ , this easier computation of prob, using the short routine erfcc, would give
  approximately the same value.
END SUBROUTINE pearsn

```

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```

SUBROUTINE spear(data1,data2,d,zd,probd,rs,probrs)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : betai,erfcc,sort2
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2
REAL(SP), INTENT(OUT) :: d,zd,probd,rs,probrs
    Given two data arrays of the same size, data1 and data2, this routine returns their sum-
    squared difference of ranks as D, the number of standard deviations by which D deviates
    from its null-hypothesis expected value as zd, the two-sided significance level of this deviation
    as probd, Spearman's rank correlation  $r_s$  as rs, and the two-sided significance level of
    its deviation from zero as probrs. data1 and data2 are not modified. A small value of
    either probd or probrs indicates a significant correlation (rs positive) or anticorrelation
    (rs negative).
INTEGER(I4B) :: n
REAL(SP) :: aved,df,en,en3n,fac,sf,sg,t,var
REAL(SP), DIMENSION(size(data1)) :: wksp1,wksp2
n=assert_eq(size(data1),size(data2),'spear')
wksp1(:)=data1(:)
wksp2(:)=data2(:)
call sort2(wksp1,wksp2)
call crank(wksp1,sf)
call sort2(wksp2,wksp1)
call crank(wksp2,sg)
wksp1(:)=wksp1(:)-wksp2(:)
d=dot_product(wksp1,wksp1)
en=n
en3n=en**3-en
aved=en3n/6.0_sp-(sf+sg)/12.0_sp
fac=(1.0_sp-sf/en3n)*(1.0_sp-sg/en3n)
vard=((en-1.0_sp)*en**2*(en+1.0_sp)**2/36.0_sp)*fac
zd=(d-aved)/sqrt(vard)
probd=erfcc(abs(zd)/SQRT2)
rs=(1.0_sp-(6.0_sp/en3n)*(d+(sf+sg)/12.0_sp))/sqrt(fac)
fac=(1.0_sp+rs)*(1.0_sp-rs)
if (fac > 0.0) then
    t=rs*sqrt((en-2.0_sp)/fac)
    df=en-2.0_sp
    probrs=betai(0.5_sp*df,0.5_sp,df/(df+t**2))
else
    probrs=0.0
end if
CONTAINS
SUBROUTINE crank(w,s)
USE nrtype; USE nrutil, ONLY : arth,array_copy
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: s
REAL(SP), DIMENSION(:), INTENT(INOUT) :: w
    Given a sorted array w, replaces the elements by their rank, including midranking of ties,
    and returns as s the sum of  $f^3 - f$ , where f is the number of elements in each tie.
INTEGER(I4B) :: i,n,ndum,nties
INTEGER(I4B), DIMENSION(size(w)) :: tstart,tend,tie,idx
n=size(w)
idx(:)=arth(1,1,n)
tie(:)=merge(1,0,w == eoshift(w,-1))
    Look for ties: Compare each element to the one before. If it's equal, it's part of a tie, and
    we put 1 into tie. Otherwise we put 0.
tie(1)=0
w(:)=idx(:)
if (all(tie == 0)) then
    s=0.0
    RETURN
end if
call array_copy(pack(idx(:),tie(:)<eoshift(tie(:),1)),tstart,nties,ndum)

```

Sort each of the data arrays, and convert the entries to ranks. The values *sf* and *sg* return the sums  $\sum(f_k^3 - f_k)$  and  $\sum(g_m^3 - g_m)$ , respectively.

Sum the squared difference of ranks.

Expectation value of *D*, and variance of *D* give number of standard deviations, and significance. Rank correlation coefficient, and its *t* value, give its significance.

Index vector.

Boundary; the first element must be zero.

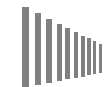
Assign ranks ignoring possible ties.

No ties—we're done.

```

Look for 0 → 1 transitions in tie, which mean that the 0 element is the start of a tie run.
Store index of each transition in tstart. nties is the number of ties found.
tend(1:nties)=pack(idx(:),tie(:)>eoshift(tie(:),1))
Look for 1 → 0 transitions in tie, which mean that the 1 element is the end of a tie run.
do i=1,nties
    w(tstart(i):tend(i))=(tstart(i)+tend(i))/2.0_sp      Midrank assignments.
end do
tend(1:nties)=tend(1:nties)-tstart(1:nties)+1          Now calculate s.
s=sum(tend(1:nties)**3-tend(1:nties))
END SUBROUTINE crank
END SUBROUTINE spear

```



To understand how the parallel version of `crank` works, let's consider an example of 9 elements in the array `w`, which is input in sorted order to `crank`. The elements in our example are given in the second line of the following table:

index	1	2	3	4	5	6	7	8	9	
data in <code>w</code>	0	0	1	1	1	2	3	4	4	
shift right	0	0	0	1	1	1	2	3	4	
compare	1	1	0	1	1	0	0	0	1	
tie array	0	1	0	1	1	0	0	0	1	
shift left	1	0	1	1	0	0	0	1	0	
0 → 1	1		3					8		start index
1 → 0		2			5				9	stop index

We look for ties by comparing this array with itself, right shifted by one element (“shift right” in table). We record a 1 for each element that is the same, a 0 for each element that is different (“compare”). A 1 indicates the element is part of a tie with the *preceding* element, so we always set the first element to 0, even if it was a 1 as in our example. This gives the “tie array.” Now wherever the tie array makes a transition 0 → 1 indicates the start of a tie run, while a 1 → 0 transition indicates the end of a tie run. We find these transitions by comparing the tie array to itself left shifted by one (“shift left”). If the tie array element is smaller than the shifted array element, we have a 0 → 1 transition and we record the corresponding index as the start of a tie. Similarly if the tie array element is larger we record the index as the end of a tie. Note that the shifts must be end-off shifts with zeros inserted in the gaps for the boundary conditions to work.



```

call array_copy(pack(idx(:),tie(:)<eoshift(tie(:),1)),
               tstart,nties,ndum)

```

The start indices (1, 3, and 8 in our example above) are here packed into the first few elements of `tstart`. `array_copy` is a useful routine in `nrutil` for copying elements from one array to another, when the number of elements to be copied is not known in advance. This line of code is equivalent to

```

tstart(:)=0
tstart(:)=pack(idx(:), tie(:) < eoshift(tie(:),1),tstart(:))
nties=count(tstart(:) > 0)

```

The point is that we don't know how many elements `pack` is going to select. We have to make sure the dimensions of both sides of the `pack` statement are the same,

so we set the optional third argument of `pack` to `tstart`. We then make a separate pass through `tstart` to count how many elements we copied. Alternatively, we could have used an additional logical array `mask` and coded this as

```
mask(:)=tie(:) < eoshift(tie(:),1)
nties=count(mask)
tstart(1:nties)=pack(idx(:),mask)
```

But we still need two passes through the `mask` array. The beauty of the `array_copy` routine is that `nties` is determined from the *size* of the first argument, without the necessity for a second pass through the array.

\* \* \*

```
SUBROUTINE kendl1(data1,data2,tau,z,prob)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : erfcc
IMPLICIT NONE
REAL(SP), INTENT(OUT) :: tau,z,prob
REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2
    Given same-size data arrays data1 and data2, this program returns Kendall's  $\tau$  as tau, its
    number of standard deviations from zero as z, and its two-sided significance level as prob.
    Small values of prob indicate a significant correlation (tau positive) or anticorrelation
    (tau negative).
INTEGER(I4B) :: is,j,n,n1,n2
REAL(SP) :: var
REAL(SP), DIMENSION(size(data1)) :: a1,a2
n=assert_eq(size(data1),size(data2),'kendl1')
n1=0
n2=0
is=0
do j=1,n-1
    a1(j+1:n)=data1(j)-data1(j+1:n)
    a2(j+1:n)=data2(j)-data2(j+1:n)
    n1=n1+count(a1(j+1:n) /= 0.0)
    n2=n2+count(a2(j+1:n) /= 0.0)
    Now accumulate the numerator in (14.6.8):
    is=is+count((a1(j+1:n) > 0.0 .and. a2(j+1:n) > 0.0) &
    .or. (a1(j+1:n) < 0.0 .and. a2(j+1:n) < 0.0)) - &
    count((a1(j+1:n) > 0.0 .and. a2(j+1:n) < 0.0) &
    .or. (a1(j+1:n) < 0.0 .and. a2(j+1:n) > 0.0))
end do
tau=real(is,sp)/sqrt(real(n1,sp)*real(n2,sp))
var=(4.0_sp*n+10.0_sp)/(9.0_sp*n*(n-1.0_sp))
z=tau/sqrt(var)
prob=erfcc(abs(z)/SQRT2)
END SUBROUTINE kendl1
```

This will be the argument of one square root in (14.6.8),  
and this the other.

This will be the numerator in (14.6.8).

For each first member of pair,  
loop over second member.

Equation (14.6.8).

Equation (14.6.9).

Significance.

```
SUBROUTINE kendl2(tab,tau,z,prob)
USE nrtype; USE nrutil, ONLY : cumsum
USE nr, ONLY : erfcc
IMPLICIT NONE
REAL(SP), DIMENSION(:, :), INTENT(IN) :: tab
REAL(SP), INTENT(OUT) :: tau,z,prob
    Given a two-dimensional table tab such that tab(k,l) contains the number of events falling
    in bin k of one variable and bin l of another, this program returns Kendall's  $\tau$  as tau, its
    number of standard deviations from zero as z, and its two-sided significance level as prob.
    Small values of prob indicate a significant correlation (tau positive) or anticorrelation (tau
```

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```

negative) between the two variables. Although tab is a real array, it will normally contain
integral values.
REAL(SP), DIMENSION(size(tab,1),size(tab,2)) :: cum,cumt
INTEGER(I4B) :: i,j,ii,jj
REAL(SP) :: sc,sd,en1,en2,points,var
ii=size(tab,1)
jj=size(tab,2)
do i=1,ii
  cumt(i,jj:1:-1)=cumsum(tab(i,jj:1:-1))
end do
en2=sum(tab(1:ii,1:jj-1)*cumt(1:ii,2:jj))
do j=1,jj
  cum(ii:1:-1,j)=cumsum(cumt(ii:1:-1,j))
end do
points=cum(1,1)
sc=sum(tab(1:ii-1,1:jj-1)*cum(2:ii,2:jj))
do j=1,jj
  cum(1:ii,j)=cumsum(cumt(1:ii,j))
end do
sd=sum(tab(2:ii,1:jj-1)*cum(1:ii-1,2:jj))
do j=1,jj
  cumt(ii:1:-1,j)=cumsum(tab(ii:1:-1,j))
end do
en1=sum(tab(1:ii-1,1:jj)*cumt(2:ii,1:jj))
tau=(sc-sd)/sqrt((en1+sc+sd)*(en2+sc+sd))
var=(4.0_sp*points+10.0_sp)/(9.0_sp*points*(points-1.0_sp))
z=tau/sqrt(var)
prob=erfcc(abs(z)/SQRT2)
END SUBROUTINE kend12

```

Get cumulative sums leftward along rows.

Tally the extra-y pairs.  
Get counts of points to lower-right of each cell in cum.

Total number of entries in table.  
Tally the concordant pairs.  
Now get counts of points to upper-right of each cell in cum,

giving tally of discordant points.  
Finally, get cumulative sums upward along columns,

giving the count of extra-x pairs,  
and compute desired results.



The underlying algorithm in kend12 might seem to require looping over all *pairs* of cells in the two-dimensional table `tab`. Actually, however, clever use of the `cumsum` utility function reduces this to a simple loop over all the cells; moreover this “loop” parallelizes into a simple parallel product and call to the `sum` intrinsic. The basic idea is shown in the following table:

		$d$	$d$
	$t$	$y$	$y$
	$x$	$c$	$c$
	$x$	$c$	$c$
	$x$	$c$	$c$

Relative to the cell marked  $t$  (which we use to denote the numerical value it contains), the cells marked  $d$  contribute to the “discordant” tally in Volume 1’s equation (14.6.8),

while the cells marked  $c$  contribute to the “concordant” tally. Likewise, the cells marked  $x$  and  $y$  contribute, respectively, to the “extra- $x$ ” and “extra- $y$ ” tallies. What about the cells left blank? Since we want to count pairs of cells only *once*, without duplication, these cells will be counted, relative to the location shown as  $t$ , when  $t$  itself moves into the blank-cell area.

Symbolically we have

$$\begin{aligned}
 \text{concordant} &= \sum_n t_n \left( \sum_{\text{lower right}} c_m \right) \\
 \text{discordant} &= \sum_n t_n \left( \sum_{\text{upper right}} d_m \right) \\
 \text{extra-}x &= \sum_n t_n \left( \sum_{\text{below}} x_m \right) \\
 \text{extra-}y &= \sum_n t_n \left( \sum_{\text{to the right}} y_m \right)
 \end{aligned} \tag{B14.1}$$

Here  $n$  varies over all the positions in the table, while the limits of the inner sums are relative to the position of  $n$ . (The letters  $t_n$ ,  $c_m$ ,  $d_m$ ,  $x_m$ ,  $y_m$  all represent the value in a cell; we use different letters only to make the relation with the above table clear.) Now the final trick is to recognize that the inner sums, over cells to the lower- or upper-right, below, and to the right can be done in parallel by cumulative sums (cumsum) sweeping to the right and up. The routine does these in a nonintuitive order merely to be able to reuse maximally the scratch spaces cum and cumt.

\* \* \*

```

SUBROUTINE ks2dis(x1,y1,quadvl,d1,prob)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : pearson,probks,quadct
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x1,y1
REAL(SP), INTENT(OUT) :: d1,prob
INTERFACE
  SUBROUTINE quadvl(x,y,fa,fb,fc,fd)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x,y
    REAL(SP), INTENT(OUT) :: fa,fb,fc,fd
  END SUBROUTINE quadvl
END INTERFACE
Two-dimensional Kolmogorov-Smirnov test of one sample against a model. Given the  $x$ -
and  $y$ -coordinates of a set of data points in arrays x1 and y1 of the same length, and given
a user-supplied function quadvl that exemplifies the model, this routine returns the two-
dimensional K-S statistic as d1, and its significance level as prob. Small values of prob
show that the sample is significantly different from the model. Note that the test is slightly
distribution-dependent, so prob is only an estimate.
INTEGER(I4B) :: j,n1
REAL(SP) :: dum,dumm,fa,fb,fc,fd,ga,gb,gc,gd,r1,rr,sqen
n1=assert_eq(size(x1),size(y1),'ks2dis')
d1=0.0

```

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```

do j=1,n1                                Loop over the data points.
  call quadct(x1(j),y1(j),x1,y1,fa,fb,fc,fd)
  call quadvl(x1(j),y1(j),ga,gb,gc,gd)
  d1=max(d1,abs(fa-ga),abs(fb-gb),abs(fc-gc),abs(fd-gd))
  For both the sample and the model, the distribution is integrated in each of four quadrants, and the maximum difference is saved.
end do
call pearsn(x1,y1,r1,dum,dumm)           Get the linear correlation coefficient r1.
sqen=sqrt(real(n1,sp))
rr=sqrt(1.0_sp-r1**2)
  Estimate the probability using the K-S probability function probks.
prob=probks(d1*sqen/(1.0_sp+rr*(0.25_sp-0.75_sp/sqen)))
END SUBROUTINE ks2d1s

```

```

SUBROUTINE quadct(x,y,xx,yy,fa,fb,fc,fd)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x,y
REAL(SP), DIMENSION(:), INTENT(IN) :: xx,yy
REAL(SP), INTENT(OUT) :: fa,fb,fc,fd
  Given an origin (x,y), and an array of points with coordinates xx and yy, count how many of them are in each quadrant around the origin, and return the normalized fractions. Quadrants are labeled alphabetically, counterclockwise from the upper right. Used by ks2d1s and ks2d2s.
INTEGER(I4B) :: na,nb,nc,nd,nn
REAL(SP) :: ff
nn=assert_eq(size(xx),size(yy),'quadct')
na=count(yy(:) > y .and. xx(:) > x)
nb=count(yy(:) > y .and. xx(:) <= x)
nc=count(yy(:) <= y .and. xx(:) <= x)
nd=nn-na-nb-nc
ff=1.0_sp/nn
fa=ff*na
fb=ff*nb
fc=ff*nc
fd=ff*nd
END SUBROUTINE quadct

```

```

SUBROUTINE quadvl(x,y,fa,fb,fc,fd)
USE nrtype
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x,y
REAL(SP), INTENT(OUT) :: fa,fb,fc,fd
  This is a sample of a user-supplied routine to be used with ks2d1s. In this case, the model distribution is uniform inside the square  $-1 < x < 1$ ,  $-1 < y < 1$ . In general this routine should return, for any point (x,y), the fraction of the total distribution in each of the four quadrants around that point. The fractions, fa, fb, fc, and fd, must add up to 1.
  Quadrants are alphabetical, counterclockwise from the upper right.
REAL(SP) :: qa,qb,qc,qd
qa=min(2.0_sp,max(0.0_sp,1.0_sp-x))
qb=min(2.0_sp,max(0.0_sp,1.0_sp-y))
qc=min(2.0_sp,max(0.0_sp,x+1.0_sp))
qd=min(2.0_sp,max(0.0_sp,y+1.0_sp))
fa=0.25_sp*qa*qb
fb=0.25_sp*qb*qc
fc=0.25_sp*qc*qd
fd=0.25_sp*qd*qa
END SUBROUTINE quadvl

```

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```

SUBROUTINE ks2d2s(x1,y1,x2,y2,d,prob)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : pearsn,probks,quadct
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x1,y1,x2,y2
REAL(SP), INTENT(OUT) :: d,prob
  Compute two-dimensional Kolmogorov-Smirnov test on two samples. Input are the x- and
  y-coordinates of the first sample in arrays x1 and y1 of the same length, and of the second
  sample in arrays x2 and y2 of the same length (possibly different from the length of the first
  sample). The routine returns the two-dimensional, two-sample K-S statistic as d, and its
  significance level as prob. Small values of prob show that the two samples are significantly
  different. Note that the test is slightly distribution-dependent, so prob is only an estimate.
INTEGER(I4B) :: j,n1,n2
REAL(SP) :: d1,d2,dum,dumm,fa,fb,fc,fd,ga,gb,gc,gd,r1,r2,rr,sqen
n1=assert_eq(size(x1),size(y1),'ks2d2s: n1')
n2=assert_eq(size(x2),size(y2),'ks2d2s: n2')
d1=0.0
do j=1,n1
  First, use points in the first sample as origins.
  call quadct(x1(j),y1(j),x1,y1,fa,fb,fc,fd)
  call quadct(x1(j),y1(j),x2,y2,ga,gb,gc,gd)
  d1=max(d1,abs(fa-ga),abs(fb-gb),abs(fc-gc),abs(fd-gd))
end do
d2=0.0
do j=1,n2
  Then, use points in the second sample as ori-
  call quadct(x2(j),y2(j),x1,y1,fa,fb,fc,fd) gins.
  call quadct(x2(j),y2(j),x2,y2,ga,gb,gc,gd)
  d2=max(d2,abs(fa-ga),abs(fb-gb),abs(fc-gc),abs(fd-gd))
end do
d=0.5_sp*(d1+d2) Average the K-S statistics.
sqen=sqrt(real(n1,sp)*real(n2,sp)/real(n1+n2,sp))
call pearsn(x1,y1,r1,dum,dumm) Get the linear correlation coefficient for each sam-
call pearsn(x2,y2,r2,dum,dumm) ple.
rr=sqrt(1.0_sp-0.5_sp*(r1**2+r2**2))
Estimate the probability using the K-S probability function probks.
prob=probks(d*sqen/(1.0_sp+rr*(0.25_sp-0.75_sp/sqen)))
END SUBROUTINE ks2d2s

```

\* \* \*

```

FUNCTION savgol(nl,nrr,ld,m)
USE nrtype; USE nrutil, ONLY : arth,assert,poly
USE nr, ONLY : lubksb,ludcmp
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: nl,nrr,ld,m
  Returns in array c, in wrap-around order (N.B.!) consistent with the argument respns in
  routine convlv, a set of Savitzky-Golay filter coefficients. nl is the number of leftward
  (past) data points used, while nrr is the number of rightward (future) data points, making
  the total number of data points used nl + nrr + 1. ld is the order of the derivative desired
  (e.g., ld = 0 for smoothed function). m is the order of the smoothing polynomial, also
  equal to the highest conserved moment; usual value is m = 2 or m = 4.
REAL(SP), DIMENSION(nl+nrr+1) :: savgol
INTEGER(I4B) :: imj,ipj,mm,np
INTEGER(I4B), DIMENSION(m+1) :: indx
REAL(SP) :: d,sm
REAL(SP), DIMENSION(m+1) :: b
REAL(SP), DIMENSION(m+1,m+1) :: a
INTEGER(I4B) :: irng(nl+nrr+1)
call assert(nl >= 0, nrr >= 0, ld <= m, nl+nrr >= m, 'savgol args')
do ipj=0,2*m
  Set up the normal equations of the desired least
  sm=sum(arth(1.0_sp,1.0_sp,nrr)**ipj)+& squares fit.
  sum(arth(-1.0_sp,-1.0_sp,nl)**ipj)

```

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```

    if (ipj == 0) sm=sm+1.0_sp
    mm=min(ipj,2*m-ipj)
    do imj=-mm,mm,2
        a(1+(ipj+imj)/2,1+(ipj-imj)/2)=sm
    end do
end do
call ludcmp(a(:, :),indx(:),d)           Solve them: LU decomposition.
b(:)=0.0
b(ld+1)=1.0                             Right-hand-side vector is unit vector, depending
call lubksb(a(:, :),indx(:),b(:))      on which derivative we want.
    Backsubstitute, giving one row of the inverse matrix.
savgol(:)=0.0                            Zero the output array (it may be bigger than
irng(:)=arth(-nl,1,nrr+nl+1)           number of coefficients).
np=nl+nrr+1
savgol(mod(np-irng(:),np)+1)=poly(real(irng(:),sp),b(:))
    Each Savitzky-Golay coefficient is the value of the polynomial in (14.8.6) at the corresponding
    integer. The polynomial coefficients are a row of the inverse matrix. The mod function takes
    care of the wrap-around order.
END FUNCTION savgol

```



do imj=-mm,mm,2 Here is an example of a loop that cannot be parallelized in the framework of Fortran 90: We need to access “skew” sections of the matrix a.

savgol...=poly(real(irng(:),sp),b(:)) The poly function in nrrutil returns the value of a polynomial, here the one in equation (14.8.6). We need the explicit kind type parameter sp in the real function, otherwise it would return type default real for the integer argument and would not automatically convert to double precision if desired.

## Chapter B15. Modeling of Data

```

SUBROUTINE fit(x,y,a,b,siga,sigb,chi2,q,sig)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : gammq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
REAL(SP), INTENT(OUT) :: a,b,siga,sigb,chi2,q
REAL(SP), DIMENSION(:), OPTIONAL, INTENT(IN) :: sig
    Given a set of data points in same-size arrays x and y, fit them to a straight line  $y = a + bx$ 
    by minimizing  $\chi^2$ . sig is an optional array of the same length containing the individual
    standard deviations. If it is present, then a,b are returned with their respective probable
    uncertainties siga and sigb, the chi-square chi2, and the goodness-of-fit probability q
    (that the fit would have  $\chi^2$  this large or larger). If sig is not present, then q is returned
    as 1.0 and the normalization of chi2 is to unit standard deviation on all points.
INTEGER(I4B) :: ndata
REAL(SP) :: sigdat,ss,sx,sxoss,sy,st2
REAL(SP), DIMENSION(size(x)), TARGET :: t
REAL(SP), DIMENSION(:), POINTER :: wt
if (present(sig)) then
    ndata=assert_eq(size(x),size(y),size(sig),'fit')
    wt=>t
    wt(:)=1.0_sp/(sig(:)**2)
    ss=sum(wt(:))
    sx=dot_product(wt,x)
    sy=dot_product(wt,y)
else
    ndata=assert_eq(size(x),size(y),'fit')
    ss=real(size(x),sp)
    sx=sum(x)
    sy=sum(y)
end if
sxoss=sx/ss
t(:)=x(:)-sxoss
if (present(sig)) then
    t(:)=t(:)/sig(:)
    b=dot_product(t,sig,y)
else
    b=dot_product(t,y)
end if
st2=dot_product(t,t)
b=b/st2
a=(sy-sx*b)/ss
siga=sqrt((1.0_sp+sx*sx/(ss*st2))/ss)
sigb=sqrt(1.0_sp/st2)
t(:)=y(:)-a-b*x(:)
q=1.0
if (present(sig)) then
    t(:)=t(:)/sig(:)
    chi2=dot_product(t,t)
    if (ndata > 2) q=gammq(0.5_sp*(size(x)-2),0.5_sp*chi2)
else
    chi2=dot_product(t,t)

```

Use temporary variable t to store weights.

Accumulate sums with weights.

Accumulate sums without weights.

Solve for  $a$ ,  $b$ ,  $\sigma_a$ , and  $\sigma_b$ .

Calculate  $\chi^2$ .

Equation (15.2.12).

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```

    sigdat=sqrt(chi2/(size(x)-2))
    siga=siga*sigdat
    sigb=sigb*sigdat
end if
END SUBROUTINE fit

```

For unweighted data evaluate typical sig using chi2, and adjust the standard deviations.

**f90** REAL(SP), DIMENSION(:), POINTER :: wt...wt=>t When standard deviations are supplied in sig, we need to compute the weights for the least squares fit in a temporary array wt. Later in the routine, we need another temporary array, which we call t to correspond to the variable in equation (15.2.15). It would be confusing to use the same name for both arrays. In Fortran 77 the arrays could share storage with an EQUIVALENCE declaration, but that is a deprecated feature in Fortran 90. We accomplish the same thing by making wt a pointer alias to t.

```

          *      *      *
SUBROUTINE fitexy(x,y,sigx,sigy,a,b,siga,sigb,chi2,q)
USE nrtype; USE nrutil, ONLY : assert_eq,swap
USE nr, ONLY : avevar,brent,fit,gammq,mnbrak,zbrent
USE chixyfit
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,sigx,sigy
REAL(SP), INTENT(OUT) :: a,b,siga,sigb,chi2,q
REAL(SP), PARAMETER :: POTN=1.571000_sp,BIG=1.0e30_sp,ACC=1.0e-3_sp
Straight-line fit to input data x and y with errors in both x and y, the respective standard
deviations being the input quantities sigx and sigy. x, y, sigx, and sigy are all arrays of
the same length. Output quantities are a and b such that  $y = a + bx$  minimizes  $\chi^2$ , whose
value is returned as chi2. The  $\chi^2$  probability is returned as q, a small value indicating
a poor fit (sometimes indicating underestimated errors). Standard errors on a and b are
returned as siga and sigb. These are not meaningful if either (i) the fit is poor, or (ii) b
is so large that the data are consistent with a vertical (infinite b) line. If siga and sigb
are returned as BIG, then the data are consistent with all values of b.
INTEGER(I4B) :: j,n
REAL(SP), DIMENSION(size(x)), TARGET :: xx,yy,sx,sy,ww
REAL(SP), DIMENSION(6) :: ang,ch
REAL(SP) :: amx,amn,varx,vary,scale,bmn,bmx,d1,d2,r2,&
dum1,dum2,dum3,dum4,dum5
n=assert_eq(size(x),size(y),size(sigx),size(sigy),'fitexy')
xyp=>xx
yyp=>yy
xsp=>sx
ysp=>sy
wyp=>ww
call avevar(x,dum1,varx)
call avevar(y,dum1,vary)
scale=sqrt(varx/vary)
xx(:)=x(:)
yy(:)=y(:)*scale
sx(:)=sigx(:)
sy(:)=sigy(:)*scale
ww(:)=sqrt(sx(:)**2+sy(:)**2)
call fit(xx,yy,dum1,b,dum2,dum3,dum4,dum5,ww)
offs=0.0
ang(1)=0.0
ang(2)=atan(b)
ang(4)=0.0
ang(5)=ang(2)
ang(6)=POTN
do j=4,6
ch(j)=chixy(ang(j))

```

Set up communication with function chixy through global variables in the module chixyfit.

Find the x and y variances, and scale the data.

Use both x and y weights in first trial fit. Trial fit for b.

Construct several angles for reference points. Make b an angle.

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```

end do
call mnbrak(ang(1),ang(2),ang(3),ch(1),ch(2),ch(3),chixy)
  Bracket the  $\chi^2$  minimum and then locate it with brent.
chi2=brent(ang(1),ang(2),ang(3),chixy,ACC,b)
chi2=chixy(b)
a=aa
q=gammq(0.5_sp*(n-2),0.5_sp*chi2)           Compute  $\chi^2$  probability.
r2=1.0_sp/sum(ww(:))                       Save inverse sum of weights at the minimum.
bmx=BIG                                     Now, find standard errors for  $b$  as points where
bmn=BIG                                      $\Delta\chi^2 = 1$ .
offs=chi2+1.0_sp
do j=1,6                                    Go through saved values to bracket the de-
  if (ch(j) > offs) then                    sired roots. Note periodicity in slope an-
    d1=mod(abs(ang(j)-b),PI)                gles.
    d2=PI-d1
    if (ang(j) < b) call swap(d1,d2)
    if (d1 < bmx) bmx=d1
    if (d2 < bmn) bmn=d2
  end if
end do
if (bmx < BIG) then                          Call zbrent to find the roots.
  bmx=zbrent(chixy,b,b+bmx,ACC)-b
  amx=aa-a
  bmn=zbrent(chixy,b,b-bmn,ACC)-b
  amn=aa-a
  sigb=sqrt(0.5_sp*(bmx**2+bmn**2))/(scale*cos(b)**2)
  siga=sqrt(0.5_sp*(amx**2+amn**2)+r2)/scale Error in  $a$  has additional piece
else                                          r2.
  sigb=BIG
  siga=BIG
end if
a=a/scale                                    Unscale the answers.
b=tan(b)/scale
END SUBROUTINE fitexy

```

**f90** USE chixyfit We need to pass arrays and other variables to chixy, but not as arguments. See §21.5 and the discussion of fminln on p. 1197 for two good ways to do this. The pointer construction here is analogous to the one used in fminln.

```

MODULE chixyfit
USE nrtype; USE nrutil, ONLY : nrerror
REAL(SP), DIMENSION(:), POINTER :: xxp, yyp, xsp, syp, wwp
REAL(SP) :: aa, offs
CONTAINS
FUNCTION chixy(bang)
IMPLICIT NONE
REAL(SP), INTENT(IN) :: bang
REAL(SP) :: chixy
REAL(SP), PARAMETER :: BIG=1.0e30_sp
  Captive function of fitexy, returns the value of  $(\chi^2 - \text{offs})$  for the slope  $b=\tan(\text{bang})$ .
  Scaled data and offs are communicated via the module chixyfit.
REAL(SP) :: avex, avey, sumw, b
if (.not. associated(wwp)) call nrerror("chixy: bad pointers")
b=tan(bang)
wwp(:)=(b*xsp(:))**2+syp(:)**2
where (wwp(:) < 1.0/BIG)
  wwp(:)=BIG
elsewhere
  wwp(:)=1.0_sp/wwp(:)
end where

```

```

sumw=sum(wwp)
avev=dot_product(wwp,xxp)/sumw
avey=dot_product(wwp,yyp)/sumw
aa=avey-b*avex
chixy=sum(wwp(:)*(yyp(:)-aa-b*xxp(:)**2)-offs)
END FUNCTION chixy
END MODULE chixyfit

```

\* \* \*

```

SUBROUTINE lfit(x,y,sig,a,maska,covar,chisq,funcs)
USE nrtype; USE nrutil, ONLY : assert_eq,diagmult,nrerror
USE nr, ONLY : covsrt,gaussj
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,sig
REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
LOGICAL(LGT), DIMENSION(:), INTENT(IN) :: maska
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: covar
REAL(SP), INTENT(OUT) :: chisq

```

```
INTERFACE
```

```

  SUBROUTINE funcs(x,arr)
  USE nrtype
  IMPLICIT NONE
  REAL(SP),INTENT(IN) :: x
  REAL(SP), DIMENSION(:), INTENT(OUT) :: arr
  END SUBROUTINE funcs

```

```
END INTERFACE
```

Given a set of  $N$  data points  $x$ ,  $y$  with individual standard deviations  $sig$ , all arrays of length  $N$ , use  $\chi^2$  minimization to fit for some or all of the  $M$  coefficients  $a$  of a function that depends linearly on  $a$ ,  $y = \sum_{i=1}^M a_i \times afunc_i(x)$ . The input logical array  $maska$  of length  $M$  indicates by true entries those components of  $a$  that should be fitted for, and by false entries those components that should be held fixed at their input values. The program returns values for  $a$ ,  $\chi^2 = chisq$ , and the  $M \times M$  covariance matrix  $covar$ . (Parameters held fixed will return zero covariances.) The user supplies a subroutine  $funcs(x, afunc)$  that returns the  $M$  basis functions evaluated at  $x = x$  in the array  $afunc$ .

```

INTEGER(I4B) :: i,j,k,l,ma,mfit,n
REAL(SP) :: sig2i,wt,ym
REAL(SP), DIMENSION(size(maska)) :: afunc
REAL(SP), DIMENSION(size(maska),1) :: beta
n=assert_eq(size(x),size(y),size(sig),'lfit: n')
ma=assert_eq(size(maska),size(a),size(covar,1),size(covar,2),'lfit: ma')
mfit=count(maska)          Number of parameters to fit for.
if (mfit == 0) call nrerror('lfit: no parameters to be fitted')
covar(1:mfit,1:mfit)=0.0    Initialize the (symmetric) matrix.
beta(1:mfit,1)=0.0
do i=1,n                    Loop over data to accumulate coefficients of
  call funcs(x(i),afunc)    the normal equations.
  ym=y(i)
  if (mfit < ma) ym=ym-sum(a(1:ma)*afunc(1:ma), mask=.not. maska)
  Subtract off dependences on known pieces of the fitting function.
  sig2i=1.0_sp/sig(i)**2
  j=0
  do l=1,ma
    if (maska(l)) then
      j=j+1
      wt=afunc(l)*sig2i
      k=count(maska(1:l))
      covar(j,1:k)=covar(j,1:k)+wt*pack(afunc(1:l),maska(1:l))
      beta(j,1)=beta(j,1)+ym*wt
    end if
  end do
end do

```

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```

end do
call diagmult(covar(1:mfit,1:mfit),0.5_sp)
covar(1:mfit,1:mfit)= &      Fill in above the diagonal from symmetry.
    covar(1:mfit,1:mfit)+transpose(covar(1:mfit,1:mfit))
call gaussj(covar(1:mfit,1:mfit),beta(1:mfit,1:1))      Matrix solution.
a(1:ma)=unpack(beta(1:ma,1),maska,a(1:ma))
    Partition solution to appropriate coefficients a.
chisq=0.0      Evaluate  $\chi^2$  of the fit.
do i=1,n
    call funcs(x(i),afunc)
    chisq=chisq+((y(i)-dot_product(a(1:ma),afunc(1:ma)))/sig(i))**2
end do
call covsrt(covar,maska)      Sort covariance matrix to true order of fitting
END SUBROUTINE lfit      coefficients.

```

**f90** if (mfit < ma) ym=ym-sum(a(1:ma)\*afunc(1:ma), mask=.not. maska)  
This is the first of several uses of maska in this routine to control which elements of an array are to be used. Here we include in the sum only elements for which maska is false, i.e., elements corresponding to parameters that are not being fitted for.

covar(j,1:k)=covar(j,1:k)+wt\*pack(afunc(1:1),maska(1:1)) Here maska controls which elements of afunc get packed into the covariance matrix.

call diagmult(covar(1:mfit,1:mfit),0.5\_sp) See discussion of diagadd after hqr on p. 1234.

a(1:ma)=unpack(beta(1:ma,1),maska,a(1:ma)) And here maska controls which elements of beta get unpacked into the appropriate slots in a. Where maska is false, corresponding elements are selected from the third argument of unpack, here a itself. The net effect is that those elements remain unchanged.

\* \* \*

```

SUBROUTINE covsrt(covar,maska)
USE nrtype; USE nrutil, ONLY : assert_eq,swap
IMPLICIT NONE
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: covar
LOGICAL(LGT), DIMENSION(:), INTENT(IN) :: maska
    Expand in storage the covariance matrix covar, so as to take into account parameters that
    are being held fixed. (For the latter, return zero covariances.)
INTEGER(I4B) :: ma,mfit,j,k
ma=assert_eq(size(covar,1),size(covar,2),size(maska),'covsrt')
mfit=count(maska)
covar(mfit+1:ma,1:ma)=0.0
covar(1:ma,mfit+1:ma)=0.0
k=mfit
do j=ma,1,-1
    if (maska(j)) then
        call swap(covar(1:ma,k),covar(1:ma,j))
        call swap(covar(k,1:ma),covar(j,1:ma))
        k=k-1
    end if
end do
END SUBROUTINE covsrt

```

\* \* \*

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```

SUBROUTINE svdfit(x,y,sig,a,v,w,chisq,funcs)
USE nrtype; USE nrutil, ONLY : assert_eq,vabs
USE nr, ONLY : svbksb,svdcmp
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,sig
REAL(SP), DIMENSION(:), INTENT(OUT) :: a,w
REAL(SP), DIMENSION(:,:), INTENT(OUT) :: v
REAL(SP), INTENT(OUT) :: chisq
INTERFACE
  FUNCTION funcs(x,n)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: x
  INTEGER(I4B), INTENT(IN) :: n
  REAL(SP), DIMENSION(n) :: funcs
  END FUNCTION funcs
END INTERFACE
REAL(SP), PARAMETER :: TOL=1.0e-5_sp
  Given a set of  $N$  data points  $x, y$  with individual standard deviations  $sig$ , all arrays of length
   $N$ , use  $\chi^2$  minimization to determine the  $M$  coefficients  $a$  of a function that depends linearly
  on  $a, y = \sum_{i=1}^M a_i \times afunc_i(x)$ . Here we solve the fitting equations using singular value
  decomposition of the  $N \times M$  matrix, as in §2.6. On output, the  $M \times M$  array  $v$  and the
  vector  $w$  of length  $M$  define part of the singular value decomposition, and can be used to
  obtain the covariance matrix. The program returns values for the  $M$  fit parameters  $a$ , and
   $\chi^2$ ,  $chisq$ . The user supplies a subroutine  $funcs(x,afunc)$  that returns the  $M$  basis
  functions evaluated at  $x = X$  in the array  $afunc$ .
INTEGER(I4B) :: i,ma,n
REAL(SP), DIMENSION(size(x)) :: b,sigi
REAL(SP), DIMENSION(size(x),size(a)) :: u,usav
n=assert_eq(size(x),size(y),size(sig),'svdfit: n')
ma=assert_eq(size(a),size(v,1),size(v,2),size(w),'svdfit: ma')
sigi=1.0_sp/sig          Accumulate coefficients of the fitting matrix in
b=y*sigi                u.
do i=1,n
  usav(i,:)=funcs(x(i),ma)
end do
u=usav*spread(sigi,dim=2,ncopies=ma)
usav=u
call svdcmp(u,w,v)      Singular value decomposition.
where (w < TOL*maxval(w)) w=0.0 Edit the singular values, given TOL from the pa-
call svbksb(u,w,v,b,a) rameter statement.
chisq=vabs(matmul(usav,a)-b)**2 Evaluate chi-square.
END SUBROUTINE svdfit

```

**f90**  $u=usav*spread(sigi,dim=2,ncopies=ma)$  Remember how `spread` works: the vector `sigi` is copied *along* the dimension 2, making a matrix whose columns are each a copy of `sigi`. The multiplication here is element by element, so each row of `usav` is multiplied by the corresponding element of `sigi`.

$chisq=vabs(matmul(usav,a)-b)**2$  Fortran 90's `matmul` intrinsic allows us to evaluate  $\chi^2$  from the mathematical definition in terms of matrices. `vabs` in `nrutil` returns the length of a vector ( $L_2$  norm).

```

SUBROUTINE svdvar(v,w,cvm)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:,:), INTENT(IN) :: v
REAL(SP), DIMENSION(:), INTENT(IN) :: w
REAL(SP), DIMENSION(:,:), INTENT(OUT) :: cvm

```

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To evaluate the covariance matrix *cvm* of the fit for *M* parameters obtained by *svdfit*, call this routine with matrices *v*, *w* as returned from *svdfit*. The dimensions are *M* for *w* and  $M \times M$  for *v* and *cvm*.

```

INTEGER(I4B) :: ma
REAL(SP), DIMENSION(size(w)) :: wti
ma=assert_eq((/size(v,1),size(v,2),size(w),size(cvm,1),size(cvm,2)/),&
'svdvar')
where (w /= 0.0)
  wti=1.0_sp/(w*w)
elsewhere
  wti=0.0
end where
cvm=v*spread(wti,dim=1,ncopies=ma)
cvm=matmul(cvm,transpose(v))      Covariance matrix is given by (15.4.20).
END SUBROUTINE svdvar

```



where (w /= 0.0)...elsewhere...end where This is the standard Fortran 90 construction for doing different things to a matrix depending on some condition. Here we want to avoid inverting elements of *w* that are zero.

*cvm=v\*spread(wti,dim=1,ncopies=ma)* Each column of *v* gets multiplied by the corresponding element of *wti*. Contrast the construction *spread(...dim=2...)* in *svdfit*.

```

          *      *      *
FUNCTION fpoly(x,n)
USE nrtype; USE nrutil, ONLY : geop
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), DIMENSION(n) :: fpoly
  Fitting routine for a polynomial of degree n - 1, returning n coefficients in fpoly.
  fpoly=geop(1.0_sp,x,n)
END FUNCTION fpoly

```

```

          *      *      *
FUNCTION fleg(x,nl)
USE nrtype
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
INTEGER(I4B), INTENT(IN) :: nl
REAL(SP), DIMENSION(nl) :: fleg
  Fitting routine for an expansion with nl Legendre polynomials evaluated at x and returned
  in the array fleg of length nl. The evaluation uses the recurrence relation as in §5.5.
INTEGER(I4B) :: j
REAL(SP) :: d,f1,f2,twox
fleg(1)=1.0
fleg(2)=x
if (nl > 2) then
  twox=2.0_sp*x
  f2=x
  d=1.0
  do j=3,nl
    f1=d
    f2=f2+twox
    d=d+1.0_sp

```

```

        fleg(j)=(f2*fleg(j-1)-f1*fleg(j-2))/d
    end do
end if
END FUNCTION fleg

```

\* \* \*

```

SUBROUTINE mrqmin(x,y,sig,a,maska,covar,alpha,chisq,funcs,alamda)
USE nrtype; USE nrutil, ONLY : assert_eq,diagmult
USE nr, ONLY : covsrt,gaussj
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,sig
REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
REAL(SP), DIMENSION(:,,:), INTENT(OUT) :: covar,alpha
REAL(SP), INTENT(OUT) :: chisq
REAL(SP), INTENT(INOUT) :: alamda
LOGICAL(LGT), DIMENSION(:), INTENT(IN) :: maska
INTERFACE
    SUBROUTINE funcs(x,a,yfit,dyda)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x,a
    REAL(SP), DIMENSION(:), INTENT(OUT) :: yfit
    REAL(SP), DIMENSION(:,,:), INTENT(OUT) :: dyda
    END SUBROUTINE funcs
END INTERFACE

```

Levenberg-Marquardt method, attempting to reduce the value  $\chi^2$  of a fit between a set of  $N$  data points  $x$ ,  $y$  with individual standard deviations  $\text{sig}$ , and a nonlinear function dependent on  $M$  coefficients  $a$ . The input logical array  $\text{maska}$  of length  $M$  indicates by true entries those components of  $a$  that should be fitted for, and by false entries those components that should be held fixed at their input values. The program returns current best-fit values for the parameters  $a$ , and  $\chi^2 = \text{chisq}$ . The  $M \times M$  arrays  $\text{covar}$  and  $\alpha$  are used as working space during most iterations. Supply a subroutine  $\text{funcs}(x,a,yfit,dyda)$  that evaluates the fitting function  $yfit$ , and its derivatives  $dyda$  with respect to the fitting parameters  $a$  at  $x$ . On the first call provide an initial guess for the parameters  $a$ , and set  $\text{alamda} < 0$  for initialization (which then sets  $\text{alamda} = .001$ ). If a step succeeds  $\text{chisq}$  becomes smaller and  $\text{alamda}$  decreases by a factor of 10. If a step fails  $\text{alamda}$  grows by a factor of 10. You must call this routine repeatedly until convergence is achieved. Then, make one final call with  $\text{alamda} = 0$ , so that  $\text{covar}$  returns the covariance matrix, and  $\alpha$  the curvature matrix. (Parameters held fixed will return zero covariances.)

```

INTEGER(I4B) :: ma,ndata
INTEGER(I4B), SAVE :: mfit
call mrqmin_private
CONTAINS
SUBROUTINE mrqmin_private
REAL(SP), SAVE :: ochisq
REAL(SP), DIMENSION(:), ALLOCATABLE, SAVE :: atry,beta
REAL(SP), DIMENSION(:,,:), ALLOCATABLE, SAVE :: da
ndata=assert_eq(size(x),size(y),size(sig),'mrqmin: ndata')
ma=assert_eq((/size(a),size(maska),size(covar,1),size(covar,2),&
    size(alpha,1),size(alpha,2)/),'mrqmin: ma')
mfit=count(maska)
if (alamda < 0.0) then
    allocate(atriy(ma),beta(ma),da(ma,1))
    alamda=0.001_sp
    call mrqcof(a,alpha,beta)
    ochisq=chisq
    atry=a
end if
covar(1:mfit,1:mfit)=alpha(1:mfit,1:mfit)
call diagmult(covar(1:mfit,1:mfit),1.0_sp/alamda)

```

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```

Alter linearized fitting matrix, by augmenting diagonal elements.
da(1:mfit,1)=beta(1:mfit)
call gaussj(covar(1:mfit,1:mfit),da(1:mfit,1:1))  Matrix solution.
if (alamda == 0.0) then  Once converged, evaluate covariance ma-
    call covsrt(covar,maska)  trix.
    call covsrt(alpha,maska)  Spread out alpha to its full size too.
    deallocate(atry,beta,da)
    RETURN
end if
atry=a+unpack(da(1:mfit,1),maska,0.0_sp)  Did the trial succeed?
call mrqcof(atry,covar,da(1:mfit,1))
if (chisq < ochisq) then  Success, accept the new solution.
    alamda=0.1_sp*alamda
    ochisq=chisq
    alpha(1:mfit,1:mfit)=covar(1:mfit,1:mfit)
    beta(1:mfit)=da(1:mfit,1)
    a=atry
else  Failure, increase alamda and return.
    alamda=10.0_sp*alamda
    chisq=ochisq
end if
END SUBROUTINE mrqmin_private

SUBROUTINE mrqcof(a,alpha,beta)
REAL(SP), DIMENSION(:), INTENT(IN) :: a
REAL(SP), DIMENSION(:), INTENT(OUT) :: beta
REAL(SP), DIMENSION(:,,:), INTENT(OUT) :: alpha
    Used by mrqmin to evaluate the linearized fitting matrix alpha, and vector beta as in
    (15.5.8), and calculate  $\chi^2$ .
INTEGER(I4B) :: j,k,l,m
REAL(SP), DIMENSION(size(x),size(a)) :: dyda
REAL(SP), DIMENSION(size(x)) :: dy,sig2i,wt,ymod
call funcs(x,a,ymod,dyda)  Loop over all the data.
sig2i=1.0_sp/(sig**2)
dy=y-ymod
j=0
do l=1,ma
    if (maska(l)) then
        j=j+1
        wt=dyda(:,l)*sig2i
        k=0
        do m=1,l
            if (maska(m)) then
                k=k+1
                alpha(j,k)=dot_product(wt,dyda(:,m))
                alpha(k,j)=alpha(j,k)  Fill in the symmetric side.
            end if
        end do
        beta(j)=dot_product(dy,wt)
    end if
end do
chisq=dot_product(dy**2,sig2i)  Find  $\chi^2$ .
END SUBROUTINE mrqcof
END SUBROUTINE mrqmin

```

**f90** The organization of this routine is similar to that of `amoeba`, discussed on p. 1209. We want to keep the argument list of `mrqcof` to a minimum, but we want to make clear what global variables it accesses, and protect `mrqmin_private`'s name space.

`REAL(SP), DIMENSION(:), ALLOCATABLE, SAVE :: atry,beta` These arrays, as well as `da`, are allocated with the correct dimensions on the first call to `mrqmin`.

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They need to retain their values between calls, so they are declared with the SAVE attribute. They get deallocated only on the final call when `alamda=0`.

`call diagmult(...)` See discussion of `diagadd` after `hqr` on p. 1234.

`atry=a+unpack(da(1:mfit,1),maska,0.0_sp)` `maska` controls which elements of `a` get incremented by `da` and which by 0.

\* \* \*

```

SUBROUTINE fgauss(x,a,y,dyda)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,a
REAL(SP), DIMENSION(:), INTENT(OUT) :: y
REAL(SP), DIMENSION(:,), INTENT(OUT) :: dyda
  y(x;a) is the sum of N/3 Gaussians (15.5.16). Here N is the length of the vectors x, y
  and a, while dyda is an N x N matrix. The amplitude, center, and width of the Gaussians
  are stored in consecutive locations of a: a(i) = Bk, a(i+1) = Ek, a(i+2) = Gk,
  k = 1,...,N/3.
INTEGER(I4B) :: i,na,nx
REAL(SP), DIMENSION(size(x)) :: arg,ex,fac
nx=assert_eq(size(x),size(y),size(dyda,1),'fgauss: nx')
na=assert_eq(size(a),size(dyda,2),'fgauss: na')
y(:)=0.0
do i=1,na-1,3
  arg(:)=(x(:)-a(i+1))/a(i+2)
  ex(:)=exp(-arg(:)**2)
  fac(:)=a(i)*ex(:)*2.0_sp*arg(:)
  y(:)=y(:)+a(i)*ex(:)
  dyda(:,i)=ex(:)
  dyda(:,i+1)=fac(:)/a(i+2)
  dyda(:,i+2)=fac(:)*arg(:)/a(i+2)
end do
END SUBROUTINE fgauss

```

\* \* \*

```

SUBROUTINE medfit(x,y,a,b,abdev)
USE nrtype; USE nrutil, ONLY : assert_eq
USE nr, ONLY : select
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
REAL(SP), INTENT(OUT) :: a,b,abdev
  Fits y = a+bx by the criterion of least absolute deviations. The same-size arrays x and y are
  the input experimental points. The fitted parameters a and b are output, along with abdev,
  which is the mean absolute deviation (in y) of the experimental points from the fitted line.
INTEGER(I4B) :: ndata
REAL(SP) :: aa
call medfit_private
CONTAINS
SUBROUTINE medfit_private
IMPLICIT NONE
REAL(SP) :: b1,b2,bb,chisq,del,f,f1,f2,sigb,sx,sxx,sxy,sy
REAL(SP), DIMENSION(size(x)) :: tmp
ndata=assert_eq(size(x),size(y),'medfit')
sx=sum(x)
sy=sum(y)
sxy=dot_product(x,y)
  As a first guess for a and b, we will find the least
  squares fitting line.

```

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```

sxx=dot_product(x,x)
del=ndata*sxx-sx**2
aa=(sxx*sy-sx*sxy)/del
bb=(ndata*sxy-sx*sy)/del
tmp(:)=y(:)-(aa+bb*x(:))
chisq=dot_product(tmp,tmp)
sigb=sqrt(chisq/del)
b1=bb
f1=rofunc(b1)
b2=bb+sign(3.0_sp*sigb,f1)
f2=rofunc(b2)
if (b2 == b1) then
  a=aa
  b=bb
  RETURN
endif
do
  if (f1*f2 <= 0.0) exit
  bb=b2+1.6_sp*(b2-b1)
  b1=b2
  f1=f2
  b2=bb
  f2=rofunc(b2)
end do
sigb=0.01_sp*sigb
do
  if (abs(b2-b1) <= sigb) exit
  bb=b1+0.5_sp*(b2-b1)
  if (bb == b1 .or. bb == b2) exit
  f=rofunc(bb)
  if (f*f1 >= 0.0) then
    f1=f
    b1=bb
  else
    f2=f
    b2=bb
  end if
end do
a=aa
b=bb
abdev=abdev/ndata
END SUBROUTINE medfit_private

FUNCTION rofunc(b)
IMPLICIT NONE
REAL(SP), INTENT(IN) :: b
REAL(SP) :: rofunc
REAL(SP), PARAMETER :: EPS=epsilon(b)
  Evaluates the right-hand side of equation (15.7.16) for a given value of b.
INTEGER(I4B) :: j
REAL(SP), DIMENSION(size(x)) :: arr,d
arr(:)=y(:)-b*x(:)
if (mod(ndata,2) == 0) then
  j=ndata/2
  aa=0.5_sp*(select(j,arr)+select(j+1,arr))
else
  aa=select((ndata+1)/2,arr)
end if
d(:)=y(:)-(b*x(:)+aa)
abdev=sum(abs(d))
where (y(:) /= 0.0) d(:)=d(:)/abs(y(:))
rofunc=sum(x(:)*sign(1.0_sp,d(:)), mask=(abs(d(:)) > EPS) )
END FUNCTION rofunc
END SUBROUTINE medfit

```

Least squares solutions.

The standard deviation will give some idea of how big an iteration step to take.

Guess bracket as  $3\text{-}\sigma$  away, in the downhill direction known from  $f_1$ .

Bracketing.

Refine until error a negligible number of standard deviations.

Bisection.

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**f90** The organization of this routine is similar to that of `amoeba` discussed on p. 1209. We want to keep the argument list of `rofunc` to a minimum, but we want to make clear what global variables it accesses and protect `medfit_private`'s name space. In the Fortran 77 version, we kept the only argument as `b` by passing the global variables in a common block. This required us to make copies of the arrays `x` and `y`. An alternative Fortran 90 implementation would be to use a module with pointers to the arguments of `medfit` like `x` and `y` that need to be passed to `rofunc`. We think the `medfit_private` construction is simpler.

# Chapter B16. Integration of Ordinary Differential Equations

```

SUBROUTINE rk4(y,dydx,x,h,yout,derivs)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: y,dydx
REAL(SP), INTENT(IN) :: x,h
REAL(SP), DIMENSION(:), INTENT(OUT) :: yout
INTERFACE
  SUBROUTINE derivs(x,y,dydx)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: x
  REAL(SP), DIMENSION(:), INTENT(IN) :: y
  REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
  END SUBROUTINE derivs
END INTERFACE
Given values for the  $N$  variables  $y$  and their derivatives  $dydx$  known at  $x$ , use the fourth-
order Runge-Kutta method to advance the solution over an interval  $h$  and return the incre-
mented variables as  $yout$ , which need not be a distinct array from  $y$ .  $y$ ,  $dydx$  and  $yout$ 
are all of length  $N$ . The user supplies the subroutine  $derivs(x,y,dydx)$ , which returns
derivatives  $dydx$  at  $x$ .
INTEGER(I4B) :: ndum
REAL(SP) :: h6,hh,xh
REAL(SP), DIMENSION(size(y)) :: dym,dyt,yt
ndum=assert_eq(size(y),size(dydx),size(yout),'rk4')
hh=h*0.5_sp
h6=h/6.0_sp
xh=x+hh
yt=y+hh*dydx
call derivs(xh,yt,dyt)
yt=y+hh*dym
call derivs(xh,yt,dym)
yt=y+h*dym
dym=dym+dym
call derivs(x+h,yt,dyt)
yout=y+h6*(dydx+dym+2.0_sp*dym)
END SUBROUTINE rk4

```

\* \* \*

```

MODULE rk4dumb_path
USE nrtype
REAL(SP), DIMENSION(:), ALLOCATABLE :: xx
REAL(SP), DIMENSION(:,:), ALLOCATABLE :: y
END MODULE rk4dumb_path
Storage of results.

```

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```

SUBROUTINE rk dumb(vstart,x1,x2,nstep,derivs)
USE nrtype; USE nrutil, ONLY : nrerror
USE nr, ONLY : rk4
USE rk dumb_path
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: vstart
REAL(SP), INTENT(IN) :: x1,x2
INTEGER(I4B), INTENT(IN) :: nstep
INTERFACE
  SUBROUTINE derivs(x,y,dydx)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: x
  REAL(SP), DIMENSION(:), INTENT(IN) :: y
  REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
  END SUBROUTINE derivs
END INTERFACE
  Starting from  $N$  initial values  $vstart$  known at  $x1$ , use fourth-order Runge-Kutta to advance  $nstep$  equal increments to  $x2$ . The user-supplied subroutine  $derivs(x,y,dydx)$  evaluates derivatives. Results are stored in the module variables  $xx$  and  $y$ .
INTEGER(I4B) :: k
REAL(SP) :: h,x
REAL(SP), DIMENSION(size(vstart)) :: dv,v
v(:)=vstart(:)      Load starting values.
if (allocated(xx)) deallocate(xx)      Clear out old stored variables if necessary.
if (allocated(y)) deallocate(y)
allocate(xx(nstep+1))      Allocate storage for saved values.
allocate(y(size(vstart),nstep+1))
y(:,1)=v(:)
xx(1)=x1
x=x1
h=(x2-x1)/nstep
do k=1,nstep      Take nstep steps.
  call derivs(x,v,dv)
  call rk4(v,dv,x,h,v,derivs)
  if (x+h == x) call nrerror('stepsize not significant in rk dumb')
  x=x+h
  xx(k+1)=x      Store intermediate steps.
  y(:,k+1)=v(:)
end do
END SUBROUTINE rk dumb

```

**f90** MODULE `rk dumb_path` This routine needs straightforward communication of arrays with the calling program. The dimension of the arrays is not known in advance, and if the routine is called a second time we need to throw away the old array information. The Fortran 90 construction for this is to declare allocatable arrays in a module, and then test them at the beginning of the routine with `if (allocated...)`.

\* \* \*

```

SUBROUTINE rkqs(y,dydx,x,htry,eps,yscal,hdid,hnext,derivs)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
USE nr, ONLY : rkck
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
REAL(SP), DIMENSION(:), INTENT(IN) :: dydx,yscal
REAL(SP), INTENT(INOUT) :: x
REAL(SP), INTENT(IN) :: htry,eps
REAL(SP), INTENT(OUT) :: hdid,hnext

```

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```

INTERFACE
  SUBROUTINE derivs(x,y,dydx)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: x
  REAL(SP), DIMENSION(:), INTENT(IN) :: y
  REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
  END SUBROUTINE derivs
END INTERFACE
Fifth order Runge-Kutta step with monitoring of local truncation error to ensure accuracy
and adjust stepsize. Input are the dependent variable vector y and its derivative dydx at
the starting value of the independent variable x. Also input are the stepsize to be attempted
htry, the required accuracy eps, and the vector yscal against which the error is scaled. y,
dydx, and yscal are all of the same length. On output, y and x are replaced by their new
values, hdid is the stepsize that was actually accomplished, and hnext is the estimated
next stepsize. derivs is the user-supplied subroutine that computes the right-hand-side
derivatives.
INTEGER(I4B) :: ndum
REAL(SP) :: errmax,h,htemp,xnew
REAL(SP), DIMENSION(size(y)) :: yerr,ytemp
REAL(SP), PARAMETER :: SAFETY=0.9_sp,PGROW=-0.2_sp,PSHRNK=-0.25_sp,&
  ERRCON=1.89e-4
  The value ERRCON equals (5/SAFETY)**(1/PGROW), see use below.
ndum=assert_eq(size(y),size(dydx),size(yscal),'rkqs')
h=htry Set stepsize to the initial trial value.
do
  call rkck(y,dydx,x,h,ytemp,yerr,derivs) Take a step.
  errmax=maxval(abs(yerr(:)/yscal(:)))/eps Evaluate accuracy.
  if (errmax <= 1.0) exit Step succeeded.
  htemp=SAFETY*h*(errmax**PSHRNK) Truncation error too large, reduce stepsize.
  h=sign(max(abs(htemp),0.1_sp*abs(h)),h) No more than a factor of 10.
  xnew=x+h
  if (xnew == x) call nrerror('stepsize underflow in rkqs')
end do Go back for another try.
if (errmax > ERRCON) then Compute size of next step.
  hnext=SAFETY*h*(errmax**PGROW)
else No more than a factor of 5 increase.
  hnext=5.0_sp*h
end if
hdid=h
x=x+h
y(:)=ytemp(:)
END SUBROUTINE rkqs

          * * *

SUBROUTINE rkck(y,dydx,x,h,yout,yerr,derivs)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: y,dydx
REAL(SP), INTENT(IN) :: x,h
REAL(SP), DIMENSION(:), INTENT(OUT) :: yout,yerr
INTERFACE
  SUBROUTINE derivs(x,y,dydx)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: x
  REAL(SP), DIMENSION(:), INTENT(IN) :: y
  REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
  END SUBROUTINE derivs
END INTERFACE
Given values for N variables y and their derivatives dydx known at x, use the fifth order
Cash-Karp Runge-Kutta method to advance the solution over an interval h and return

```

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the incremented variables as `yout`. Also return an estimate of the local truncation error in `yout` using the embedded fourth order method. The user supplies the subroutine `derivs(x,y,dydx)`, which returns derivatives `dydx` at `x`.

```

INTEGER(I4B) :: ndum
REAL(SP), DIMENSION(size(y)) :: ak2,ak3,ak4,ak5,ak6,ytemp
REAL(SP), PARAMETER :: A2=0.2_sp,A3=0.3_sp,A4=0.6_sp,A5=1.0_sp,&
  A6=0.875_sp,B21=0.2_sp,B31=3.0_sp/40.0_sp,B32=9.0_sp/40.0_sp,&
  B41=0.3_sp,B42=-0.9_sp,B43=1.2_sp,B51=-11.0_sp/54.0_sp,&
  B52=2.5_sp,B53=-70.0_sp/27.0_sp,B54=35.0_sp/27.0_sp,&
  B61=1631.0_sp/55296.0_sp,B62=175.0_sp/512.0_sp,&
  B63=575.0_sp/13824.0_sp,B64=44275.0_sp/110592.0_sp,&
  B65=253.0_sp/4096.0_sp,C1=37.0_sp/378.0_sp,&
  C3=250.0_sp/621.0_sp,C4=125.0_sp/594.0_sp,&
  C6=512.0_sp/1771.0_sp,DC1=C1-2825.0_sp/27648.0_sp,&
  DC3=C3-18575.0_sp/48384.0_sp,DC4=C4-13525.0_sp/55296.0_sp,&
  DC5=-277.0_sp/14336.0_sp,DC6=C6-0.25_sp
ndum=assert_eq(size(y),size(dydx),size(yout),size(yerr),'rkck')
ytemp=y+B21*h*dydx           First step.
call derivs(x+A2*h,ytemp,ak2) Second step.
ytemp=y+h*(B31*dydx+B32*ak2)
call derivs(x+A3*h,ytemp,ak3) Third step.
ytemp=y+h*(B41*dydx+B42*ak2+B43*ak3)
call derivs(x+A4*h,ytemp,ak4) Fourth step.
ytemp=y+h*(B51*dydx+B52*ak2+B53*ak3+B54*ak4)
call derivs(x+A5*h,ytemp,ak5) Fifth step.
ytemp=y+h*(B61*dydx+B62*ak2+B63*ak3+B64*ak4+B65*ak5)
call derivs(x+A6*h,ytemp,ak6) Sixth step.
yout=y+h*(C1*dydx+C3*ak3+C4*ak4+C6*ak6) Accumulate increments with proper weights.
yerr=h*(DC1*dydx+DC3*ak3+DC4*ak4+DC5*ak5+DC6*ak6)
  Estimate error as difference between fourth and fifth order methods.
END SUBROUTINE rkck

```

\* \* \*

#### MODULE ode\_path

```

USE nrtype
INTEGER(I4B) :: nok,nbad,kount
LOGICAL(LGT), SAVE :: save_steps=.false.
REAL(SP) :: dxsav
REAL(SP), DIMENSION(:), POINTER :: xp
REAL(SP), DIMENSION(:, :), POINTER :: yp
END MODULE ode_path

```

On output `nok` and `nbad` are the number of good and bad (but retried and fixed) steps taken. If `save_steps` is set to true in the calling program, then intermediate values are stored in `xp` and `yp` at intervals greater than `dxsav`. `kount` is the total number of saved steps.

```

SUBROUTINE odeint(ystart,x1,x2,eps,h1,hmin,derivs,rkqs)
USE nrtype; USE nrutil, ONLY : nrerror,reallocate
USE ode_path
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: ystart
REAL(SP), INTENT(IN) :: x1,x2,eps,h1,hmin
INTERFACE
  SUBROUTINE derivs(x,y,dydx)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: x
  REAL(SP), DIMENSION(:), INTENT(IN) :: y
  REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
  END SUBROUTINE derivs
  SUBROUTINE rkqs(y,dydx,x,htry,eps,yscal,hdid,hnext,derivs)
  USE nrtype

```

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```

IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
REAL(SP), DIMENSION(:), INTENT(IN) :: dydx,yscal
REAL(SP), INTENT(INOUT) :: x
REAL(SP), INTENT(IN) :: htry,eps
REAL(SP), INTENT(OUT) :: hdid,hnext
INTERFACE
  SUBROUTINE derivs(x,y,dydx)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP), DIMENSION(:), INTENT(IN) :: y
    REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
  END SUBROUTINE derivs
END INTERFACE
END SUBROUTINE rkqs
END INTERFACE
REAL(SP), PARAMETER :: TINY=1.0e-30_sp
INTEGER(I4B), PARAMETER :: MAXSTP=10000
  Runge-Kutta driver with adaptive stepsize control. Integrate the array of starting values
  ystart from x1 to x2 with accuracy eps, storing intermediate results in the module
  variables in ode_path. h1 should be set as a guessed first stepsize, hmin as the minimum
  allowed stepsize (can be zero). On output ystart is replaced by values at the end of the
  integration interval. derivs is the user-supplied subroutine for calculating the right-hand-
  side derivative, while rkqs is the name of the stepper routine to be used.
INTEGER(I4B) :: nstp
REAL(SP) :: h,hdid,hnext,x,xsav
REAL(SP), DIMENSION(size(ystart)) :: dydx,y,yscal
x=x1
h=sign(h1,x2-x1)
nok=0
nbad=0
kount=0
y(:)=ystart(:)
if (save_steps) then
  xsav=x-2.0_sp*dxsav
  nullify(xp,yp)
  allocate(xp(256))
  allocate(yp(size(ystart),size(xp)))
end if
do nstp=1,MAXSTP
  call derivs(x,y,dydx)
  yscal(:)=abs(y(:))+abs(h*dydx(:))+TINY
  Scaling used to monitor accuracy. This general purpose choice can be modified if need
  be.
  if (save_steps .and. (abs(x-xsav) > abs(dxsav))) & Store intermediate results.
    call save_a_step
  if ((x+h-x2)*(x+h-x1) > 0.0) h=x2-x If stepsize can overshoot, decrease.
  call rkqs(y,dydx,x,h,eps,yscal,hdid,hnext,derivs)
  if (hdid == h) then
    nok=nok+1
  else
    nbad=nbad+1
  end if
  if ((x-x2)*(x2-x1) >= 0.0) then Are we done?
    ystart(:)=y(:)
    if (save_steps) call save_a_step Save final step.
    RETURN Normal exit.
  end if
  if (abs(hnext) < hmin)&
    call nrerror('stepsize smaller than minimum in odeint')
  h=hnext
end do
call nrerror('too many steps in odeint')

```

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CONTAINS

```

SUBROUTINE save_a_step
kount=kount+1
if (kount > size(xp)) then
  xp=>reallocate(xp,2*size(xp))
  yp=>reallocate(yp,size(yp,1),size(xp))
end if
xp(kount)=x
yp(:,kount)=y(:)
xsav=x
END SUBROUTINE save_a_step
END SUBROUTINE odeint

```

**f90** MODULE `ode_path` The situation here is similar to `rkdumb_path`, except we don't know at run time how much storage to allocate. We may need to use `reallocate` from `nrutil` to increase the storage. The solution is pointers to arrays, with a `nullify` to be sure the pointer status is well-defined at the beginning of the routine.

SUBROUTINE `save_a_step` An internal subprogram with no arguments is like a macro in C: you could imagine just copying its code wherever it is called in the parent routine.

\* \* \*

```

SUBROUTINE mmid(y,dydx,xs,htot,nstep,yout,derivs)
USE nrtype; USE nrutil, ONLY : assert_eq,swap
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: nstep
REAL(SP), INTENT(IN) :: xs,htot
REAL(SP), DIMENSION(:), INTENT(IN) :: y,dydx
REAL(SP), DIMENSION(:), INTENT(OUT) :: yout
INTERFACE
  SUBROUTINE derivs(x,y,dydx)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: x
  REAL(SP), DIMENSION(:), INTENT(IN) :: y
  REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
  END SUBROUTINE derivs
END INTERFACE
  Modified midpoint step. Dependent variable vector y and its derivative vector dydx are
  input at xs. Also input is htot, the total step to be taken, and nstep, the number of
  substeps to be used. The output is returned as yout, which need not be a distinct array
  from y; if it is distinct, however, then y and dydx are returned undamaged. y, dydx, and
  yout must all have the same length.
  INTEGER(I4B) :: n,ndum
  REAL(SP) :: h,h2,x
  REAL(SP), DIMENSION(size(y)) :: ym,yn
  ndum=assert_eq(size(y),size(dydx),size(yout),'mmid')
  h=htot/nstep           Stepsize this trip.
  ym=y
  yn=y+h*dydx           First step.
  x=xs+h
  call derivs(x,yn,yout) Will use yout for temporary storage of derivatives.
  h2=2.0_sp*h
  do n=2,nstep           General step.
    call swap(ym,yn)
    yn=yn+h2*yout
  end do

```

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```

    x=x+h
    call derivs(x,yn,yout)
end do
yout=0.5_sp*(ym+yn+h*yout)          Last step.
END SUBROUTINE mmid

```

\* \* \*

```

SUBROUTINE bsstep(y,dydx,x,htry,eps,yscal,hdid,hnext,derivs)
USE nrtype; USE nrutil, ONLY : arth,assert_eq,cumsum,iminloc,nrerror,&
    outerdiff,outerprod,upper_triangle
USE nr, ONLY : mmid,pzextr
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
REAL(SP), DIMENSION(:), INTENT(IN) :: dydx,yscal
REAL(SP), INTENT(INOUT) :: x
REAL(SP), INTENT(IN) :: htry,eps
REAL(SP), INTENT(OUT) :: hdid,hnext
INTERFACE
  SUBROUTINE derivs(x,y,dydx)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP), DIMENSION(:), INTENT(IN) :: y
    REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
  END SUBROUTINE derivs
END INTERFACE
INTEGER(I4B), PARAMETER :: IMAX=9, KMAXX=IMAX-1
REAL(SP), PARAMETER :: SAFE1=0.25_sp,SAFE2=0.7_sp,REDMAX=1.0e-5_sp,&
  REDMIN=0.7_sp,TINY=1.0e-30_sp,SCALMX=0.1_sp

```

Bulirsch-Stoer step with monitoring of local truncation error to ensure accuracy and adjust stepsize. Input are the dependent variable vector  $y$  and its derivative  $dydx$  at the starting value of the independent variable  $x$ . Also input are the stepsize to be attempted  $htry$ , the required accuracy  $eps$ , and the vector  $yscal$  against which the error is scaled. On output,  $y$  and  $x$  are replaced by their new values,  $hdid$  is the stepsize that was actually accomplished, and  $hnext$  is the estimated next stepsize.  $derivs$  is the user-supplied subroutine that computes the right-hand-side derivatives.  $y$ ,  $dydx$ , and  $yscal$  must all have the same length. Be sure to set  $htry$  on successive steps to the value of  $hnext$  returned from the previous step, as is the case if the routine is called by `odeint`.

Parameters:  $KMAXX$  is the maximum row number used in the extrapolation;  $IMAX$  is the next row number;  $SAFE1$  and  $SAFE2$  are safety factors;  $REDMAX$  is the maximum factor used when a stepsize is reduced,  $REDMIN$  the minimum;  $TINY$  prevents division by zero;  $1/SCALMX$  is the maximum factor by which a stepsize can be increased.

```

INTEGER(I4B) :: k,km,ndum
INTEGER(I4B), DIMENSION(IMAX) :: nseq = (/ 2,4,6,8,10,12,14,16,18 /)
INTEGER(I4B), SAVE :: kopt,kmax
REAL(SP), DIMENSION(KMAXX,KMAXX), SAVE :: alf
REAL(SP), DIMENSION(KMAXX) :: err
REAL(SP), DIMENSION(IMAX), SAVE :: a
REAL(SP), SAVE :: epsold = -1.0_sp,xnew
REAL(SP) :: eps1,errmax,fact,h,red,scale,wrkmin,xest
REAL(SP), DIMENSION(size(y)) :: yerr,ysav,yseq
LOGICAL(LGT) :: reduct
LOGICAL(LGT), SAVE :: first=.true.
ndum=assert_eq(size(y),size(dydx),size(yscal),'bsstep')
if (eps /= epsold) then
  hnext=-1.0e29_sp
  xnew=-1.0e29_sp
  eps1=SAFE1*eps
  a(:)=cumsum(nseq,1)
  Compute  $\alpha(k,q)$ :
  where (upper_triangle(KMAXX,KMAXX)) alf=eps1** &
    (outerdiff(a(2:),a(2:))/outerprod(arth( &

```

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```

    3.0_sp,2.0_sp,KMAXX), (a(2:)-a(1)+1.0_sp)))
    epsold=eps
    do kopt=2,KMAXX-1
        if (a(kopt+1) > a(kopt)*alf(kopt-1,kopt)) exit
    end do
    kmax=kopt
end if
h=htry
ysav(:)=y(:)
if (h /= hnext .or. x /= xnew) then
    first=.true.
    kopt=kmax
end if
reduct=.false.
main_loop: do
    do k=1,kmax
        xnew=x+h
        if (xnew == x) call nrerror('step size underflow in bstep')
        call mmid(ysav,dydx,x,h,nseq(k),yseq,derivs)
        xest=(h/nseq(k))*2
        call pzextr(k,xest,yseq,y,yerr)
        if (k /= 1) then
            errmax=maxval(abs(yerr(:)/yscal(:)))
            errmax=max(TINY,errmax)/eps
            km=k-1
            err(km)=(errmax/SAFE1)**(1.0_sp/(2*k+1))
        end if
        if (k /= 1 .and. (k >= kopt-1 .or. first)) then
            if (errmax < 1.0) exit main_loop
            if (k == kmax .or. k == kopt+1) then
                red=SAFE2/err(km)
                exit
            else if (k == kopt) then
                if (alf(kopt-1,kopt) < err(km)) then
                    red=1.0_sp/err(km)
                    exit
                end if
            else if (kopt == kmax) then
                if (alf(km,kmax-1) < err(km)) then
                    red=alf(km,kmax-1)*SAFE2/err(km)
                    exit
                end if
            else if (alf(km,kopt) < err(km)) then
                red=alf(km,kopt-1)/err(km)
                exit
            end if
        end if
    end do
    red=max(min(red,REDMIN),REDMAX)
    h=h*red
    reduct=.true.
end do main_loop
x=xnew
hdid=h
first=.false.
kopt=1+iminloc(a(2:k+1)*max(err(1:k),SCALMX))
scale=max(err(kopt-1),SCALMX)
wrkmin=scale*a(kopt)
hnext=h/scale
if (kopt >= k .and. kopt /= kmax .and. .not. reduct) then
    fact=max(scale/alf(kopt-1,kopt),SCALMX)
    if (a(kopt+1)*fact <= wrkmin) then
        hnext=h/fact
    end if
end if

```

Determine optimal row number for convergence.

Save the starting values.

A new stepsize or a new integration: Re-establish the order window.

Evaluate the sequence of modified midpoint integrations.

Squared, since error series is even.

Perform extrapolation.

Compute normalized error estimate  $\epsilon(k)$ .

Scale error relative to tolerance.

In order window.

Converged. Check for possible stepsize reduction.

Reduce stepsize by at least REDMIN and at most REDMAX.

Try again. Successful step taken.

Check for possible order increase, but not if stepsize was just reduced.

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```

    kopt=kopt+1
  end if
end if
END SUBROUTINE bsstep

```

**f90** `a(:)=cumsum(nseq,1)` The function `cumsum` in `nrutil` with the optional argument `seed=1` gives a direct implementation of equation (16.4.6).

where `(upper_triangle(KMAXX,KMAXX))...` The `upper_triangle` function in `nrutil` returns an upper triangular logical mask. As used here, the mask is true everywhere in the upper triangle of a  $KMAXX \times KMAXX$  matrix, excluding the diagonal. An optional integer argument `extra` allows additional diagonals to be set to true. With `extra=1` the upper triangle including the diagonal would be true.

`main_loop: do` Using a named do-loop provides clear structured code that required `goto`'s in the Fortran 77 version.

`kopt=1+iminloc(...)` See the discussion of `imaxloc` on p. 1017.

\* \* \*

```

SUBROUTINE pzextr(iest,xest,yest,yz,dy)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: iest
REAL(SP), INTENT(IN) :: xest
REAL(SP), DIMENSION(:), INTENT(IN) :: yest
REAL(SP), DIMENSION(:), INTENT(OUT) :: yz,dy
  Use polynomial extrapolation to evaluate  $N$  functions at  $x = 0$  by fitting a polynomial to
  a sequence of estimates with progressively smaller values  $x = xest$ , and corresponding
  function vectors yest. This call is number iest in the sequence of calls. Extrapolated
  function values are output as yz, and their estimated error is output as dy. yest, yz, and
  dy are arrays of length  $N$ .
INTEGER(I4B), PARAMETER :: IEST_MAX=16
INTEGER(I4B) :: j,nv
INTEGER(I4B), SAVE :: nvold=-1
REAL(SP) :: delta,f1,f2
REAL(SP), DIMENSION(size(yz)) :: d,tmp,q
REAL(SP), DIMENSION(IEST_MAX), SAVE :: x
REAL(SP), DIMENSION(:,:), ALLOCATABLE, SAVE :: qcol
nv=assert_eq(size(yz),size(yest),size(dy),'pzextr')
if (iest > IEST_MAX) call &
  nrerror('pzextr: probable misuse, too much extrapolation')
if (nv /= nvold) then
  Set up internal storage.
  if (allocated(qcol)) deallocate(qcol)
  allocate(qcol(nv,IEST_MAX))
  nvold=nv
end if
x(iest)=xest
  Save current independent variable.
dy(:)=yest(:)
yz(:)=yest(:)
if (iest == 1) then
  Store first estimate in first column.
  qcol(:,1)=yest(:)
else
  d(:)=yest(:)
  do j=1,iest-1
    delta=1.0_sp/(x(iest-j)-xest)
    f1=xest*delta
    f2=x(iest-j)*delta
    q(:)=qcol(:,j)
  Propagate tableau 1 diagonal more.
  
```

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```

        qcol(:,j)=dy(:)
        tmp(:)=d(:)-q(:)
        dy(:)=f1*tmp(:)
        d(:)=f2*tmp(:)
        yz(:)=yz(:)+dy(:)
    end do
    qcol(:,iest)=dy(:)
end if
END SUBROUTINE pzextr

```

**f**<sub>90</sub> REAL(SP), DIMENSION(:,:), ALLOCATABLE, SAVE :: qcol The second dimension of qcol is known at compile time to be IEST\_MAX, but the first dimension is known only at run time, from size(yz). The language requires us to have all dimensions allocatable if any one of them is.

if (nv /= nvold) then... This routine generally gets called many times with iest cycling repeatedly through the values 1, 2, ..., up to some value less than IEST\_MAX. The number of variables, nv, is fixed during the solution of the problem. The routine might be called again in solving a different problem with a new value of nv. This if block ensures that qcol is dimensioned correctly both for the first and subsequent problems, if any.

```

SUBROUTINE rzextr(iest,xest,yest,yz,dy)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: iest
REAL(SP), INTENT(IN) :: xest
REAL(SP), DIMENSION(:), INTENT(IN) :: yest
REAL(SP), DIMENSION(:), INTENT(OUT) :: yz,dy
    Exact substitute for pzextr, but uses diagonal rational function extrapolation instead of
    polynomial extrapolation.
INTEGER(I4B), PARAMETER :: IEST_MAX=16
INTEGER(I4B) :: k,nv
INTEGER(I4B), SAVE :: nvold=-1
REAL(SP), DIMENSION(size(yz)) :: yy,v,c,b,b1,ddy
REAL(SP), DIMENSION(:,:), ALLOCATABLE, SAVE :: d
REAL(SP), DIMENSION(IEST_MAX), SAVE :: fx,x
nv=assert_eq(size(yz),size(dy),size(yest),'rzextr')
if (iest > IEST_MAX) call &
    nrerror('rzextr: probable misuse, too much extrapolation')
if (nv /= nvold) then
    if (allocated(d)) deallocate(d)
    allocate(d(nv,IEST_MAX))
    nvold=nv
end if
x(iest)=xest           Save current independent variable.
if (iest == 1) then
    yz=yest
    d(:,1)=yest
    dy=yest
else
    fx(2:iest)=x(iest-1:1:-1)/xest
    yy=yest           Evaluate next diagonal in tableau.
    v=d(1:nv,1)
    c=yy
    d(1:nv,1)=yy
    do k=2,iest
        b1=fx(k)*v
        b=b1-c
        where (b /= 0.0)

```



```

        b=(c-v)/b
        ddy=c*b
        c=b1*b
    elsewhere          Care needed to avoid division by 0.
        ddy=v
    end where
    if (k /= iest) v=d(1:nv,k)
    d(1:nv,k)=ddy
    yy=yy+ddy
end do
dy=ddy
yz=yy
end if
END SUBROUTINE rzextr

```

\* \* \*

```

SUBROUTINE stoerm(y,d2y,xs,htot,nstep,yout,derivs)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(IN) :: y,d2y
REAL(SP), INTENT(IN) :: xs,htot
INTEGER(I4B), INTENT(IN) :: nstep
REAL(SP), DIMENSION(:), INTENT(OUT) :: yout
INTERFACE

```

```

    SUBROUTINE derivs(x,y,dydx)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP), DIMENSION(:), INTENT(IN) :: y
    REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
    END SUBROUTINE derivs
END INTERFACE

```

Stoermer's rule for integrating  $y'' = f(x, y)$  for a system of  $n$  equations. On input  $y$  contains  $y$  in its first  $n$  elements and  $y'$  in its second  $n$  elements, all evaluated at  $x_s$ .  $d2y$  contains the right-hand-side function  $f$  (also evaluated at  $x_s$ ) in its first  $n$  elements. Its second  $n$  elements are not referenced. Also input is  $htot$ , the total step to be taken, and  $nstep$ , the number of substeps to be used. The output is returned as  $yout$ , with the same storage arrangement as  $y$ . `derivs` is the user-supplied subroutine that calculates  $f$ .

```

INTEGER(I4B) :: neqn,neqn1,nn,nv
REAL(SP) :: h,h2,halfh,x
REAL(SP), DIMENSION(size(y)) :: ytemp
nv=assert_eq(size(y),size(d2y),size(yout),'stoerm')
neqn=nv/2          Number of equations.
neqn1=neqn+1
h=htot/nstep      Stepsize this trip.
halfh=0.5_sp*h    First step.
ytemp(neqn1:nv)=h*(y(neqn1:nv)+halfh*d2y(1:neqn))
ytemp(1:neqn)=y(1:neqn)+ytemp(neqn1:nv)
x=xs+h
call derivs(x,ytemp,yout)      Use yout for temporary storage of deriva-
h2=h*h                      tives.
do nn=2,nstep                General step.
    ytemp(neqn1:nv)=ytemp(neqn1:nv)+h2*yout(1:neqn)
    ytemp(1:neqn)=ytemp(1:neqn)+ytemp(neqn1:nv)
    x=x+h
    call derivs(x,ytemp,yout)
end do
yout(neqn1:nv)=ytemp(neqn1:nv)/h+halfh*yout(1:neqn)  Last step.
yout(1:neqn)=ytemp(1:neqn)
END SUBROUTINE stoerm

```

\* \* \*

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```

SUBROUTINE stiff(y,dydx,x,htry,eps,yscal,hdid,hnext,derivs)
USE nrtype; USE nrutil, ONLY : assert_eq,diagadd,nrerror
USE nr, ONLY : lubksb,ludcmp
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
REAL(SP), DIMENSION(:), INTENT(IN) :: dydx,yscal
REAL(SP), INTENT(INOUT) :: x
REAL(SP), INTENT(IN) :: htry,eps
REAL(SP), INTENT(OUT) :: hdid,hnext
INTERFACE
  SUBROUTINE derivs(x,y,dydx)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP), DIMENSION(:), INTENT(IN) :: y
    REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
  END SUBROUTINE derivs

  SUBROUTINE jacobn(x,y,dfdx,dfdy)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP), DIMENSION(:), INTENT(IN) :: y
    REAL(SP), DIMENSION(:), INTENT(OUT) :: dfdx
    REAL(SP), DIMENSION(:,,:), INTENT(OUT) :: dfdy
  END SUBROUTINE jacobn
END INTERFACE
INTEGER(I4B), PARAMETER :: MAXTRY=40
REAL(SP), PARAMETER :: SAFETY=0.9_sp,GROW=1.5_sp,PGROW=-0.25_sp,&
  SHRNK=0.5_sp,PSHRNK=-1.0_sp/3.0_sp,ERRCON=0.1296_sp,&
  GAM=1.0_sp/2.0_sp,&
  A21=2.0_sp,A31=48.0_sp/25.0_sp,A32=6.0_sp/25.0_sp,C21=-8.0_sp,&
  C31=372.0_sp/25.0_sp,C32=12.0_sp/5.0_sp,&
  C41=-112.0_sp/125.0_sp,C42=-54.0_sp/125.0_sp,&
  C43=-2.0_sp/5.0_sp,B1=19.0_sp/9.0_sp,B2=1.0_sp/2.0_sp,&
  B3=25.0_sp/108.0_sp,B4=125.0_sp/108.0_sp,E1=17.0_sp/54.0_sp,&
  E2=7.0_sp/36.0_sp,E3=0.0_sp,E4=125.0_sp/108.0_sp,&
  C1X=1.0_sp/2.0_sp,C2X=-3.0_sp/2.0_sp,C3X=121.0_sp/50.0_sp,&
  C4X=29.0_sp/250.0_sp,A2X=1.0_sp,A3X=3.0_sp/5.0_sp
Fourth order Rosenbrock step for integrating stiff ODEs, with monitoring of local trun-
cation error to adjust stepsize. Input are the dependent variable vector y and its derivative
dydx at the starting value of the independent variable x. Also input are the stepsize
to be attempted htry, the required accuracy eps, and the vector yscal against which the
error is scaled. On output, y and x are replaced by their new values, hdid is the stepsize
that was actually accomplished, and hnext is the estimated next stepsize. derivs is a
user-supplied subroutine that computes the derivatives of the right-hand side with respect
to x, while jacobn (a fixed name) is a user-supplied subroutine that computes the Jacobi
matrix of derivatives of the right-hand side with respect to the components of y. y, dydx,
and yscal must have the same length.
Parameters: GROW and SHRNK are the largest and smallest factors by which stepsize can
change in one step; ERRCON=(GROW/SAFETY)**(1/PGROW) and handles the case when
errmax  $\simeq$  0.
INTEGER(I4B) :: jtry,ndum
INTEGER(I4B), DIMENSION(size(y)) :: indx
REAL(SP), DIMENSION(size(y)) :: dfdx,dytmp,err,g1,g2,g3,g4,ysav
REAL(SP), DIMENSION(size(y),size(y)) :: a,dfdy
REAL(SP) :: d,errmax,h,xsav
ndum=assert_eq(size(y),size(dydx),size(yscal),'stiff')
xsav=x Save initial values.
ysav(:)=y(:)
call jacobn(xsav,ysav,dfdx,dfdy)
The user must supply this subroutine to return the  $n \times n$  matrix dfdy and the vector dfdx.
h=htry Set stepsize to the initial trial value.
do jtry=1,MAXTRY

```

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```

a(:, :)= -dfdy(:, :)           Set up the matrix  $\mathbf{1} - \gamma h \mathbf{f}'$ .
call diagadd(a, 1.0_sp/(GAM*h))
call ludcmp(a, indx, d)         LU decomposition of the matrix.
g1=dydx+h*C1X*dfdx             Set up right-hand side for  $\mathbf{g}_1$ .
call lubksb(a, indx, g1)       Solve for  $\mathbf{g}_1$ .
y=ysav+A21*g1                  Compute intermediate values of y and x.
x=xsav+A2X*h
call derivs(x, y, dytmp)       Compute dydx at the intermediate values.
g2=dytmp+h*C2X*dfdx+C21*g1/h   Set up right-hand side for  $\mathbf{g}_2$ .
call lubksb(a, indx, g2)       Solve for  $\mathbf{g}_2$ .
y=ysav+A31*g1+A32*g2          Compute intermediate values of y and x.
x=xsav+A3X*h
call derivs(x, y, dytmp)       Compute dydx at the intermediate values.
g3=dytmp+h*C3X*dfdx+(C31*g1+C32*g2)/h   Set up right-hand side for  $\mathbf{g}_3$ .
call lubksb(a, indx, g3)       Solve for  $\mathbf{g}_3$ .
g4=dytmp+h*C4X*dfdx+(C41*g1+C42*g2+C43*g3)/h   Set up right-hand side for  $\mathbf{g}_4$ .
call lubksb(a, indx, g4)       Solve for  $\mathbf{g}_4$ .
y=ysav+B1*g1+B2*g2+B3*g3+B4*g4   Get fourth order estimate of y and error estimate.
err=E1*g1+E2*g2+E3*g3+E4*g4
x=xsav+h
if (x == xsav) call &
  nrerror('stepsize not significant in stiff')
errmax=maxval(abs(err/yscal))/eps   Evaluate accuracy.
if (errmax <= 1.0) then           Step succeeded. Compute size of next step
  hdid=h                           and return.
  hnext=merge(SAFETY*h*errmax**PGROW, GROW*h, &
    errmax > ERRCON)
  RETURN
else                                Truncation error too large, reduce stepsize.
  hnext=SAFETY*h*errmax**PSHRNK
  h=sign(max(abs(hnext), SHRNK*abs(h)), h)
end if
end do                               Go back and retry step.
call nrerror('exceeded MAXTRY in stiff')
END SUBROUTINE stiff

```



call diagadd(...) See discussion of diagadd after hqr on p. 1234.

```

SUBROUTINE jacobn(x, y, dfdx, dfdy)
USE nrtype
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(IN) :: y
REAL(SP), DIMENSION(:), INTENT(OUT) :: dfdx
REAL(SP), DIMENSION(:, :), INTENT(OUT) :: dfdy
  Routine for Jacobi matrix corresponding to example in equations (16.6.27).
  dfdx(:)=0.0
  dfdy(1,1)=-0.013_sp-1000.0_sp*y(3)
  dfdy(1,2)=0.0
  dfdy(1,3)=-1000.0_sp*y(1)
  dfdy(2,1)=0.0
  dfdy(2,2)=-2500.0_sp*y(3)
  dfdy(2,3)=-2500.0_sp*y(2)
  dfdy(3,1)=-0.013_sp-1000.0_sp*y(3)
  dfdy(3,2)=-2500.0_sp*y(3)
  dfdy(3,3)=-1000.0_sp*y(1)-2500.0_sp*y(2)
END SUBROUTINE jacobn

```

```

SUBROUTINE derivs(x,y,dydx)
USE nrtype
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(IN) :: y
REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
  Routine for right-hand side of example in equations (16.6.27).
dydx(1)=-0.013_sp*y(1)-1000.0_sp*y(1)*y(3)
dydx(2)=-2500.0_sp*y(2)*y(3)
dydx(3)=-0.013_sp*y(1)-1000.0_sp*y(1)*y(3)-2500.0_sp*y(2)*y(3)
END SUBROUTINE derivs

```

\* \* \*

```

SUBROUTINE simpr(y,dydx,dfdx,dfdy,xs,htot,nstep,yout,derivs)
USE nrtype; USE nrutil, ONLY : assert_eq,diagadd
USE nr, ONLY : lubksb,ludcmp
IMPLICIT NONE
REAL(SP), INTENT(IN) :: xs,htot
REAL(SP), DIMENSION(:), INTENT(IN) :: y,dydx,dfdx
REAL(SP), DIMENSION(:,:), INTENT(IN) :: dfdy
INTEGER(I4B), INTENT(IN) :: nstep
REAL(SP), DIMENSION(:), INTENT(OUT) :: yout
INTERFACE
  SUBROUTINE derivs(x,y,dydx)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP), DIMENSION(:), INTENT(IN) :: y
    REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
  END SUBROUTINE derivs
END INTERFACE

```

Performs one step of semi-implicit midpoint rule. Input are the dependent variable  $y$ , its derivative  $dydx$ , the derivative of the right-hand side with respect to  $x$ ,  $dfdx$ , which are all vectors of length  $N$ , and the  $N \times N$  Jacobian  $dfdy$  at  $xs$ . Also input are  $htot$ , the total step to be taken, and  $nstep$ , the number of substeps to be used. The output is returned as  $yout$ , a vector of length  $N$ .  $derivs$  is the user-supplied subroutine that calculates  $dydx$ .

```

INTEGER(I4B) :: ndum,nn
INTEGER(I4B), DIMENSION(size(y)) :: indx
REAL(SP) :: d,h,x
REAL(SP), DIMENSION(size(y)) :: del,ytemp
REAL(SP), DIMENSION(size(y),size(y)) :: a
ndum=assert_eq((/size(y),size(dydx),size(dfdx),size(dfdy,1),&
  size(dfdy,2),size(yout)/),'simpr')
h=htot/nstep           Stepsize this trip.
a(:,:)=h*dfdy(:,:)    Set up the matrix  $\mathbf{1} - h\mathbf{f}'$ .
call diagadd(a,1.0_sp)
call ludcmp(a,indx,d)  LU decomposition of the matrix.
yout=h*(dydx+h*dfdx)  Set up right-hand side for first step. Use yout for
call lubksb(a,indx,yout) temporary storage.
del=yout              First step.
ytemp=y+del
x=xs+h
call derivs(x,ytemp,yout) Use yout for temporary storage of derivatives.
do nn=2,nstep         General step.
  yout=h*yout-del     Set up right-hand side for general step.
  call lubksb(a,indx,yout)
  del=del+2.0_sp*yout
  ytemp=ytemp+del
  x=x+h
  call derivs(x,ytemp,yout)

```

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```

end do
yout=h*yout-del           Set up right-hand side for last step.
call lubksb(a,indx,yout)
yout=ytemp+yout          Take last step.
END SUBROUTINE simprr

```



call diagadd(...) See discussion of diagadd after hqr on p. 1234.

\* \* \*

```

SUBROUTINE stifbs(y,dydx,x,htry,eps,yscal,hdid,hnext,derivs)
USE nrtype; USE nrutil, ONLY : arth,assert_eq,cumsum,iminloc,nrerror,&
  outerdiff,outerprod,upper_triangle
USE nr, ONLY : simprr,pzextr
IMPLICIT NONE
REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
REAL(SP), DIMENSION(:), INTENT(IN) :: dydx,yscal
REAL(SP), INTENT(IN) :: htry,eps
REAL(SP), INTENT(INOUT) :: x
REAL(SP), INTENT(OUT) :: hdid,hnext
INTERFACE
  SUBROUTINE derivs(x,y,dydx)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP), DIMENSION(:), INTENT(IN) :: y
    REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
  END SUBROUTINE derivs
  SUBROUTINE jacobn(x,y,dfdx,dfdy)
    USE nrtype
    IMPLICIT NONE
    REAL(SP), INTENT(IN) :: x
    REAL(SP), DIMENSION(:), INTENT(IN) :: y
    REAL(SP), DIMENSION(:), INTENT(OUT) :: dfdx
    REAL(SP), DIMENSION(:,:), INTENT(OUT) :: dfdy
  END SUBROUTINE jacobn
END INTERFACE
INTEGER(I4B), PARAMETER :: IMAX=8, KMAXX=IMAX-1
REAL(SP), PARAMETER :: SAFE1=0.25_sp,SAFE2=0.7_sp,REDMAX=1.0e-5_sp,&
  REDMIN=0.7_sp,TINY=1.0e-30_sp,SCALMX=0.1_sp
Semi-implicit extrapolation step for integrating stiff ODEs, with monitoring of local truncation error to adjust stepsize. Input are the dependent variable vector y and its derivative dydx at the starting value of the independent variable x. Also input are the stepsize to be attempted htry, the required accuracy eps, and the vector yscal against which the error is scaled. On output, y and x are replaced by their new values, hdid is the stepsize that was actually accomplished, and hnext is the estimated next stepsize. derivs is a user-supplied subroutine that computes the derivatives of the right-hand side with respect to x, while jacobn (a fixed name) is a user-supplied subroutine that computes the Jacobi matrix of derivatives of the right-hand side with respect to the components of y. y, dydx, and yscal must all have the same length. Be sure to set htry on successive steps to the value of hnext returned from the previous step, as is the case if the routine is called by odeint.
INTEGER(I4B) :: k,km,ndum
INTEGER(I4B), DIMENSION(IMAX) :: nseq = (/ 2,6,10,14,22,34,50,70 /)
Sequence is different from bsstep.
INTEGER(I4B), SAVE :: kopt,kmax,nvold=-1
REAL(SP), DIMENSION(KMAXX,KMAXX), SAVE :: alf
REAL(SP), DIMENSION(KMAXX) :: err
REAL(SP), DIMENSION(IMAX), SAVE :: a
REAL(SP), SAVE :: epsold = -1.0
REAL(SP) :: eps1,errmax,fact,h,red,scale,wrkmin,xest

```

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```

REAL(SP), SAVE :: xnew
REAL(SP), DIMENSION(size(y)) :: dfdx,yerr,ysav,yseq
REAL(SP), DIMENSION(size(y),size(y)) :: dfdy
LOGICAL(LGT) :: reduct
LOGICAL(LGT), SAVE :: first=.true.
ndum=assert_eq(size(y),size(dydx),size(yscal),'stifbs')
if (eps /= epsold .or. nvold /= size(y)) then      Reinitialize also if number of vari-
    hnext=-1.0e29_sp                               ables has changed.
    xnew=-1.0e29_sp
    eps1=SAFE1*eps
    a(:)=cumsum(nseq,1)
    where (upper_triangle(KMAXX,KMAXX)) alf=eps1** &
        (outerdiff(a(2:),a(2:))/outerprod(arth( &
            3.0_sp,2.0_sp,KMAXX),(a(2:)-a(1)+1.0_sp)))
    epsold=eps
    nvold=size(y)                                  Save number of variables.
    a(:)=cumsum(nseq,1+nvold)                       Add cost of Jacobian evaluations to work co-
    do kopt=2,KMAXX-1                                efficient.
        if (a(kopt+1) > a(kopt)*alf(kopt-1,kopt)) exit
    end do
    kmax=kopt
end if
h=htry
ysav(:)=y(:)
call jacobn(x,y,dfdx,dfdy)                          Evaluate Jacobian.
if (h /= hnext .or. x /= xnew) then
    first=.true.
    kopt=kmax
end if
reduct=.false.
main_loop: do
    do k=1,kmax
        xnew=x+h
        if (xnew == x) call nrerror('step size underflow in stifbs')
        call simpr(ysav,dydx,dfdx,dfdy,x,h,nseq(k),yseq,derivs)
        Here is the call to the semi-implicit midpoint rule.
        xest=(h/nseq(k))*2                          The rest of the routine is identical to bsstep.
        call pzextr(k,xest,yseq,y,yerr)
        if (k /= 1) then
            errmax=maxval(abs(yerr(:))/yscal(:))
            errmax=max(TINY,errmax)/eps
            km=k-1
            err(km)=(errmax/SAFE1)**(1.0_sp/(2*km+1))
        end if
        if (k /= 1 .and. (k >= kopt-1 .or. first)) then
            if (errmax < 1.0) exit main_loop
            if (k == kmax .or. k == kopt+1) then
                red=SAFE2/err(km)
                exit
            else if (k == kopt) then
                if (alf(kopt-1,kopt) < err(km)) then
                    red=1.0_sp/err(km)
                    exit
                end if
            else if (kopt == kmax) then
                if (alf(km,kmax-1) < err(km)) then
                    red=alf(km,kmax-1)*SAFE2/err(km)
                    exit
                end if
            else if (alf(km,kopt) < err(km)) then
                red=alf(km,kopt-1)/err(km)
                exit
            end if
        end if
    end do
end if

```

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```
      end do
      red=max(min(red,REDMIN),REDMAX)
      h=h*red
      reduct=.true.
end do main_loop
x=xnew
hdid=h
first=.false.
kopt=1+iminloc(a(2:km+1)*max(err(1:km),SCALMX))
scale=max(err(kopt-1),SCALMX)
wrkmin=scale*a(kopt)
hnext=h/scale
if (kopt >= k .and. kopt /= kmax .and. .not. reduct) then
  fact=max(scale/alf(kopt-1,kopt),SCALMX)
  if (a(kopt+1)*fact <= wrkmin) then
    hnext=h/fact
    kopt=kopt+1
  end if
end if
END SUBROUTINE stifbs
```



This routine is very similar to `bsstep`, and the same remarks about Fortran 90 constructions on p. 1305 apply here.

## Chapter B17. Two Point Boundary Value Problems

```

! FUNCTION shoot(v) is named "funcv" for use with "newt"
FUNCTION funcv(v)
  USE nrtype
  USE nr, ONLY : odeint, rkqs
  USE sphoot_caller, ONLY : nvar, x1, x2; USE ode_path, ONLY : xp, yp
  IMPLICIT NONE
  REAL(SP), DIMENSION(:), INTENT(IN) :: v
  REAL(SP), DIMENSION(size(v)) :: funcv
  REAL(SP), PARAMETER :: EPS=1.0e-6_sp
  Routine for use with newt to solve a two point boundary value problem for  $N$  coupled
  ODEs by shooting from  $x_1$  to  $x_2$ . Initial values for the ODEs at  $x_1$  are generated from
  the  $n_2$  input coefficients  $v$ , using the user-supplied routine load. The routine integrates
  the ODEs to  $x_2$  using the Runge-Kutta method with tolerance EPS, initial stepsize  $h_1$ ,
  and minimum stepsize  $h_{min}$ . At  $x_2$  it calls the user-supplied subroutine score to evaluate
  the  $n_2$  functions  $funcv$  that ought to be zero to satisfy the boundary conditions at  $x_2$ .
  The functions  $funcv$  are returned on output. newt uses a globally convergent Newton's
  method to adjust the values of  $v$  until the functions  $funcv$  are zero. The user-supplied
  subroutine derivs(x,y,dydx) supplies derivative information to the ODE integrator (see
  Chapter 16). The module sphoot_caller receives its values from the main program so
  that funcv can have the syntax required by newt. Set nvar =  $N$  in the main program.
  REAL(SP) :: h1, hmin
  REAL(SP), DIMENSION(nvar) :: y
  INTERFACE
    SUBROUTINE derivs(x,y,dydx)
      USE nrtype
      IMPLICIT NONE
      REAL(SP), INTENT(IN) :: x
      REAL(SP), DIMENSION(:), INTENT(IN) :: y
      REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
    END SUBROUTINE derivs

    SUBROUTINE load(x1,v,y)
      USE nrtype
      IMPLICIT NONE
      REAL(SP), INTENT(IN) :: x1
      REAL(SP), DIMENSION(:), INTENT(IN) :: v
      REAL(SP), DIMENSION(:), INTENT(OUT) :: y
    END SUBROUTINE load

    SUBROUTINE score(x2,y,f)
      USE nrtype
      IMPLICIT NONE
      REAL(SP), INTENT(IN) :: x2
      REAL(SP), DIMENSION(:), INTENT(IN) :: y
      REAL(SP), DIMENSION(:), INTENT(OUT) :: f
    END SUBROUTINE score
  END INTERFACE
  h1=(x2-x1)/100.0_sp

```

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```

hmin=0.0
call load(x1,v,y)
if (associated(xp)) deallocate(xp,yp)      Prevent memory leak if save_steps set
call odeint(y,x1,x2,EPS,h1,hmin,derivs,rkqs) to .true.
call score(x2,y,funcv)
END FUNCTION funcv

```

\* \* \*

```

! FUNCTION shootf(v) is named "funcv" for use with "newt"
FUNCTION funcv(v)
  USE nrtype
  USE nr, ONLY : odeint,rkqs
  USE sphfpt_caller, ONLY : x1,x2,xf,nn2; USE ode_path, ONLY : xp,yp
  IMPLICIT NONE
  REAL(SP), DIMENSION(:), INTENT(IN) :: v
  REAL(SP), DIMENSION(size(v)) :: funcv
  REAL(SP), PARAMETER :: EPS=1.0e-6_sp
  Routine for use with newt to solve a two point boundary value problem for  $N$  coupled
  ODEs by shooting from  $x_1$  and  $x_2$  to a fitting point  $xf$ . Initial values for the ODEs at
   $x_1$  ( $x_2$ ) are generated from the  $n_2$  ( $n_1$ ) coefficients  $V_1$  ( $V_2$ ), using the user-supplied
  routine load1 (load2). The coefficients  $V_1$  and  $V_2$  should be stored in a single array
   $v$  of length  $N$  in the main program, and referenced by pointers as  $v_1=>v(1:n_2)$ ,
   $v_2=>v(n_2+1:N)$ . Here  $N = n_1 + n_2$ . The routine integrates the ODEs to  $xf$  using
  the Runge-Kutta method with tolerance  $EPS$ , initial stepsize  $h_1$ , and minimum stepsize
   $hmin$ . At  $xf$  it calls the user-supplied subroutine score to evaluate the  $N$  functions  $f_1$ 
  and  $f_2$  that ought to match at  $xf$ . The differences  $funcv$  are returned on output. newt
  uses a globally convergent Newton's method to adjust the values of  $v$  until the functions
   $funcv$  are zero. The user-supplied subroutine derivs( $x,y,dydx$ ) supplies derivative information
  to the ODE integrator (see Chapter 16). The module sphfpt_caller receives its values from
  the main program so that  $funcv$  can have the syntax required by newt.
  Set  $nn2 = n_2$  in the main program.
  REAL(SP) :: h1,hmin
  REAL(SP), DIMENSION(size(v)) :: f1,f2,y
  INTERFACE
    SUBROUTINE derivs(x,y,dydx)
      USE nrtype
      IMPLICIT NONE
      REAL(SP), INTENT(IN) :: x
      REAL(SP), DIMENSION(:), INTENT(IN) :: y
      REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
    END SUBROUTINE derivs

    SUBROUTINE load1(x1,v1,y)
      USE nrtype
      IMPLICIT NONE
      REAL(SP), INTENT(IN) :: x1
      REAL(SP), DIMENSION(:), INTENT(IN) :: v1
      REAL(SP), DIMENSION(:), INTENT(OUT) :: y
    END SUBROUTINE load1

    SUBROUTINE load2(x2,v2,y)
      USE nrtype
      IMPLICIT NONE
      REAL(SP), INTENT(IN) :: x2
      REAL(SP), DIMENSION(:), INTENT(IN) :: v2
      REAL(SP), DIMENSION(:), INTENT(OUT) :: y
    END SUBROUTINE load2

    SUBROUTINE score(x2,y,f)
      USE nrtype
      IMPLICIT NONE
      REAL(SP), INTENT(IN) :: x2
      REAL(SP), DIMENSION(:), INTENT(IN) :: y

```

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```

    REAL(SP), DIMENSION(:), INTENT(OUT) :: f
    END SUBROUTINE score
END INTERFACE
h1=(x2-x1)/100.0_sp
hmin=0.0
call load1(x1,v,y)           Path from x1 to xf with best trial values V1.
if (associated(xp)) deallocate(xp,yp)   Prevent memory leak if save_steps set
call odeint(y,x1,xf,EPS,h1,hmin,derivs,rkqs) to .true.
call score(xf,y,f1)
call load2(x2,v(nn2+1:),y)       Path from x2 to xf with best trial values V2.
call odeint(y,x2,xf,EPS,h1,hmin,derivs,rkqs)
call score(xf,y,f2)
funcv(:)=f1(:)-f2(:)
END FUNCTION funcv

```

\* \* \*

```

SUBROUTINE solvde(itmax,conv,slowc,scalv,indexv,nb,y)
USE nrtype; USE nrutil, ONLY : assert_eq,imaxloc,nrerror
USE nr, ONLY : difeq
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: itmax,nb
REAL(SP), INTENT(IN) :: conv,slowc
REAL(SP), DIMENSION(:), INTENT(IN) :: scalv
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: indexv
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: y
  Driver routine for solution of two point boundary value problems with  $N$  equations by
  relaxation. itmax is the maximum number of iterations. conv is the convergence criterion
  (see text). slowc controls the fraction of corrections actually used after each iteration.
  scalv, a vector of length  $N$ , contains typical sizes for each dependent variable, used to
  weight errors. indexv, also of length  $N$ , lists the column ordering of variables used to
  construct the matrix  $s$  of derivatives. (The nb boundary conditions at the first mesh point
  must contain some dependence on the first nb variables listed in indexv.) There are a total
  of  $M$  mesh points. y is the  $N \times M$  array that contains the initial guess for all the dependent
  variables at each mesh point. On each iteration, it is updated by the calculated correction.
INTEGER(I4B) :: ic1,ic2,ic3,ic4,it,j,j1,j2,j3,j4,j5,j6,j7,j8,&
j9,jc1,jcf,jv,k,k1,k2,km,kp,m,ne,nvars
INTEGER(I4B), DIMENSION(size(scalv)) :: kmax
REAL(SP) :: err,fac
REAL(SP), DIMENSION(size(scalv)) :: ermax
REAL(SP), DIMENSION(size(scalv),2*size(scalv)+1) :: s
REAL(SP), DIMENSION(size(scalv),size(scalv)-nb+1,size(y,2)+1) :: c
ne=assert_eq(size(scalv),size(indexv),size(y,1),'solvde: ne')
m=size(y,2)
k1=1                               Set up row and column markers.
k2=m
nvars=ne*m
j1=1
j2=nb
j3=nb+1
j4=ne
j5=j4+j1
j6=j4+j2
j7=j4+j3
j8=j4+j4
j9=j8+j1
ic1=1
ic2=ne-nb
ic3=ic2+1
ic4=ne
jc1=1
jcf=ic3
do it=1,itmax
  k=k1                               Primary iteration loop.
                                     Boundary conditions at first point.

```

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```

call difeq(k,k1,k2,j9,ic3,ic4,indxv,s,y)
call pinvs(ic3,ic4,j5,j9,jc1,k1,c,s)
do k=k1+1,k2                               Finite difference equations at all point
    kp=k-1                                   pairs.
    call difeq(k,k1,k2,j9,ic1,ic4,indxv,s,y)
    call red(ic1,ic4,j1,j2,j3,j4,j9,ic3,jc1,jcf,kp,c,s)
    call pinvs(ic1,ic4,j3,j9,jc1,k,c,s)
end do
k=k2+1                                       Final boundary conditions.
call difeq(k,k1,k2,j9,ic1,ic2,indxv,s,y)
call red(ic1,ic2,j5,j6,j7,j8,j9,ic3,jc1,jcf,k2,c,s)
call pinvs(ic1,ic2,j7,j9,jcf,k2+1,c,s)
call bksub(ne,nb,jcf,k1,k2,c)                Backsubstitution.
do j=1,ne                                     Convergence check, accumulate average
    jv=indxv(j)                               error.
    km=imaxloc(abs(c(jv,1,k1:k2)))+k1-1
        Find point with largest error, for each dependent variable.
    ermax(j)=c(jv,1,km)
    kmax(j)=km
end do
ermax(:)=ermax(:)/scalv(:)                  Weighting for each dependent variable.
err=sum(sum(abs(c(indxv(:),1,k1:k2)),dim=2)/scalv(:))/nvars
fac=slowc/max(slowc,err)
Reduce correction applied when error is large.
y(:,k1:k2)=y(:,k1:k2)-fac*c(indxv(:),1,k1:k2)   Apply corrections.
write(*,'(1x,i4,2f12.6)') it,err,fac
Summary of corrections for this step. Point with largest error for each variable can be
monitored by writing out kmax and ermax.
if (err < conv) RETURN
end do
call nrerror('itmax exceeded in solvde')       Convergence failed.
CONTAINS
SUBROUTINE bksub(ne,nb,jf,k1,k2,c)
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: ne,nb,jf,k1,k2
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: c
Backsubstitution, used internally by solvde.
INTEGER(I4B) :: im,k,nbf
nbf=ne-nb
im=1
do k=k2,k1,-1
    Use recurrence relations to eliminate remaining dependences.
    if (k == k1) im=nbf+1                       Special handling of first point.
    c(im:ne,jf,k)=c(im:ne,jf,k)-matmul(c(im:ne,1:nbf,k),c(1:nbf,jf,k+1))
end do
c(1:nb,1,k1:k2)=c(1+nbf:nb+nbf,jf,k1:k2)       Reorder corrections to be in column 1.
c(1+nbf:nbf+nb,1,k1:k2)=c(1:nbf,jf,k1+1:k2+1)
END SUBROUTINE bksub
SUBROUTINE pinvs(ie1,ie2,je1,jcf,jc1,k,c,s)
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: ie1,ie2,je1,jcf,jc1,k
REAL(SP), DIMENSION(:,:), INTENT(OUT) :: c
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: s
Diagonalize the square subsection of the s matrix, and store the recursion coefficients in
c; used internally by solvde.
INTEGER(I4B) :: i,icoff,id,ipiv,jcoff,je2,jp,jpiv,js1
INTEGER(I4B), DIMENSION(ie2) :: indxr
REAL(SP) :: big,piv,pivinv
REAL(SP), DIMENSION(ie2) :: pscl
je2=je1+ie2-ie1
js1=je2+1
pscl(ie1:ie2)=maxval(abs(s(ie1:ie2,je1:je2)),dim=2)
Implicit pivoting, as in §2.1.

```

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```

if (any(psc1(ie1:ie2) == 0.0)) &
  call nrerror('singular matrix, row all 0 in pinvs')
psc1(ie1:ie2)=1.0_sp/psc1(ie1:ie2)
indxr(ie1:ie2)=0
do id=ie1,ie2
  piv=0.0
  do i=ie1,ie2
    Find pivot element.
    if (indxr(i) == 0) then
      jp=imaxloc(abs(s(i,je1:je2)))+je1-1
      big=abs(s(i,jp))
      if (big*psc1(i) > piv) then
        ipiv=i
        jpiv=jp
        piv=big*psc1(i)
      end if
    end if
  end do
  if (s(ipiv,jpiv) == 0.0) call nrerror('singular matrix in pinvs')
  indxr(ipiv)=jpiv
  pivinv=1.0_sp/s(ipiv,jpiv)
  s(ipiv,je1:jsf)=s(ipiv,je1:jsf)*pivinv
  s(ipiv,jpiv)=1.0
  do i=ie1,ie2
    Reduce nonpivot elements in column.
    if (indxr(i) /= jpiv .and. s(i,jpiv) /= 0.0) then
      s(i,je1:jsf)=s(i,je1:jsf)-s(i,jpiv)*s(ipiv,je1:jsf)
      s(i,jpiv)=0.0
    end if
  end do
end do
jcoff=jc1-js1
icoff=ie1-je1
c(indxr(ie1:ie2)+icoff,js1+jcoff:jsf+jcoff,k)=s(ie1:ie2,js1:jsf)
END SUBROUTINE pinvs

SUBROUTINE red(iz1,iz2,jz1,jz2,jm1,jm2,jmf,ic1,jc1,jcf,kc,c,s)
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: iz1,iz2,jz1,jz2,jm1,jm2,jmf,ic1,jc1,jcf,kc
REAL(SP), DIMENSION(:,,:), INTENT(INOUT) :: s
REAL(SP), DIMENSION(:,,:), INTENT(IN) :: c
  Reduce columns jz1-jz2 of the s matrix, using previous results as stored in the c matrix.
  Only columns jm1-jm2,jmf are affected by the prior results. red is used internally by
  solvde.
INTEGER(I4B) :: ic,l,loff
loff=jc1-jm1
ic=ic1
do j=jz1,jz2
  Loop over columns to be zeroed.
  do l=jm1,jm2
    Loop over columns altered.
    s(iz1:iz2,l)=s(iz1:iz2,l)-s(iz1:iz2,j)*c(ic,l+loff,kc)
    Loop over rows.
  end do
  s(iz1:iz2,jmf)=s(iz1:iz2,jmf)-s(iz1:iz2,j)*c(ic,jcf,kc)
  Plus final element.
  ic=ic+1
end do
END SUBROUTINE red
END SUBROUTINE solvde

```



km=imaxloc... See discussion of imaxloc on p. 1017.

★ ★ ★

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```

MODULE sfroid_data                                Communicates with difeq.
USE nrtype
INTEGER(I4B), PARAMETER :: M=41
INTEGER(I4B) :: mm,n
REAL(SP) :: anorm,c2,h
REAL(SP), DIMENSION(M) :: x
END MODULE sfroid_data

PROGRAM sfroid
USE nrtype; USE nrutil, ONLY : arth
USE nr, ONLY : plgndr,solvde
USE sfroid_data
IMPLICIT NONE
INTEGER(I4B), PARAMETER :: NE=3,NB=1
  Sample program using solvde. Computes eigenvalues of spheroidal harmonics  $S_{mn}(x; c)$ 
  for  $m \geq 0$  and  $n \geq m$ . In the program,  $m$  is mm,  $c^2$  is c2, and  $\gamma$  of equation (17.4.20)
  is anorm.
INTEGER(I4B) :: itmax
INTEGER(I4B), DIMENSION(NE) :: indexv
REAL(SP) :: conv,slowc
REAL(SP), DIMENSION(M) :: deriv,fac1,fac2
REAL(SP), DIMENSION(NE) :: scalv
REAL(SP), DIMENSION(NE,M) :: y
itmax=100
conv=5.0e-6_sp
slowc=1.0
h=1.0_sp/(M-1)
c2=0.0
write(*,*) 'ENTER M,N'
read(*,*) mm,n
indexv(1:3)=merge( (/ 1, 2, 3 /), (/ 2, 1, 3 /), (mod(n+mm,2) == 1) )
  No interchanges necessary if n+mm is odd; otherwise interchange  $y_1$  and  $y_2$ .
anorm=1.0                                Compute  $\gamma$ .
if (mm /= 0) then
  anorm=(-0.5_sp)**mm*product(&
    arth(n+1,1,mm)*arth(real(n,sp),-1.0_sp,mm)/arth(1,1,mm))
end if
x(1:M-1)=arth(0,1,M-1)*h
fac1(1:M-1)=1.0_sp-x(1:M-1)**2          Compute initial guess.
fac2(1:M-1)=fac1(1:M-1)**(-mm/2.0_sp)
y(1,1:M-1)=plgndr(n,mm,x(1:M-1))*fac2(1:M-1)   $P_n^m$  from §6.8.
deriv(1:M-1)=-((n-mm+1)*plgndr(n+1,mm,x(1:M-1))-(n+1)*&
  x(1:M-1)*plgndr(n,mm,x(1:M-1)))/fac1(1:M-1)
  Derivative of  $P_n^m$  from a recurrence relation.
y(2,1:M-1)=mm*x(1:M-1)*y(1,1:M-1)/fac1(1:M-1)+deriv(1:M-1)*fac2(1:M-1)
y(3,1:M-1)=n*(n+1)-mm*(mm+1)
x(M)=1.0                                Initial guess at  $x = 1$  done separately.
y(1,M)=anorm
y(3,M)=n*(n+1)-mm*(mm+1)
y(2,M)=(y(3,M)-c2)*y(1,M)/(2.0_sp*(mm+1.0_sp))
scalv(1:3)=(/ abs(anorm), max(abs(anorm),y(2,M)), max(1.0_sp,y(3,M)) /)
do
  write(*,*) 'ENTER C**2 OR 999 TO END'
  read(*,*) c2
  if (c2 == 999.0) exit
  call solvde(itmax,conv,slowc,scalv,indexv,NB,y)
  write(*,*) ' M = ',mm,' N = ',n,&
    ' C**2 = ',c2,' LAMBDA = ',y(3,1)+mm*(mm+1)
end do
  Go back for another value of  $c^2$ .
END PROGRAM sfroid

```

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MODULE sfroid\_data This module functions just like a common block to communicate variables with difeq. The advantage of a module is that it allows complete specification of the variables.

anorm=(-0.5\_sp)\*\*mm\*product(...) This statement computes equation (17.4.20) by direct multiplication.

```

          *      *      *

SUBROUTINE difeq(k,k1,k2,jsf,is1,isf,indexv,s,y)
USE nrtype
USE sfroid_data
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: is1,isf,jsf,k,k1,k2
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: indexv
REAL(SP), DIMENSION(:,,:), INTENT(OUT) :: s
REAL(SP), DIMENSION(:,,:), INTENT(IN) :: y
  Returns matrix s(i,j) for solvde.
REAL(SP) :: temp,temp2
INTEGER(I4B), DIMENSION(3) :: indexv3
indexv3(1:3)=3+indexv(1:3)
if (k == k1) then      Boundary condition at first point.
  if (mod(n+mm,2) == 1) then
    s(3,indexv3(1:3))= (/ 1.0_sp, 0.0_sp, 0.0_sp /)      Equation (17.4.32).
    s(3,jsf)=y(1,1)      Equation (17.4.31).
  else
    s(3,indexv3(1:3))= (/ 0.0_sp, 1.0_sp, 0.0_sp /)      Equation (17.4.32).
    s(3,jsf)=y(2,1)      Equation (17.4.31).
  end if
else if (k > k2) then  Boundary conditions at last point.
  s(1,indexv3(1:3))= (/ -(y(3,M)-c2)/(2.0_sp*(mm+1.0_sp)),&
    1.0_sp, -y(1,M)/(2.0_sp*(mm+1.0_sp)) /)      Equation (17.4.35).
  s(1,jsf)=y(2,M)-(y(3,M)-c2)*y(1,M)/(2.0_sp*(mm+1.0_sp))      Equation (17.4.33).
  s(2,indexv3(1:3))= (/ 1.0_sp, 0.0_sp, 0.0_sp /)      Equation (17.4.36).
  s(2,jsf)=y(1,M)-anorm      Equation (17.4.34).
else
  Interior point.
  s(1,indexv(1:3))= (/ -1.0_sp, -0.5_sp*h, 0.0_sp /)      Equation (17.4.28).
  s(1,indexv3(1:3))= (/ 1.0_sp, -0.5_sp*h, 0.0_sp /)
  temp=h/(1.0_sp-(x(k)+x(k-1))*2*0.25_sp)
  temp2=0.5_sp*(y(3,k)+y(3,k-1))-c2*0.25_sp*(x(k)+x(k-1))*2
  s(2,indexv(1:3))= (/ temp*temp2*0.5_sp,&
    -1.0_sp-0.5_sp*temp*(mm+1.0_sp)*(x(k)+x(k-1)),&
    0.25_sp*temp*(y(1,k)+y(1,k-1)) /)      Equation (17.4.29).
  s(2,indexv3(1:3))=s(2,indexv(1:3))
  s(2,indexv3(2))=s(2,indexv3(2))+2.0_sp
  s(3,indexv(1:3))= (/ 0.0_sp, 0.0_sp, -1.0_sp /)      Equation (17.4.30).
  s(3,indexv3(1:3))= (/ 0.0_sp, 0.0_sp, 1.0_sp /)
  s(1,jsf)=y(1,k)-y(1,k-1)-0.5_sp*h*(y(2,k)+y(2,k-1))      Equation (17.4.23).
  s(2,jsf)=y(2,k)-y(2,k-1)-temp*((x(k)+x(k-1))*&
    0.5_sp*(mm+1.0_sp)*(y(2,k)+y(2,k-1))-temp2*&
    0.5_sp*(y(1,k)+y(1,k-1)))      Equation (17.4.24).
  s(3,jsf)=y(3,k)-y(3,k-1)      Equation (17.4.27).
end if
END SUBROUTINE difeq

```

\* \* \*

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```

MODULE sphoot_data                                Communicates with load, score, and derivs.
USE nrtype
INTEGER(I4B) :: m,n
REAL(SP) :: c2,dx,gamma
END MODULE sphoot_data

MODULE sphoot_caller                              Communicates with shoot.
USE nrtype
INTEGER(I4B) :: nvar
REAL(SP) :: x1,x2
END MODULE sphoot_caller

PROGRAM sphoot
  Sample program using shoot. Computes eigenvalues of spheroidal harmonics  $S_{mn}(x; c)$  for
   $m \geq 0$  and  $n \geq m$ . Be sure that routine funcv for newt is provided by shoot (§17.1).
  USE nrtype; USE nrutil, ONLY : arth
  USE nr, ONLY : newt
  USE sphoot_data
  USE sphoot_caller
  IMPLICIT NONE
  INTEGER(I4B), PARAMETER :: NV=3,N2=1
  REAL(SP), DIMENSION(N2) :: v
  LOGICAL(LGT) :: check
  nvar=NV
  dx=1.0e-4_sp
  do
    write(*,*) 'input m,n,c-squared (999 to end)'
    read(*,*) m,n,c2
    if (c2 == 999.0) exit
    if ((n < m) .or. (m < 0)) cycle
    gamma=(-0.5_sp)**m*product(&
      arth(n+1,1,m)*(arth(real(n,sp),-1.0_sp,m)/arth(1,1,m)))
    v(1)=n*(n+1)-m*(m+1)+c2/2.0_sp
    x1=-1.0_sp+dx
    x2=0.0
    call newt(v,check)
    if (check) then
      write(*,*) 'shoot failed; bad initial guess'
      exit
    else
      write(*,'(1x,t6,a)') 'mu(m,n)'
      write(*,'(1x,f12.6)') v(1)
    end if
  end do
END PROGRAM sphoot

  Number of equations.
  Avoid evaluating derivatives exactly at  $x = -1$ .
  Compute  $\gamma$  of equation (17.4.20).
  Initial guess for eigenvalue.
  Set range of integration.
  Find v that zeros function f in score.

SUBROUTINE load(x1,v,y)
USE nrtype
USE sphoot_data
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x1
REAL(SP), DIMENSION(:), INTENT(IN) :: v
REAL(SP), DIMENSION(:), INTENT(OUT) :: y
  Supplies starting values for integration at  $x = -1 + dx$ .
REAL(SP) :: y1
y(3)=v(1)
y1=merge(gamma,-gamma, mod(n-m,2) == 0 )
y(2)=-y(3)-c2*y1/(2*(m+1))
y(1)=y1+y(2)*dx
END SUBROUTINE load

```

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```

SUBROUTINE score(x2,y,f)
USE nrtype
USE sphoot_data
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x2
REAL(SP), DIMENSION(:), INTENT(IN) :: y
REAL(SP), DIMENSION(:), INTENT(OUT) :: f
    Tests whether boundary condition at  $x = 0$  is satisfied.
f(1)=merge(y(2),y(1), mod(n-m,2) == 0 )
END SUBROUTINE score

```

**f90** MODULE sphoot\_data...MODULE sphoot\_caller These modules function just like common blocks to communicate variables from sphoot to the various subsidiary routines. The advantage of a module is that it allows complete specification of the variables.

```

SUBROUTINE derivs(x,y,dydx)
USE nrtype
USE sphoot_data
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(IN) :: y
REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
    Evaluates derivatives for odeint.
dydx(1)=y(2)
dydx(2)=(2.0_sp*x*(m+1.0_sp)*y(2)-(y(3)-c2*x*x)*y(1))/(1.0_sp-x*x)
dydx(3)=0.0
END SUBROUTINE derivs

```

\* \* \*

```

MODULE sphfpt_data
USE nrtype
INTEGER(I4B) :: m,n
REAL(SP) :: c2,dx,gamma
END MODULE sphfpt_data

```

Communicates with load1, load2, score,  
and derivs.

```

MODULE sphfpt_caller
USE nrtype
INTEGER(I4B) :: nn2
REAL(SP) :: x1,x2,xf
END MODULE sphfpt_caller

```

Communicates with shootf.

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```

PROGRAM sphfpt
  Sample program using shootf. Computes eigenvalues of spheroidal harmonics  $S_{mn}(x; c)$ 
  for  $m \geq 0$  and  $n \geq m$ . Be sure that routine funcv for newt is provided by shootf (§17.2).
  The routine derivs is the same as for sphoot.
  USE nrtype; USE nrutil, ONLY : arth
  USE nr, ONLY : newt
  USE sphfpt_data
  USE sphfpt_caller
  IMPLICIT NONE
  INTEGER(I4B), PARAMETER :: N1=2, N2=1, NTOT=N1+N2
  REAL(SP), PARAMETER :: DXX=1.0e-4_sp
  REAL(SP), DIMENSION(:), POINTER :: v1, v2
  REAL(SP), DIMENSION(NTOT), TARGET :: v
  LOGICAL(LGT) :: check
  v1=>v(1:N2)
  v2=>v(N2+1:NTOT)
  nn2=N2
  dx=DXX
  do
    Avoid evaluating derivatives exactly at  $x = \pm 1$ .
    write(*,*) 'input m,n,c-squared (999 to end)'
    read(*,*) m,n,c2
    if (c2 == 999.0) exit
    if ((n < m) .or. (m < 0)) cycle
    gamma=(-0.5_sp)**m*product(&      Compute  $\gamma$  of equation (17.4.20).
      arth(n+1,1,m)*(arth(real(n,sp),-1.0_sp,m)/arth(1,1,m)))
    v1(1)=n*(n+1)-m*(m+1)+c2/2.0_sp  Initial guess for eigenvalue and function value.
    v2(2)=v1(1)
    v2(1)=gamma*(1.0_sp-(v2(2)-c2)*dx/(2*(m+1)))
    x1=-1.0_sp+dx                    Set range of integration.
    x2=1.0_sp-dx
    xf=0.0                            Fitting point.
    call newt(v,check)                 Find v that zeros function f in score.
    if (check) then
      write(*,*) 'shootf failed; bad initial guess'
      exit
    else
      write(*,'(1x,t6,a)') 'mu(m,n)'
      write(*,'(1x,f12.6)') v1(1)
    end if
  end do
END PROGRAM sphfpt

SUBROUTINE load1(x1,v1,y)
  USE nrtype
  USE sphfpt_data
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: x1
  REAL(SP), DIMENSION(:), INTENT(IN) :: v1
  REAL(SP), DIMENSION(:), INTENT(OUT) :: y
  Supplies starting values for integration at  $x = -1 + dx$ .
  REAL(SP) :: y1
  y(3)=v1(1)
  y1=merge(gamma,-gamma,mod(n-m,2) == 0)
  y(2)=- (y(3)-c2)*y1/(2*(m+1))
  y(1)=y1+y(2)*dx
END SUBROUTINE load1

```

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```


SUBROUTINE load2(x2,v2,y)
USE nrtype
USE sphfpt_data
IMPLICIT NONE
REAL(SP), INTENT(IN) :: x2
REAL(SP), DIMENSION(:), INTENT(IN) :: v2
REAL(SP), DIMENSION(:), INTENT(OUT) :: y
    Supplies starting values for integration at  $x = 1 - dx$ .
y(3)=v2(2)
y(1)=v2(1)
y(2)=(y(3)-c2)*y(1)/(2*(m+1))
END SUBROUTINE load2

```

```

SUBROUTINE score(xf,y,f)
USE nrtype
USE sphfpt_data
IMPLICIT NONE
REAL(SP), INTENT(IN) :: xf
REAL(SP), DIMENSION(:), INTENT(IN) :: y
REAL(SP), DIMENSION(:), INTENT(OUT) :: f
    Tests whether solutions match at fitting point  $x = 0$ .
f(1:3)=y(1:3)
END SUBROUTINE score

```

 MODULE sphfpt\_data...MODULE sphfpt\_caller These modules function just like common blocks to communicate variables from sphfpt to the various subsidiary routines. The advantage of a module is that it allows complete specification of the variables.

# Chapter B18. Integral Equations and Inverse Theory

```

SUBROUTINE fred2(a,b,t,f,w,g,ak)
USE nrtype; USE nrutil, ONLY : assert_eq,unit_matrix
USE nr, ONLY : gauleg,lubksb,ludcmp
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP), DIMENSION(:), INTENT(OUT) :: t,f,w
INTERFACE
  FUNCTION g(t)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), DIMENSION(:), INTENT(IN) :: t
  REAL(SP), DIMENSION(size(t)) :: g
  END FUNCTION g

  FUNCTION ak(t,s)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), DIMENSION(:), INTENT(IN) :: t,s
  REAL(SP), DIMENSION(size(t),size(s)) :: ak
  END FUNCTION ak
END INTERFACE
Solves a linear Fredholm equation of the second kind by  $N$ -point Gaussian quadrature. On input, a and b are the limits of integration. g and ak are user-supplied external functions. g returns  $g(t)$  as a vector of length  $N$  for a vector of  $N$  arguments, while ak returns  $\lambda K(t,s)$  as an  $N \times N$  matrix. The routine returns arrays t and f of length  $N$  containing the abscissas  $t_i$  of the Gaussian quadrature and the solution  $f$  at these abscissas. Also returned is the array w of length  $N$  of Gaussian weights for use with the Nystrom interpolation routine fredin.
INTEGER(I4B) :: n
INTEGER(I4B), DIMENSION(size(f)) :: indx
REAL(SP) :: d
REAL(SP), DIMENSION(size(f),size(f)) :: omk
n=assert_eq(size(f),size(t),size(w),'fred2')
call gauleg(a,b,t,w)
call unit_matrix(omk)
omk=omk-ak(t,t)*spread(w,dim=1,ncopies=n)
f=g(t)
call ludcmp(omk,indx,d)
call lubksb(omk,indx,f)
END SUBROUTINE fred2

```



call unit\_matrix(omk) The unit\_matrix routine in nrutil does exactly what its name suggests.

Replace gauleg with another routine if not using Gauss-Legendre quadrature.  
Form  $\mathbf{I} - \lambda \mathbf{K}$ .  
Solve linear equations.

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omk=omk-ak(t,t)\*spread(w,dim=1,ncopies=n) By now this idiom should be second nature: the first column of ak gets multiplied by the first element of w, and so on.

\* \* \*

```

FUNCTION fredin(x,a,b,t,f,w,g,ak)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(SP), INTENT(IN) :: a,b
REAL(SP), DIMENSION(:), INTENT(IN) :: x,t,f,w
REAL(SP), DIMENSION(size(x)) :: fredin
INTERFACE
  FUNCTION g(t)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), DIMENSION(:), INTENT(IN) :: t
  REAL(SP), DIMENSION(size(t)) :: g
  END FUNCTION g

  FUNCTION ak(t,s)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), DIMENSION(:), INTENT(IN) :: t,s
  REAL(SP), DIMENSION(size(t),size(s)) :: ak
  END FUNCTION ak
END INTERFACE
Input are arrays t and w of length N containing the abscissas and weights of the N-point
Gaussian quadrature, and the solution array f of length N from fred2. The function
fredin returns the array of values of f at an array of points x using the Nystrom interpo-
lation formula. On input, a and b are the limits of integration. g and ak are user-supplied
external functions. g returns g(t) as a vector of length N for a vector of N arguments,
while ak returns  $\lambda K(t,s)$  as an  $N \times N$  matrix.
INTEGER(I4B) :: n
n=assert_eq(size(f),size(t),size(w),'fredin')
fredin=g(x)+matmul(ak(x,t),w*f)
END FUNCTION fredin

```



fredin=g(x)+matmul... Fortran 90 allows very concise coding here, which also happens to be much closer to the mathematical formulation than the loops required in Fortran 77.

\* \* \*

```

SUBROUTINE voltra(t0,h,t,f,g,ak)
USE nrtype; USE nrutil, ONLY : array_copy,assert_eq,unit_matrix
USE nr, ONLY : lubksb,ludcmp
IMPLICIT NONE
REAL(SP), INTENT(IN) :: t0,h
REAL(SP), DIMENSION(:), INTENT(OUT) :: t
REAL(SP), DIMENSION(:,,:), INTENT(OUT) :: f
INTERFACE
  FUNCTION g(t)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: t
  REAL(SP), DIMENSION(:), POINTER :: g
  END FUNCTION g

  FUNCTION ak(t,s)

```

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```

USE nrtype
IMPLICIT NONE
REAL(SP), INTENT(IN) :: t,s
REAL(SP), DIMENSION(:,:), POINTER :: ak
END FUNCTION ak
END INTERFACE
Solves a set of  $M$  linear Volterra equations of the second kind using the extended trapezoidal
rule. On input,  $t_0$  is the starting point of the integration. The routine takes  $N - 1$  steps
of size  $h$  and returns the abscissas in  $t$ , a vector of length  $N$ . The solution at these points
is returned in the  $M \times N$  matrix  $f$ .  $g$  is a user-supplied external function that returns a
pointer to the  $M$ -dimensional vector of functions  $g_k(t)$ , while  $ak$  is another user-supplied
external function that returns a pointer to the  $M \times M$  matrix  $K(t, s)$ .
INTEGER(I4B) :: i,j,n,ncop,nerr,m
INTEGER(I4B), DIMENSION(size(f,1)) :: indx
REAL(SP) :: d
REAL(SP), DIMENSION(size(f,1)) :: b
REAL(SP), DIMENSION(size(f,1),size(f,1)) :: a
n=assert_eq(size(f,2),size(t),'voltra: n')
t(1)=t0
call array_copy(g(t(1)),f(:,1),ncop,nerr)
m=assert_eq(size(f,1),ncop,ncop+nerr,'voltra: m')
do i=2,n
  t(i)=t(i-1)+h
  b=g(t(i))+0.5_sp*h*matmul(ak(t(i),t(1)),f(:,1))
  do j=2,i-1
    b=b+h*matmul(ak(t(i),t(j)),f(:,j))
  end do
  call unit_matrix(a)
  a=a-0.5_sp*h*ak(t(i),t(i))
  call ludcmp(a,indx,d)
  call lubksb(a,indx,b)
  f(:,i)=b(:)
end do
END SUBROUTINE voltra

```

Initialize.

Take a step  $h$ .

Accumulate right-hand side of linear equations in  $b$ .

Left-hand side goes in matrix  $a$ .

Solve linear equations.

**f90** FUNCTION  $g(t)$ ...REAL(SP), DIMENSION(:), POINTER ::  $g$  The routine  $voltra$  requires an argument that is a function returning a vector, but we don't know the dimension of the vector at compile time. The solution is to make the function return a *pointer* to the vector. This is not the same thing as a pointer to a function, which is not allowed in Fortran 90. When you use the pointer in the routine, Fortran 90 figures out from the context that you want the vector of values, so the code remains highly readable. Similarly, the argument  $ak$  is a function returning a pointer to a matrix.

The coding of the user-supplied functions  $g$  and  $ak$  deserves some comment: functions returning pointers to arrays are potential memory leaks if the arrays are allocated dynamically in the functions. Here the user knows in advance the dimension of the problem, and so there is no need to use dynamical allocation in the functions. For example, in a two-dimensional problem, you can code  $g$  as follows:

```

FUNCTION g(t)
USE nrtype
IMPLICIT NONE
REAL(SP), INTENT(IN) :: t
REAL(SP), DIMENSION(:), POINTER :: g
REAL(SP), DIMENSION(2), TARGET, SAVE :: gg
g=>gg
g(1)=...
g(2)=...
END FUNCTION g

```

and similarly for ak.

Suppose, however, we coded g with dynamical allocation:

```
FUNCTION g(t)
  USE nrtype
  IMPLICIT NONE
  REAL(SP), INTENT(IN) :: t
  REAL(SP), DIMENSION(:), POINTER :: g
  allocate(g(2))
  g(1)=...
  g(2)=...
END FUNCTION g
```

Now g never gets deallocated; each time we call the function fresh memory gets consumed. If you have a problem that really does require dynamical allocation in a pointer function, you have to be sure to deallocate the pointer in the calling routine. In *voltra*, for example, we would declare pointers gtemp and aktemp. Then instead of writing simply

```
b=g(t(i))+...
```

we would write

```
gtemp=>g(t(i))
b=gtemp+...
deallocate(gtemp)
```

and similarly for each pointer function invocation.

call array\_copy(g(t(1)),f(:,1),ncop,nerr) The routine would work if we replaced this statement with simply  $f(:,1)=g(t(1))$ . The purpose of using `array_copy` from `nrutil` is that we can check that `f` and `g` have consistent dimensions with a call to `assert_eq`.

\* \* \*

```
FUNCTION wghts(n,h,kermom)
  USE nrtype; USE nrutil, ONLY : geop
  IMPLICIT NONE
  INTEGER(I4B), INTENT(IN) :: n
  REAL(SP), INTENT(IN) :: h
  REAL(SP), DIMENSION(n) :: wghts
  INTERFACE
    FUNCTION kermom(y,m)
      USE nrtype
      IMPLICIT NONE
      REAL(DP), INTENT(IN) :: y
      INTEGER(I4B), INTENT(IN) :: m
      REAL(DP), DIMENSION(m) :: kermom
    END FUNCTION kermom
  END INTERFACE
```

Returns in `wghts(1:n)` weights for the `n`-point equal-interval quadrature from 0 to  $(n-1)h$  of a function  $f(x)$  times an arbitrary (possibly singular) weight function  $w(x)$  whose indefinite-integral moments  $F_n(y)$  are provided by the user-supplied function `kermom`.

```
INTEGER(I4B) :: j
REAL(DP) :: hh,hi,c,a,b
REAL(DP), DIMENSION(4) :: wold,wnew,w
hh=h
hi=1.0_dp/hh
wghts(1:n)=0.0
wold(1:4)=kermom(0.0_dp,4)
```

Double precision on internal calculations even though the interface is in single precision.  
Zero all the weights so we can sum into them.  
Evaluate indefinite integrals at lower end.

```

if (n >= 4) then
  b=0.0
  do j=1,n-3
    c=j-1
    a=b
    b=a+hh
    if (j == n-3) b=(n-1)*hh
    wnew(1:4)=kermom(b,4)
    w(1:4)=(wnew(1:4)-wold(1:4))*geop(1.0_dp,hi,4)
    wghts(j:j+3)=wghts(j:j+3)+(/&
      ((c+1.0_dp)*(c+2.0_dp)*(c+3.0_dp)*w(1)&
      -(11.0_dp+c*(12.0_dp+c*3.0_dp))*w(2)&
      +3.0_dp*(c+2.0_dp)*w(3)-w(4))/6.0_dp,&
      (-c*(c+2.0_dp)*(c+3.0_dp)*w(1)&
      +(6.0_dp+c*(10.0_dp+c*3.0_dp))*w(2)&
      -(3.0_dp*c+5.0_dp)*w(3)+w(4))*0.50_dp,&
      (c*(c+1.0_dp)*(c+3.0_dp)*w(1)&
      -(3.0_dp*c*(8.0_dp+c*3.0_dp))*w(2)&
      +(3.0_dp*c+4.0_dp)*w(3)-w(4))*0.50_dp,&
      (-c*(c+1.0_dp)*(c+2.0_dp)*w(1)&
      +(2.0_dp+c*(6.0_dp+c*3.0_dp))*w(2)&
      -3.0_dp*(c+1.0_dp)*w(3)+w(4))/6.0_dp /)
    wold(1:4)=wnew(1:4)
  end do
else if (n == 3) then
  wnew(1:3)=kermom(hh+hh,3)
  w(1:3)= (/ wnew(1)-wold(1), hi*(wnew(2)-wold(2)),&
    hi**2*(wnew(3)-wold(3)) /)
  wghts(1:3)= (/ w(1)-1.50_dp*w(2)+0.50_dp*w(3),&
    2.0_dp*w(2)-w(3), 0.50_dp*(w(3)-w(2)) /)
else if (n == 2) then
  wnew(1:2)=kermom(hh,2)
  wghts(2)=hi*(wnew(2)-wold(2))
  wghts(1)=wnew(1)-wold(1)-wghts(2)
end if
END FUNCTION wghts

```

\* \* \*

```

MODULE kermom_info
USE nrtype
REAL(DP) :: kermom_x
END MODULE kermom_info

```

```

FUNCTION kermom(y,m)
USE nrtype
USE kermom_info
IMPLICIT NONE
REAL(DP), INTENT(IN) :: y
INTEGER(I4B), INTENT(IN) :: m
REAL(DP), DIMENSION(m) :: kermom
  Returns in kermom(1:m) the first m indefinite-integral moments of one row of the singular
  part of the kernel. (For this example, m is hard-wired to be 4.) The input variable y labels
  the column, while kermom_x (in the module kermom_info) is the row.
REAL(DP) :: x,d,df,clog,x2,x3,x4
x=kermom_x
if (y >= x) then
  d=y-x
  df=2.0_dp*sqrt(d)*d
  kermom(1:4) = (/ df/3.0_dp, df*(x/3.0_dp+d/5.0_dp),&

```

Use highest available order.

For another problem, you might change this lower limit.

This is called  $k$  in equation (18.3.5).

Set upper and lower limits for this step.

Last interval: go all the way to end.

Equation (18.3.4).

Equation (18.3.5).

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```

df*((x/3.0_dp + 0.4_dp*d)*x + d**2/7.0_dp),&
df*((x/3.0_dp + 0.6_dp*d)*x + 3.0_dp*d**2/7.0_dp)*x&
+ d**3/9.0_dp) /)
else
  x2=x**2
  x3=x2*x
  x4=x2*x2
  d=x-y
  clog=log(d)
  kermom(1:4) = (/ d*(clog-1.0_dp),&
-0.25_dp*(3.0_dp*x+y-2.0_dp*clog*(x+y))*d,&
(-11.0_dp*x3+y*(6.0_dp*x2+y*(3.0_dp*x+2.0_dp*y))&
+6.0_dp*clog*(x3-y**3))/18.0_dp,&
(-25.0_dp*x4+y*(12.0_dp*x3+y*(6.0_dp*x2+y*
(4.0_dp*x+3.0_dp*y)))+12.0_dp*clog*(x4-y**4))/48.0_dp /)
end if
END FUNCTION kermom

```



MODULE kermom\_info This module functions just like a common block to share the variable `kermom_x` with the routine `quadmx`.

\* \* \*

```

SUBROUTINE quadmx(a)
USE nrtype; USE nrutil, ONLY : arth,assert_eq,diagadd,outerprod
USE nr, ONLY : wwgths,kermom
USE kermom_info
IMPLICIT NONE
REAL(SP), DIMENSION(:, :), INTENT(OUT) :: a
  Constructs in the  $N \times N$  array a the quadrature matrix for an example Fredholm equation of
  the second kind. The nonsingular part of the kernel is computed within this routine, while
  the quadrature weights that integrate the singular part of the kernel are obtained via calls
  to wwgths. An external routine kermom, which supplies indefinite-integral moments of the
  singular part of the kernel, is passed to wwgths.
INTEGER(I4B) :: j,n
REAL(SP) :: h,x
REAL(SP), DIMENSION(size(a,1)) :: wt
n=assert_eq(size(a,1),size(a,2),'quadmx')
h=PI/(n-1)
do j=1,n
  x=(j-1)*h
  kermom_x=x Put x in the module kermom_info for use by kermom.
  wt(:)=wwgths(n,h,kermom) Part of nonsingular kernel.
  a(j,:)=wt(:) Put together all the pieces of the kernel.
end do
wt(:)=cos(arth(0,1,n)*h)
a(:, :)=a(:, :)*outerprod(wt(:),wt(:))
call diagadd(a,1.0_sp) Since equation of the second kind, there is diagonal
END SUBROUTINE quadmx piece independent of h.

```



call `diagadd...` See discussion of `diagadd` after `hqr` on p. 1234.

\* \* \*

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```

PROGRAM fredex
USE nrtype; USE nrutil, ONLY : arth
USE nr, ONLY : quadmx,ludcmp,lubksb
IMPLICIT NONE
INTEGER(I4B), PARAMETER :: N=40
INTEGER(I4B) :: j
INTEGER(I4B), DIMENSION(N) :: indx
REAL(SP) :: d
REAL(SP), DIMENSION(N) :: g,x
REAL(SP), DIMENSION(N,N) :: a

```

This sample program shows how to solve a Fredholm equation of the second kind using the product Nystrom method and a quadrature rule especially constructed for a particular, singular, kernel.

Parameter: N is the size of the grid.

```

call quadmx(a)           Make the quadrature matrix; all the action is here.
call ludcmp(a,indx,d)    Decompose the matrix.
x(:)=arth(0,1,n)*PI/(n-1)
g(:)=sin(x(:))           Construct the right-hand side, here sin x.
call lubksb(a,indx,g)    Backsubstitute.
do j=1,n                 Write out the solution.
  write (*,*) j,x(j),g(j)
end do
write (*,*) 'normal completion'
END PROGRAM fredex

```

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## Chapter B19. Partial Differential Equations

```

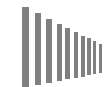
SUBROUTINE sor(a,b,c,d,e,f,u,rjac)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
IMPLICIT NONE
REAL(DP), DIMENSION(:,:) , INTENT(IN) :: a,b,c,d,e,f
REAL(DP), DIMENSION(:,:) , INTENT(INOUT) :: u
REAL(DP), INTENT(IN) :: rjac
INTEGER(I4B), PARAMETER :: MAXITS=1000
REAL(DP), PARAMETER :: EPS=1.0e-5_dp
    Successive overrelaxation solution of equation (19.5.25) with Chebyshev acceleration. a, b,
    c, d, e, and f are input as the coefficients of the equation, each dimensioned to the grid
    size  $J \times J$ . u is input as the initial guess to the solution, usually zero, and returns with the
    final value. rjac is input as the spectral radius of the Jacobi iteration, or an estimate of
    it. Double precision is a good idea for  $J$  bigger than about 25.
REAL(DP), DIMENSION(size(a,1),size(a,1)) :: resid
INTEGER(I4B) :: jmax,jm1,jm2,jm3,n
REAL(DP) :: anorm,anormf,omega
jmax=assert_eq(/size(a,1),size(a,2),size(b,1),size(b,2), &
    size(c,1),size(c,2),size(d,1),size(d,2),size(e,1), &
    size(e,2),size(f,1),size(f,2),size(u,1),size(u,2)/), 'sor')
jm1=jmax-1
jm2=jmax-2
jm3=jmax-3
anormf=sum(abs(f(2:jm1,2:jm1)))
    Compute initial norm of residual and terminate iteration when norm has been reduced by a
    factor EPS. This computation assumes initial u is zero.
omega=1.0
do n=1,MAXITS
    First do the even-even and odd-odd squares of the grid, i.e., the red squares of the
    checkerboard:
    resid(2:jm1:2,2:jm1:2)=a(2:jm1:2,2:jm1:2)*u(3:jmax:2,2:jm1:2)+&
        b(2:jm1:2,2:jm1:2)*u(1:jm2:2,2:jm1:2)+&
        c(2:jm1:2,2:jm1:2)*u(2:jm1:2,3:jmax:2)+&
        d(2:jm1:2,2:jm1:2)*u(2:jm1:2,1:jm2:2)+&
        e(2:jm1:2,2:jm1:2)*u(2:jm1:2,2:jm1:2)-f(2:jm1:2,2:jm1:2)
    u(2:jm1:2,2:jm1:2)=u(2:jm1:2,2:jm1:2)-omega*&
        resid(2:jm1:2,2:jm1:2)/e(2:jm1:2,2:jm1:2)
    resid(3:jm2:2,3:jm2:2)=a(3:jm2:2,3:jm2:2)*u(4:jm1:2,3:jm2:2)+&
        b(3:jm2:2,3:jm2:2)*u(2:jm3:2,3:jm2:2)+&
        c(3:jm2:2,3:jm2:2)*u(3:jm2:2,4:jm1:2)+&
        d(3:jm2:2,3:jm2:2)*u(3:jm2:2,2:jm3:2)+&
        e(3:jm2:2,3:jm2:2)*u(3:jm2:2,3:jm2:2)-f(3:jm2:2,3:jm2:2)
    u(3:jm2:2,3:jm2:2)=u(3:jm2:2,3:jm2:2)-omega*&
        resid(3:jm2:2,3:jm2:2)/e(3:jm2:2,3:jm2:2)
    omega=merge(1.0_dp/(1.0_dp-0.5_dp*rjac**2), &
        1.0_dp/(1.0_dp-0.25_dp*rjac**2*omega), n == 1)
    Now do even-odd and odd-even squares of the grid, i.e., the black squares of the checker-
    board:
    resid(3:jm2:2,2:jm1:2)=a(3:jm2:2,2:jm1:2)*u(4:jm1:2,2:jm1:2)+&
        b(3:jm2:2,2:jm1:2)*u(2:jm3:2,2:jm1:2)+&

```

```

      c(3:jm2:2,2:jm1:2)*u(3:jm2:2,3:jmax:2)+&
      d(3:jm2:2,2:jm1:2)*u(3:jm2:2,1:jm2:2)+&
      e(3:jm2:2,2:jm1:2)*u(3:jm2:2,2:jm1:2)-f(3:jm2:2,2:jm1:2)
      u(3:jm2:2,2:jm1:2)=u(3:jm2:2,2:jm1:2)-omega*&
      resid(3:jm2:2,2:jm1:2)/e(3:jm2:2,2:jm1:2)
      resid(2:jm1:2,3:jm2:2)=a(2:jm1:2,3:jm2:2)*u(3:jmax:2,3:jm2:2)+&
      b(2:jm1:2,3:jm2:2)*u(1:jm2:2,3:jm2:2)+&
      c(2:jm1:2,3:jm2:2)*u(2:jm1:2,4:jm1:2)+&
      d(2:jm1:2,3:jm2:2)*u(2:jm1:2,2:jm3:2)+&
      e(2:jm1:2,3:jm2:2)*u(2:jm1:2,3:jm2:2)-f(2:jm1:2,3:jm2:2)
      u(2:jm1:2,3:jm2:2)=u(2:jm1:2,3:jm2:2)-omega*&
      resid(2:jm1:2,3:jm2:2)/e(2:jm1:2,3:jm2:2)
      omega=1.0_dp/(1.0_dp-0.25_dp*rjac**2*omega)
      anorm=sum(abs(resid(2:jm1,2:jm1)))
      if (anorm < EPS*anormf) exit
end do
if (n > MAXITS) call nrerror('MAXITS exceeded in sor')
END SUBROUTINE sor

```



Red-black iterative schemes like the one used in `sor` are easily parallelizable. Updating the red grid points requires information only from the black grid points, so they can all be updated independently. Similarly the black grid points can all be updated independently. Since nearest neighbors are involved in the updating, communication costs can be kept to a minimum.

There are several possibilities for coding the red-black iteration in a data parallel way using only Fortran 90 and no parallel language extensions. One way is to define an  $N \times N$  logical mask `red` that is true on the red grid points and false on the black. Then each iteration consists of an update governed by a `where(red) ... end where block` and a `where(.not. red) ... end where block`. We have chosen a more direct coding that avoids the need for storage of the array `red`. The red update corresponds to the even-even and odd-odd grid points, the black to the even-odd and odd-even points. We can code each of these four cases directly with array sections, as in the routine above.

The array section notation used in `sor` is rather dense and hard to read. We could use pointer aliases to try to simplify things, but since each array section is different, we end up merely giving names to each term that was there all along. Pointer aliases do help if we code `sor` using a logical mask. Since there may be machines on which this version is faster, and since it is of some pedagogic interest, we give the alternative code:

```

SUBROUTINE sor_mask(a,b,c,d,e,f,u,rjac)
USE nrtyp; USE nrutil, ONLY : assert_eq,nrerror
IMPLICIT NONE
REAL(DP), DIMENSION(:,:), TARGET, INTENT(IN) :: a,b,c,d,e,f
REAL(DP), DIMENSION(:,:), TARGET, INTENT(INOUT) :: u
REAL(DP), INTENT(IN) :: rjac
INTEGER(I4B), PARAMETER :: MAXITS=1000
REAL(DP), PARAMETER :: EPS=1.0e-5_dp
REAL(DP), DIMENSION(:,:), ALLOCATABLE :: resid
REAL(DP), DIMENSION(:,:), POINTER :: u_int,u_down,u_up,u_left,&
  u_right,a_int,b_int,c_int,d_int,e_int,f_int
INTEGER(I4B) :: jmax,jm1,jm2,jm3,n
REAL(DP) anorm,anormf,omega
LOGICAL, DIMENSION(:,:), ALLOCATABLE :: red
jmax=assert_eq(/size(a,1),size(a,2),size(b,1),size(b,2), &

```

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```

      size(c,1),size(c,2),size(d,1),size(d,2),size(e,1), &
      size(e,2),size(f,1),size(f,2),size(u,1),size(u,2)/), 'sor')
jm1=jmax-1
jm2=jmax-2
jm3=jmax-3
allocate(resid(jm2,jm2),red(jm2,jm2))      Interior is (jmax - 2) × (jmax - 2).
red=.false.
red(1:jm2:2,1:jm2:2)=.true.
red(2:jm3:2,2:jm3:2)=.true.
u_int=>u(2:jm1,2:jm1)
u_down=>u(3:jmax,2:jm1)
u_up=>u(1:jm2,2:jm1)
u_left=>u(2:jm1,1:jm2)
u_right=>u(2:jm1,3:jmax)
a_int=>a(2:jm1,2:jm1)
b_int=>b(2:jm1,2:jm1)
c_int=>c(2:jm1,2:jm1)
d_int=>d(2:jm1,2:jm1)
e_int=>e(2:jm1,2:jm1)
f_int=>f(2:jm1,2:jm1)
anormf=sum(abs(f_int))
omega=1.0
do n=1,MAXITS
  where(red)
    resid=a_int*u_down+b_int*u_up+c_int*u_right+&
          d_int*u_left+e_int*u_int-f_int
    u_int=u_int-omega*resid/e_int
  end where
  omega=merge(1.0_dp/(1.0_dp-0.5_dp*rjac**2), &
             1.0_dp/(1.0_dp-0.25_dp*rjac**2*omega), n == 1)
  where(.not.red)
    resid=a_int*u_down+b_int*u_up+c_int*u_right+&
          d_int*u_left+e_int*u_int-f_int
    u_int=u_int-omega*resid/e_int
  end where
  omega=1.0_dp/(1.0_dp-0.25_dp*rjac**2*omega)
  anorm=sum(abs(resid))
  if(anorm < EPS*anormf)exit
end do
deallocate(resid,red)
if (n > MAXITS) call nrerror('MAXITS exceeded in sor')
END SUBROUTINE sor_mask

```

\* \* \*

```

SUBROUTINE mglin(u,ncycle)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
USE nr, ONLY : interp,rstrct,slvsml
IMPLICIT NONE
REAL(DP), DIMENSION(:,:) , INTENT(INOUT) :: u
INTEGER(I4B), INTENT(IN) :: ncycle
  Full Multigrid Algorithm for solution of linear elliptic equation, here the model problem
  (19.0.6). On input u contains the right-hand side  $\rho$  in an  $N \times N$  array, while on output
  it returns the solution. The dimension  $N$  is related to the number of grid levels used in
  the solution, ng below, by  $N = 2**ng+1$ . ncycle is the number of V-cycles to be used
  at each level.
INTEGER(I4B) :: j,jcycle,n,ng,ngrid,nn
TYPE ptr2d                                     Define a type so we can have an array of pointers
REAL(DP), POINTER :: a(:,:)                  to arrays of grid variables.
END TYPE ptr2d
TYPE(ptr2d), ALLOCATABLE :: rho(:)

```

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```

REAL(DP), DIMENSION(:, :), POINTER :: uj,uj_1
n=assert_eq(size(u,1),size(u,2),'mglin')
ng=nint(log(n-1.0)/log(2.0))
if (n /= 2**ng+1) call nrerror('n-1 must be a power of 2 in mglin')
allocate(rho(ng))
nn=n
ngrid=ng
allocate(rho(ngrid)%a(nn,nn))           Allocate storage for r.h.s. on grid ng,
rho(ngrid)%a=u                          and fill it with the input r.h.s.
do                                       Similarly allocate storage and fill r.h.s. on all coarse
    if (nn <= 3) exit                    grids by restricting from finer grids.
    nn=nn/2+1
    ngrid=ngrid-1
    allocate(rho(ngrid)%a(nn,nn))
    rho(ngrid)%a=rstrct(rho(ngrid+1)%a)
end do
nn=3
allocate(uj(nn,nn))
call slvsml(uj,rho(1)%a)                 Initial solution on coarsest grid.
do j=2,ng                                 Nested iteration loop.
    nn=2*nn-1
    uj_1=>uj
    allocate(uj(nn,nn))
    uj=interp(uj_1)                       Interpolate from grid j-1 to next finer grid j.
    deallocate(uj_1)
    do jcycle=1,ncycle                     V-cycle loop.
        call mg(j,uj,rho(j)%a)
    end do
end do
u=uj                                       Return solution in u.
deallocate(uj)
do j=1,ng
    deallocate(rho(j)%a)
end do
deallocate(rho)
CONTAINS
RECURSIVE SUBROUTINE mg(j,u,rhs)
USE nrtype
USE nr, ONLY : interp,relax,resid,rstrct,slvsml
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: j
REAL(DP), DIMENSION(:, :), INTENT(INOUT) :: u
REAL(DP), DIMENSION(:, :), INTENT(IN) :: rhs
INTEGER(I4B), PARAMETER :: NPRE=1,NPOST=1
    Recursive multigrid iteration. On input, j is the current level, u is the current value of the
    solution, and rhs is the right-hand side. On output u contains the improved solution at the
    current level.
    Parameters: NPRE and NPOST are the number of relaxation sweeps before and after the
    coarse-grid correction is computed.
INTEGER(I4B) :: jpost,jpre
REAL(DP), DIMENSION((size(u,1)+1)/2,(size(u,1)+1)/2) :: res,v
if (j == 1) then                          Bottom of V: Solve on coarsest grid.
    call slvsml(u,rhs)
else                                       On downward stroke of the V.
    do jpre=1,NPRE                          Pre-smoothing.
        call relax(u,rhs)
    end do
    res=rstrct(resid(u,rhs))                Restriction of the residual is the next r.h.s.
    v=0.0                                   Zero for initial guess in next relaxation.
    call mg(j-1,v,res)                      Recursive call for the coarse grid correction.
    u=interp(v)                              On upward stroke of V.
    do jpost=1,NPOST                          Post-smoothing.
        call relax(u,rhs)
    end do
end if
end subroutine mg

```

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```

    end do
  end if
END SUBROUTINE mg
END SUBROUTINE mglin

```

**f90** The Fortran 90 version of `mglin` (and of `mgfas` below) is quite different from the Fortran 77 version, although the algorithm is identical. First, we use a recursive implementation. This makes the code much more transparent. It also makes the memory management much better: we simply define the new arrays `res` and `v` as automatic arrays of the appropriate dimension on each recursive call to a coarser level. And a third benefit is that it is trivial to change the code to increase the number of multigrid iterations done at level  $j - 1$  by each iteration at level  $j$ , i.e., to set the quantity  $\gamma$  in §19.6 to a value greater than one. (Recall that  $\gamma = 1$  as chosen in `mglin` gives V-cycles,  $\gamma = 2$  gives W-cycles.) Simply enclose the recursive call in a `do-loop`:

```

do i=1,merge(gamma,1,j /= 2)
  call mg(j-1,v,res)
end do

```

The `merge` expression ensures that there is no more than one call to the coarsest level, where the problem is solved exactly.

A second improvement in the Fortran 90 version is to make the procedures `resid`, `interp`, and `rstrct` functions instead of subroutines. This allows us to code the algorithm exactly as written mathematically.

`TYPE ptr2d...` The right-hand-side quantity  $\rho$  is supplied initially on the finest grid in the argument `u`. It has to be defined on the coarser grids by restriction, and then supplied as the right-hand side to `mg` in the nested iteration loop. This loop starts at the coarsest level and progresses up to the finest level. We thus need a data structure to store  $\rho$  on all the grid levels. A convenient way to implement this in Fortran 90 is to define a type `ptr2d`, a pointer to a two-dimensional array that represents a grid. (In three dimensions, a would of course be three-dimensional.) We then declare the variable  $\rho$  as an allocatable array of type `ptr2d`:

```

TYPE(ptr2d), ALLOCATABLE :: rho(:)

```

Next we allocate storage for  $\rho$  on each level. The number of levels or grids, `ng`, is known only at run time:

```

allocate(rho(ng))

```

Then we allocate storage as needed on particular sized grids. For example,

```

allocate(rho(ngrid)%a(nn,nn))

```

allocates an  $nn \times nn$  grid for  $\rho$  on grid number `ngrid`.

The various subsidiary routines of `mglin` such as `rstrct` and `interp` are written to accept two-dimensional arrays as arguments. With the data structure we've employed, using these routines is simple. For example,

```

rho(ngrid)%a=rstrct(rho(ngrid+1)%a)

```

will restrict  $\rho$  from the grid `ngrid+1` to the grid `ngrid`. The statement is even more readable if we mentally ignore the `%a` that is tagged onto each variable. (If

we actually did omit %a in the code, the compiler would think we meant the array of type ptr2d instead of the grid array.)

Note that while Fortran 90 does not allow you to declare an array of pointers directly, you can achieve the same effect by declaring your own type, as we have done with ptr2d in this example.

```

FUNCTION rstruct(uf)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(DP), DIMENSION(:, :), INTENT(IN) :: uf
REAL(DP), DIMENSION((size(uf,1)+1)/2, (size(uf,1)+1)/2) :: rstruct
    Half-weighting restriction. If  $N_c$  is the coarse-grid dimension, the fine-grid solution is input
    in the  $(2N_c - 1) \times (2N_c - 1)$  array uf, the coarse-grid solution is returned in the  $N_c \times N_c$ 
    array rstruct.
INTEGER(I4B) :: nc, nf
nf=assert_eq(size(uf,1), size(uf,2), 'rstruct')
nc=(nf+1)/2
rstruct(2:nc-1, 2:nc-1)=0.5_dp*uf(3:nf-2:2, 3:nf-2:2)+0.125_dp*(&    Interior points.
    uf(4:nf-1:2, 3:nf-2:2)+uf(2:nf-3:2, 3:nf-2:2)+&
    uf(3:nf-2:2, 4:nf-1:2)+uf(3:nf-2:2, 2:nf-3:2))
rstruct(1:nc, 1)=uf(1:nf:2, 1)    Boundary points.
rstruct(1:nc, nc)=uf(1:nf:2, nf)
rstruct(1, 1:nc)=uf(1, 1:nf:2)
rstruct(nc, 1:nc)=uf(nf, 1:nf:2)
END FUNCTION rstruct

```

```

FUNCTION interp(uc)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(DP), DIMENSION(:, :), INTENT(IN) :: uc
REAL(DP), DIMENSION(2*size(uc,1)-1, 2*size(uc,1)-1) :: interp
    Coarse-to-fine prolongation by bilinear interpolation. If  $N_f$  is the fine-grid dimension and
     $N_c$  the coarse-grid dimension, then  $N_f = 2N_c - 1$ . The coarse-grid solution is input as uc,
    the fine-grid solution is returned in interp.
INTEGER(I4B) :: nc, nf
nc=assert_eq(size(uc,1), size(uc,2), 'interp')
nf=2*nc-1
interp(1:nf:2, 1:nf:2)=uc(1:nc, 1:nc)
    Do elements that are copies.
interp(2:nf-1:2, 1:nf:2)=0.5_dp*(interp(3:nf:2, 1:nf:2)+ &
    interp(1:nf-2:2, 1:nf:2))
    Do odd-numbered columns, interpolating vertically.
interp(1:nf, 2:nf-1:2)=0.5_dp*(interp(1:nf, 3:nf:2)+interp(1:nf, 1:nf-2:2))
    Do even-numbered columns, interpolating horizontally.
END FUNCTION interp

```

```

SUBROUTINE slvsml(u, rhs)
USE nrtype
IMPLICIT NONE
REAL(DP), DIMENSION(3,3), INTENT(OUT) :: u
REAL(DP), DIMENSION(3,3), INTENT(IN) :: rhs
    Solution of the model problem on the coarsest grid, where  $h = \frac{1}{2}$ . The right-hand side is
    input in rhs(1:3, 1:3) and the solution is returned in u(1:3, 1:3).
REAL(DP) :: h
u=0.0
h=0.5_dp
u(2,2)=-h*h*rhs(2,2)/4.0_dp
END SUBROUTINE slvsml

```

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```

SUBROUTINE relax(u,rhs)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(DP), DIMENSION(:,:), INTENT(INOUT) :: u
REAL(DP), DIMENSION(:,:), INTENT(IN) :: rhs
  Red-black Gauss-Seidel relaxation for model problem. The current value of the solution u is
  updated, using the right-hand-side function rhs. u and rhs are square arrays of the same
  odd dimension.
INTEGER(I4B) :: n
REAL(DP) :: h,h2
n=assert_eq(size(u,1),size(u,2),size(rhs,1),size(rhs,2),'relax')
h=1.0_dp/(n-1)
h2=h*h
  First do the even-even and odd-odd squares of the grid, i.e., the red squares of the checker-
  board:
u(2:n-1:2,2:n-1:2)=0.25_dp*(u(3:n:2,2:n-1:2)+u(1:n-2:2,2:n-1:2)+&
  u(2:n-1:2,3:n:2)+u(2:n-1:2,1:n-2:2)-h2*rhs(2:n-1:2,2:n-1:2))
u(3:n-2:2,3:n-2:2)=0.25_dp*(u(4:n-1:2,3:n-2:2)+u(2:n-3:2,3:n-2:2)+&
  u(3:n-2:2,4:n-1:2)+u(3:n-2:2,2:n-3:2)-h2*rhs(3:n-2:2,3:n-2:2))
  Now do even-odd and odd-even squares of the grid, i.e., the black squares of the checker-
  board:
u(3:n-2:2,2:n-1:2)=0.25_dp*(u(4:n-1:2,2:n-1:2)+u(2:n-3:2,2:n-1:2)+&
  u(3:n-2:2,3:n:2)+u(3:n-2:2,1:n-2:2)-h2*rhs(3:n-2:2,2:n-1:2))
u(2:n-1:2,3:n-2:2)=0.25_dp*(u(3:n:2,3:n-2:2)+u(1:n-2:2,3:n-2:2)+&
  u(2:n-1:2,4:n-1:2)+u(2:n-1:2,2:n-3:2)-h2*rhs(2:n-1:2,3:n-2:2))
END SUBROUTINE relax

```



See the discussion of red-black relaxation after sor on p. 1333.

```

FUNCTION resid(u,rhs)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(DP), DIMENSION(:,:), INTENT(IN) :: u,rhs
REAL(DP), DIMENSION(size(u,1),size(u,1)) :: resid
  Returns minus the residual for the model problem. Input quantities are u and rhs, while
  the residual is returned in resid. All three quantities are square arrays with the same odd
  dimension.
INTEGER(I4B) :: n
REAL(DP) :: h,h2i
n=assert_eq(/size(u,1),size(u,2),size(rhs,1),size(rhs,2)/),'resid')
n=size(u,1)
h=1.0_dp/(n-1)
h2i=1.0_dp/(h*h)
resid(2:n-1,2:n-1)=-h2i*(u(3:n,2:n-1)+u(1:n-2,2:n-1)+u(2:n-1,3:n)+&
  u(2:n-1,1:n-2)-4.0_dp*u(2:n-1,2:n-1))+rhs(2:n-1,2:n-1)  Interior points.
resid(1:n,1)=0.0                                             Boundary points.
resid(1:n,n)=0.0
resid(1,1:n)=0.0
resid(n,1:n)=0.0
END FUNCTION resid

```

★ ★ ★

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```

SUBROUTINE mgfas(u,maxcyc)
USE nrtype; USE nrutil, ONLY : assert_eq,nrerror
USE nr, ONLY : interp,lop,rstrct,slvsm2
IMPLICIT NONE
REAL(DP), DIMENSION(:,:), INTENT(INOUT) :: u
INTEGER(I4B), INTENT(IN) :: maxcyc
  Full Multigrid Algorithm for FAS solution of nonlinear elliptic equation, here equation
  (19.6.44). On input u contains the right-hand side  $\rho$  in an  $N \times N$  array, while on out-
  put it returns the solution. The dimension  $N$  is related to the number of grid levels used
  in the solution, ng below, by  $N = 2**ng+1$ . maxcyc is the maximum number of V-cycles
  to be used at each level.
INTEGER(I4B) :: j,jcycle,n,ng,ngrid,nn
REAL(DP) :: res,trerr
TYPE ptr2d
  REAL(DP), POINTER :: a(:,:)
END TYPE ptr2d
TYPE(ptr2d), ALLOCATABLE :: rho(:)
REAL(DP), DIMENSION(:,:), POINTER :: uj,uj_1
n=assert_eq(size(u,1),size(u,2),'mgfas')
ng=nint(log(n-1.0)/log(2.0))
if (n /= 2**ng+1) call nrerror('n-1 must be a power of 2 in mgfas')
allocate(rho(ng))
nn=n
ngrid=ng
allocate(rho(ngrid)%a(nn,nn))
rho(ngrid)%a=u
do
  if (nn <= 3) exit
  nn=nn/2+1
  ngrid=ngrid-1
  allocate(rho(ngrid)%a(nn,nn))
  rho(ngrid)%a=rstrct(rho(ngrid+1)%a)
end do
nn=3
allocate(uj(nn,nn))
call slvsm2(uj,rho(1)%a)
do j=2,ng
  nn=2*nn-1
  uj_1=>uj
  allocate(uj(nn,nn))
  uj=interp(uj_1)
  deallocate(uj_1)
  do jcycle=1,maxcyc
    call mg(j,uj,trerr=trerr)
    res=sqrt(sum((lop(uj)-rho(j)%a)**2))/nn
    if (res < trerr) exit
  end do
end do
u=uj
deallocate(uj)
do j=1,ng
  deallocate(rho(j)%a)
end do
deallocate(rho)
CONTAINS
RECURSIVE SUBROUTINE mg(j,u,rhs,trerr)
USE nrtype
USE nr, ONLY : interp,lop,relax2,rstrct,slvsm2
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: j
REAL(DP), DIMENSION(:,:), INTENT(INOUT) :: u
REAL(DP), DIMENSION(:,:), INTENT(IN), OPTIONAL :: rhs
REAL(DP), INTENT(OUT), OPTIONAL :: trerr

```

Define a type so we can have an array of pointers to arrays of grid variables.

Allocate storage for r.h.s. on grid ng, and fill it with  $\rho$  from the fine grid. Similarly allocate storage and fill r.h.s. by restriction on all coarse grids.

Initial solution on coarsest grid. Nested iteration loop.

Interpolate from grid j-1 to next finer grid j. V-cycle loop.

Form residual  $\|d_h\|$ . No more V-cycles needed if residual small enough.

Return solution in u.

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```

INTEGER(I4B), PARAMETER :: NPRE=1,NPOST=1
REAL(DP), PARAMETER :: ALPHA=0.33_dp
Recursive multigrid iteration. On input, j is the current level and u is the current value
of the solution. For the first call on a given level, the right-hand side is zero, and the
optional argument rhs is not present. Subsequent recursive calls supply a nonzero rhs as
in equation (19.6.33). On output u contains the improved solution at the current level.
When the first call on a given level is made, the relative truncation error  $\tau$  is returned in
the optional argument trerr.
Parameters: NPRE and NPOST are the number of relaxation sweeps before and after the
coarse-grid correction is computed; ALPHA relates the estimated truncation error to the
norm of the residual.
INTEGER(I4B) :: jpost,jpre
REAL(DP), DIMENSION((size(u,1)+1)/2,(size(u,1)+1)/2) :: v,ut,tau
if (j == 1) then                                Bottom of V: Solve on coarsest grid.
  call slvsm2(u,rhs+rho(j)%a)
else
  do jpre=1,NPRE                                On downward stoke of the V.
    Pre-smoothing.
    if (present(rhs)) then
      call relax2(u,rhs+rho(j)%a)
    else
      call relax2(u,rho(j)%a)
    end if
  end do
  ut=rstrct(u)                                   $\mathcal{R}\tilde{u}_h$ .
  v=ut                                          Make a copy in v.
  if (present(rhs)) then
    tau=lop(ut)-rstrct(lop(u)-rhs)              Form  $\tilde{\tau}_h + f_H = \mathcal{L}_H(\mathcal{R}\tilde{u}_h) - \mathcal{R}\mathcal{L}_h(\tilde{u}_h) + f_H$ .
  else
    tau=lop(ut)-rstrct(lop(u))
    trerr=ALPHA*sqrt(sum(tau**2))/size(tau,1)   Estimate truncation error  $\tau$ .
  end if
  call mg(j-1,v,tau)                            Recursive call for the coarse-grid correction.
  u=u+interp(v-ut)                               $\tilde{u}_h^{\text{new}} = \tilde{u}_h + \mathcal{P}(\tilde{u}_H - \mathcal{R}\tilde{u}_h)$ 
  do jpost=1,NPOST
    if (present(rhs)) then
      call relax2(u,rhs+rho(j)%a)
    else
      call relax2(u,rho(j)%a)
    end if
  end do
end if
END SUBROUTINE mg
END SUBROUTINE mgfas

```



See the discussion after `mg1in` on p. 1336 for the changes made in the Fortran 90 versions of the multigrid routines from the Fortran 77 versions.

`TYPE ptr2d...` See discussion after `mg1in` on p. 1336.

RECURSIVE SUBROUTINE `mg(j,u,rhs,trerr)` Recall that `mgfas` solves the problem  $\mathcal{L}u = 0$ , but that nonzero right-hand sides appear during the solution. We implement this by having `rhs` be an optional argument to `mg`. On the first call at a given level `j`, the right-hand side is zero and so you just omit it from the calling sequence. On the other hand, the truncation error `trerr` is computed only on the first call at a given level, so it is also an optional argument that does get supplied on the first call:

```
call mg(j,uj,trerr=trerr)
```

The second and subsequent calls at a given level supply `rhs=tau` but omit `trerr`:

```
call mg(j-1,v,tau)
```

Note that we can omit the keyword `rhs` from this call because the variable `tau` appears in the correct order of arguments. However, in the other call above, the keyword `trerr` must be supplied because `rhs` has been omitted.

The example equation that is solved in `mgfas`, equation (19.6.44), is almost linear, and the code is set up so that  $\rho$  is supplied as part of the right-hand side instead of pulling it over to the left-hand side. The variable `rho` is visible to `mg` by host association. Note also that the function `lop` does not include `rho`, but that the statement

```
tau=lop(ut)-rstrct(lop(u))
```

is nevertheless correct, since `rho` would cancel out if it were included in `lop`. This feature is also true in the Fortran 77 code.

```
SUBROUTINE relax2(u,rhs)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(DP), DIMENSION(:,:) , INTENT(INOUT) :: u
REAL(DP), DIMENSION(:,:) , INTENT(IN) :: rhs
  Red-black Gauss-Seidel relaxation for equation (19.6.44). The current value of the solution
  u is updated, using the right-hand-side function rhs. u and rhs are square arrays of the
  same odd dimension.
INTEGER(I4B) :: n
REAL(DP) :: foh2,h,h2i
REAL(DP) :: res(size(u,1),size(u,1))
n=assert_eq(size(u,1),size(u,2),size(rhs,1),size(rhs,2),'relax2')
h=1.0_dp/(n-1)
h2i=1.0_dp/(h*h)
foh2=-4.0_dp*h2i
  First do the even-even and odd-odd squares of the grid, i.e., the red squares of the checker-
  board:
res(2:n-1:2,2:n-1:2)=h2i*(u(3:n-2,2:n-1:2)+u(1:n-2:2,2:n-1:2)+&
  u(2:n-1:2,3:n-2)+u(2:n-1:2,1:n-2:2)-4.0_dp*u(2:n-1:2,2:n-1:2))&
  +u(2:n-1:2,2:n-1:2)**2-rhs(2:n-1:2,2:n-1:2)
u(2:n-1:2,2:n-1:2)=u(2:n-1:2,2:n-1:2)-res(2:n-1:2,2:n-1:2)/&
  (foh2+2.0_dp*u(2:n-1:2,2:n-1:2))
res(3:n-2:2,3:n-2:2)=h2i*(u(4:n-1:2,3:n-2:2)+u(2:n-3:2,3:n-2:2)+&
  u(3:n-2:2,4:n-1:2)+u(3:n-2:2,2:n-3:2)-4.0_dp*u(3:n-2:2,3:n-2:2))&
  +u(3:n-2:2,3:n-2:2)**2-rhs(3:n-2:2,3:n-2:2)
u(3:n-2:2,3:n-2:2)=u(3:n-2:2,3:n-2:2)-res(3:n-2:2,3:n-2:2)/&
  (foh2+2.0_dp*u(3:n-2:2,3:n-2:2))
  Now do even-odd and odd-even squares of the grid, i.e., the black squares of the checker-
  board:
res(3:n-2:2,2:n-1:2)=h2i*(u(4:n-1:2,2:n-1:2)+u(2:n-3:2,2:n-1:2)+&
  u(3:n-2:2,3:n-2)+u(3:n-2:2,1:n-2:2)-4.0_dp*u(3:n-2:2,2:n-1:2))&
  +u(3:n-2:2,2:n-1:2)**2-rhs(3:n-2:2,2:n-1:2)
u(3:n-2:2,2:n-1:2)=u(3:n-2:2,2:n-1:2)-res(3:n-2:2,2:n-1:2)/&
  (foh2+2.0_dp*u(3:n-2:2,2:n-1:2))
res(2:n-1:2,3:n-2:2)=h2i*(u(3:n-2,3:n-2:2)+u(1:n-2:2,3:n-2:2)+&
  u(2:n-1:2,4:n-1:2)+u(2:n-1:2,2:n-3:2)-4.0_dp*u(2:n-1:2,3:n-2:2))&
  +u(2:n-1:2,3:n-2:2)**2-rhs(2:n-1:2,3:n-2:2)
u(2:n-1:2,3:n-2:2)=u(2:n-1:2,3:n-2:2)-res(2:n-1:2,3:n-2:2)/&
  (foh2+2.0_dp*u(2:n-1:2,3:n-2:2))
END SUBROUTINE relax2
```



See the discussion of red-black relaxation after sor on p. 1333.

```

SUBROUTINE slvsm2(u,rhs)
USE nrtype
IMPLICIT NONE
REAL(DP), DIMENSION(3,3), INTENT(OUT) :: u
REAL(DP), DIMENSION(3,3), INTENT(IN) :: rhs
    Solution of equation (19.6.44) on the coarsest grid, where  $h = \frac{1}{5}$ . The right-hand side is
    input in rhs(1:3,1:3) and the solution is returned in u(1:3,1:3).
REAL(DP) :: disc,fact,h
u=0.0
h=0.5_dp
fact=2.0_dp/h**2
disc=sqrt(fact**2+rhs(2,2))
u(2,2)=-rhs(2,2)/(fact+disc)
END SUBROUTINE slvsm2

```

```

FUNCTION lop(u)
USE nrtype; USE nrutil, ONLY : assert_eq
IMPLICIT NONE
REAL(DP), DIMENSION(:, :), INTENT(IN) :: u
REAL(DP), DIMENSION(size(u,1),size(u,1)) :: lop
    Given u, returns  $\mathcal{L}_h(\tilde{u}_h)$  for equation (19.6.44). u and lop are square arrays of the same
    odd dimension.
INTEGER(I4B) :: n
REAL(DP) :: h,h2i
n=assert_eq(size(u,1),size(u,2),'lop')
h=1.0_dp/(n-1)
h2i=1.0_dp/(h*h)
lop(2:n-1,2:n-1)=h2i*(u(3:n,2:n-1)+u(1:n-2,2:n-1)+u(2:n-1,3:n)+&
    u(2:n-1,1:n-2)-4.0_dp*u(2:n-1,2:n-1))+u(2:n-1,2:n-1)**2   Interior points.
lop(1:n,1)=0.0                                                    Boundary points.
lop(1:n,n)=0.0
lop(1,1:n)=0.0
lop(n,1:n)=0.0
END FUNCTION lop

```

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## Chapter B20. Less-Numerical Algorithms

**f90** Volume 1's Fortran 77 routine `machar` performed various clever contortions (due to Cody, Malcolm, and others) to discover the underlying properties of a machine's floating-point representation. Fortran 90, by contrast, provides a built-in set of "numeric inquiry functions" that accomplish the same goal. The routine `machar` included here makes use of these and is included largely for compatibility with the previous version.

```
SUBROUTINE machar(ibeta,it,irnd,ngrd,machep,negep,iexp,minexp,&
    maxexp,eps,epsneg,xmin,xmax)
USE nrtype
IMPLICIT NONE
INTEGER(I4B), INTENT(OUT) :: ibeta,iexp,irnd,it,machep,maxexp,minexp,negep,ngrd
REAL(SP), INTENT(OUT) :: eps,epsneg,xmax,xmin
REAL(SP), PARAMETER :: RX=1.0
```

Determines and returns machine-specific parameters affecting floating-point arithmetic. Returned values include `ibeta`, the floating-point radix; `it`, the number of base-`ibeta` digits in the floating-point mantissa; `eps`, the smallest positive number that, added to 1.0, is not equal to 1.0; `epsneg`, the smallest positive number that, subtracted from 1.0, is not equal to 1.0; `xmin`, the smallest representable positive number; and `xmax`, the largest representable positive number. See text for description of other returned parameters. Change all `REAL(SP)` declarations to `REAL(DP)` to find double-precision parameters.

```
REAL(SP) :: a,beta,betah,one,temp,tempa,two,zero
ibeta=radix(RX)           Most of the parameters are easily determined
it=digits(RX)            from intrinsic functions.
machep=exponent(nearest(RX,RX)-RX)-1
negep=exponent(nearest(RX,-RX)-RX)-1
minexp=minexponent(RX)-1
maxexp=maxexponent(RX)
iexp=nint(log(real(maxexp-minexp+2,sp))/log(2.0_sp))
eps=real(ibeta,sp)**machep
epsneg=real(ibeta,sp)**negep
xmax=huge(RX)
xmin=tiny(RX)
one=RX                    Determine irnd.
two=one+one
zero=one-one
beta=real(ibeta,sp)
a=beta**(-negep)
irnd=0
betah=beta/two
temp=a+betah
if (temp-a /= zero) irnd=1
tempa=a+beta
temp=tempa+betah
if ((irnd == 0) .and. (temp-tempa /= zero)) irnd=2
ngrd=0                    Determine ngrd.
```

```

temp=one+eps
if ((irnd == 0) .and. (temp*one-one /= zero)) ngrd=1
temp=xmin/two
if (temp /= zero) irnd=irnd+3          Adjust irnd to reflect partial underflow.
END SUBROUTINE machar

```

\* \* \*

```

FUNCTION igray(n,is)
USE nrtype
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n,is
INTEGER(I4B) :: igray
  For zero or positive values of is, return the Gray code of n; if is is negative, return the
  inverse Gray code of n.
INTEGER(I4B) :: idiv,ish
if (is >= 0) then          This is the easy direction!
  igray=ieor(n,n/2)
else
  This is the more complicated direction: In hierarchical stages,
  starting with a one-bit right shift, cause each bit to be
  XORed with all more significant bits.
  ish=-1
  igray=n
  do
    idiv=ishft(igray,ish)
    igray=ieor(igray,idiv)
    if (idiv <= 1 .or. ish == -16) RETURN
    ish=ish+ish          Double the amount of shift on the next cycle.
  end do
end if
END FUNCTION igray

```

\* \* \*

```

FUNCTION icrc(crc,buf,jinit,jrev)
USE nrtype
IMPLICIT NONE
CHARACTER(1), DIMENSION(:), INTENT(IN) :: buf
INTEGER(I2B), INTENT(IN) :: crc,jinit
INTEGER(I4B), INTENT(IN) :: jrev
INTEGER(I2B) :: icrc
  Computes a 16-bit Cyclic Redundancy Check for an array buf of bytes, using any of several
  conventions as determined by the settings of jinit and jrev (see accompanying table).
  The result is returned both as an integer icrc and as a 2-byte array crc. If jinit is neg-
  ative, then crc is used on input to initialize the remainder register, in effect concatenating
  buf to the previous call.
INTEGER(I4B), SAVE :: init=0
INTEGER(I2B) :: j,cword,ich
INTEGER(I2B), DIMENSION(0:255), SAVE :: icrc1,icrc2,rchr
INTEGER(I2B), DIMENSION(0:15) :: it = &          Table of 4-bit bit-reverses.
  (/ 0,8,4,12,2,10,6,14,1,9,5,13,3,11,7,15 /)
if (init == 0) then          Do we need to initialize tables?
  init=1
  do j=0,255
    The two tables are: CRCs of all characters,
    icrc1(j)=icrc1(ishft(j,8),char(0))          and bit-reverses of all characters.
    rchr(j)=ishft(it(iand(j,15_I2B)),4)+it(ishft(j,-4))
  end do
end if
cword=crc
if (jinit >= 0) then          Initialize the remainder register.
  cword=ior(jinit,ishft(jinit,8))

```

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```

else if (jrev < 0) then                If not initializing, do we reverse the register?
  cword=ior(rchr(hibyte()),ishft(rchr(lobyte()),8))
end if
do j=1,size(buf)                       Main loop over the characters in the array.
  ich=ichar(buf(j))
  if (jrev < 0) ich=rchr(ich)
  cword=ieor(icrc1(ieor(ich,hibyte()),ishft(lobyte(),8)))
end do
icrc=merge(cword, &                    Do we need to reverse the output?
  ior(rchr(hibyte()),ishft(rchr(lobyte()),8)), jrev >= 0)
CONTAINS
FUNCTION hibyte()
INTEGER(I2B) :: hibyte
  Extracts the high byte of the 2-byte integer cword.
hibyte = ishft(cword,-8)
END FUNCTION hibyte

FUNCTION lobyte()
INTEGER(I2B) :: lobyte
  Extracts the low byte of the 2-byte integer cword.
lobyte = iand(cword,255_I2B)
END FUNCTION lobyte

FUNCTION icrc1(crc,onech)
INTEGER(I2B), INTENT(IN) :: crc
CHARACTER(1), INTENT(IN) :: onech
INTEGER(I2B) :: icrc1
  Given a remainder up to now, return the new CRC after one character is added. This routine is
  functionally equivalent to icrc(,-1,1), but slower. It is used by icrc to initialize its table.
INTEGER(I2B) :: i,ich, bit16, ccitt
DATA bit16,ccitt /Z'8000', Z'1021'/
ich=ichar(onech)                       Here is where the character is folded into the
icrc1=ieor(crc,ishft(ich,8))            register.
do i=1,8                                Here is where 8 one-bit shifts, and some XORs
  icrc1=merge(ieor(ccitt,ishft(icrc1,1)), & with the generator polynomial,
  ishft(icrc1,1), iand(icrc1,bit16) /= 0) are done.
end do
END FUNCTION icrc1
END FUNCTION icrc

```



The embedded functions `hibyte` and `lobyte` always act on the same variable, `cword`. Thus they don't need any explicit argument.

\* \* \*

```

FUNCTION decchk(string,ch)
USE nrtype; USE nrutil, ONLY : ifirstloc
IMPLICIT NONE
CHARACTER(1), DIMENSION(:), INTENT(IN) :: string
CHARACTER(1), INTENT(OUT) :: ch
LOGICAL(LGT) :: decchk
  Decimal check digit computation or verification. Returns as ch a check digit for appending
  to string. In this mode, ignore the returned logical value. If string already ends with
  a check digit, returns the function value .true. if the check digit is valid, otherwise
  .false. In this mode, ignore the returned value of ch. Note that string and ch contain
  ASCII characters corresponding to the digits 0-9, not byte values in that range. Other ASCII
  characters are allowed in string, and are ignored in calculating the check digit.
INTEGER(I4B) :: i,j,k,m
INTEGER(I4B) :: ip(0:9,0:7) = reshape((/ &      Group multiplication and permuta-
  0,1,2,3,4,5,6,7,8,9,1,5,7,6,2,8,3,0,9,4,&      tion tables.
  5,8,0,3,7,9,6,1,4,2,8,9,1,6,0,4,3,5,2,7,9,4,5,3,1,2,6,8,7,0,&
  4,2,8,6,5,7,3,9,0,1,2,7,9,3,8,0,6,4,1,5,7,0,4,6,9,1,3,2,5,8 /),&

```

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```

(/ 10,8 /) )
INTEGER(I4B) :: ij(0:9,0:9) = reshape(/ &
  0,1,2,3,4,5,6,7,8,9,1,2,3,4,0,9,5,6,7,8,2,3,4,0,1,8,9,5,6,&
  7,3,4,0,1,2,7,8,9,5,6,4,0,1,2,3,6,7,8,9,5,5,6,7,8,9,0,1,2,3,&
  4,6,7,8,9,5,4,0,1,2,3,7,8,9,5,6,3,4,0,1,2,8,9,5,6,7,2,3,4,0,&
  1,9,5,6,7,8,1,2,3,4,0 /),(/ 10,10 /))
k=0
m=0
do j=1,size(string)           Look at successive characters.
  i=ichar(string(j))
  if (i >= 48 .and. i <= 57) then  Ignore everything except digits.
    k=ij(k,ip(mod(i+2,10),mod(m,8)))
    m=m+1
  end if
end do
decchk=logical(k == 0,kind=lgf)
i=mod(m,8)                   Find which appended digit will check properly.
i=ifirstloc(ij(k,ip(0:9,i)) == 0)-1
ch=char(i+48)                Convert to ASCII.
END FUNCTION decchk

```



Note the use of the utility function `ifirstloc` to find the first (in this case, the only) correct check digit.

\* \* \*



The Huffman and arithmetic coding routines exemplify the use of modules to encapsulate user-defined data types. In these algorithms, “the code” is a fairly complicated construct containing scalar and array data. We define types `huffcode` and `arithcode`, then can pass “the code” from the routine that constructs it to the routine that uses it as a single variable.

```

MODULE huf_info
USE nrtype
IMPLICIT NONE
TYPE huffcode
  INTEGER(I4B) :: nch,nodemax
  INTEGER(I4B), DIMENSION(:), POINTER :: icode,left,iright,ncode
END TYPE huffcode
CONTAINS
SUBROUTINE huff_allocate(hcode,mc)
USE nrtype
IMPLICIT NONE
TYPE(huffcode) :: hcode
INTEGER(I4B) :: mc
INTEGER(I4B) :: mq
mq=2*mc-1
allocate(hcode%icode(mq),hcode%ncode(mq),hcode%left(mq),hcode%iright(mq))
hcode%icode(:)=0
hcode%ncode(:)=0
END SUBROUTINE huff_allocate

SUBROUTINE huff_deallocate(hcode)
USE nrtype
IMPLICIT NONE
TYPE(huffcode) :: hcode
deallocate(hcode%iright,hcode%left,hcode%ncode,hcode%icode)
nullify(hcode%icode)
nullify(hcode%ncode)
nullify(hcode%left)
nullify(hcode%iright)

```

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```
END SUBROUTINE huff_deallocate
END MODULE huf_info
```

```
SUBROUTINE hufmak(nfreq, ilong, nlong, hcode)
USE nrtype; USE nrutil, ONLY : array_copy, arth, imaxloc, nrerror
USE huf_info
IMPLICIT NONE
INTEGER(I4B), INTENT(OUT) :: ilong, nlong
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: nfreq
TYPE(huffcode) :: hcode
  Given the frequency of occurrence table nfreq of size(nfreq) characters, return the
  Huffman code hcode. Returned values ilong and nlong are the character number that
  produced the longest code symbol, and the length of that symbol.
INTEGER(I4B) :: ibit, j, k, n, node, nused, nerr
INTEGER(I4B), DIMENSION(2*size(nfreq)-1) :: indx, iup, nprob
hcode%nch=size(nfreq)      Initialization.
call huff_allocate(hcode, size(nfreq))
nused=0
nprob(1:hcode%nch)=nfreq(1:hcode%nch)
call array_copy(pack(arth(1,1,hcode%nch), nfreq(1:hcode%nch) /= 0 ), &
  indx, nused, nerr)
do j=nused,1,-1           Sort nprob into a heap structure in indx.
  call hufapp(j)
end do
k=hcode%nch
do                         Combine heap nodes, remaking the heap at each stage.
  if (nused <= 1) exit
  node=indx(1)
  indx(1)=indx(nused)
  nused=nused-1
  call hufapp(1)
  k=k+1
  nprob(k)=nprob(indx(1))+nprob(node)
  hcode%left(k)=node      Store left and right children of a node.
  hcode%iright(k)=indx(1)
  iup(indx(1))=-k        Indicate whether a node is a left or right child of its par-
  iup(node)=k            ent.
  indx(1)=k
  call hufapp(1)
end do
hcode%nodemax=k
iup(hcode%nodemax)=0
do j=1,hcode%nch         Make the Huffman code from the tree.
  if (nprob(j) /= 0) then
    n=0
    ibit=0
    node=iup(j)
    do
      if (node == 0) exit
      if (node < 0) then
        n=ibset(n, ibit)
        node=-node
      end if
      node=iup(node)
      ibit=ibit+1
    end do
    hcode%icode(j)=n
    hcode%ncode(j)=ibit
  end if
end do
ilong=imaxloc(hcode%ncode(1:hcode%nch))
nlong=hcode%ncode(ilong)
```

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```

if (nlong > bit_size(1_i4b)) call &          Check nlong not larger than word length.
    nrrror('hufmak: Number of possible bits for code exceeded')
CONTAINS
SUBROUTINE hufapp(l)
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: l
    Used by hufmak to maintain a heap structure in the array indx(1:l).
INTEGER(I4B) :: i,j,k,n
n=nused
i=1
k=indx(i)
do
    if (i > n/2) exit
    j=i+i
    if (j < n .and. nprob(indx(j)) > nprob(indx(j+1))) &
        j=j+1
    if (nprob(k) <= nprob(indx(j))) exit
    indx(i)=indx(j)
    i=j
end do
indx(i)=k
END SUBROUTINE hufapp
END SUBROUTINE hufmak

```

```

SUBROUTINE hufenc(ich,codep,nb,hcode)
USE nrtype; USE nrutil, ONLY : nrrror,reallocate
USE huf_info
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: ich
INTEGER(I4B), INTENT(INOUT) :: nb
CHARACTER(1), DIMENSION(:), POINTER :: codep
TYPE(huffcode) :: hcode
    Huffman encode the single character ich (in the range 0..nch-1) using the code in hcode,
    write the result to the character array pointed to by codep starting at bit nb (whose smallest
    valid value is zero), and increment nb appropriately. This routine is called repeatedly to
    encode consecutive characters in a message, but must be preceded by a single initializing
    call to hufmak.
INTEGER(I4B) :: k,l,n,nc,ntmp
k=ich+1
if (k > hcode%nch .or. k < 1) call &          Convert character range 0..nch-1 to ar-
    nrrror('hufenc: ich out of range')         ray index range 1..nch.
do n=hcode%ncode(k),1,-1                      Loop over the bits in the stored Huffman
    nc=nb/8+1                                  code for ich.
    if (nc > size(codep)) codep=>reallocate(codep,2*size(codep))
    l=mod(nb,8)
    if (l == 0) codep(nc)=char(0)
    if (btest(hcode%icode(k),n-1)) then       Set appropriate bits in codep.
        ntmp=ibset(ichar(codep(nc)),l)
        codep(nc)=char(ntmp)
    end if
    nb=nb+1
end do
END SUBROUTINE hufenc

```

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```

SUBROUTINE hufdec(ich,code,nb,hcode)
USE nrtype
USE huf_info
IMPLICIT NONE
INTEGER(I4B), INTENT(OUT) :: ich
INTEGER(I4B), INTENT(INOUT) :: nb
CHARACTER(1), DIMENSION(:), INTENT(IN) :: code
TYPE(huffcode) :: hcode
  Starting at bit number nb in the character array code, use the Huffman code in hcode
  to decode a single character (returned as ich in the range 0..nch-1) and increment nb
  appropriately. Repeated calls, starting with nb = 0, will return successive characters in a
  compressed message. The returned value ich=nch indicates end-of-message. This routine
  must be preceded by a single initializing call to hufmak.
INTEGER(I4B) :: l,nc,node
node=hcode%nodemax
do
  nc=nb/8+1
  if (nc > size(code)) then
    ich=hcode%nch
    RETURN
  end if
  l=mod(nb,8)
  nb=nb+1
  if (btest(ichar(code(nc)),l)) then
    node=hcode%iright(node)
  else
    node=hcode%left(node)
  end if
  if (node <= hcode%nch) then
    ich=node-1
    RETURN
  end if
end do
END SUBROUTINE hufdec

```

Set node to the top of the decoding tree.  
Loop until a valid character is obtained.

Ran out of input; return with ich=nch  
indicating end of message.

Now decoding this bit.

Branch left or right in tree, depending on  
its value.

If we reach a terminal node, we have a  
complete character and can return.

\* \* \*

```

MODULE arcode_info
USE nrtype
IMPLICIT NONE
INTEGER(I4B), PARAMETER :: NWK=20
  NWK is the number of working digits (see text).
TYPE arithcode
  INTEGER(I4B), DIMENSION(:), POINTER :: ilob,iupb,ncumfq
  INTEGER(I4B) :: jdif,nc,minint,nch,ncum,nrad
END TYPE arithcode
CONTAINS
SUBROUTINE arcode_allocate(acode,mc)
USE nrtype
IMPLICIT NONE
TYPE(arithcode) :: acode
INTEGER(I4B) :: mc
allocate(acode%ilob(NWK),acode%iupb(NWK),acode%ncumfq(mc+2))
END SUBROUTINE arcode_allocate

SUBROUTINE arcode_deallocate(acode)
USE nrtype
IMPLICIT NONE
TYPE(arithcode) :: acode
deallocate(acode%ncumfq,acode%iupb,acode%ilob)
nullify(acode%ilob)
nullify(acode%iupb)

```

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```

nullify(acode%ncumfq)
END SUBROUTINE arcode_deallocate
END MODULE arcode_info

```

```

SUBROUTINE arcmak(nfreq,nradd,acode)
USE nrtype; USE nrutil, ONLY : cumsum,nrerror
USE arcode_info
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: nradd
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: nfreq
TYPE(arithcode) :: acode
INTEGER(I4B), PARAMETER :: MAXINT=huge(nradd)
    Given a table nfreq of the frequency of occurrence of size(nfreq) symbols, and given
    a desired output radix nradd, initialize the cumulative frequency table and other variables
    for arithmetic compression. Store the code in acode.
    MAXINT is a large positive integer that does not overflow.
if (nradd > 256) call nrerror('output radix may not exceed 256 in arcmak')
acode%minint=MAXINT/nradd
acode%nch=size(nfreq)
acode%nradd=nradd
call arcode_allocate(acode,acode%nch)
acode%ncumfq(1)=0
acode%ncumfq(2:acode%nch+1)=cumsum(max(nfreq(1:acode%nch),1))
acode%ncumfq(acode%nch+2)=acode%ncumfq(acode%nch+1)+1
acode%ncum=acode%ncumfq(acode%nch+2)
END SUBROUTINE arcmak

```

```

SUBROUTINE arcode(ich,codep,lcd,isign,acode)
USE nrtype; USE nrutil, ONLY : nrerror,reallocate
USE arcode_info
IMPLICIT NONE
INTEGER(I4B), INTENT(INOUT) :: ich,lcd
INTEGER(I4B), INTENT(IN) :: isign
CHARACTER(1), DIMENSION(:), POINTER :: codep
TYPE(arithcode) :: acode
    Compress (isign = 1) or decompress (isign = -1) the single character ich into or out of
    the character array pointed to by codep, starting with byte codep(lcd) and (if necessary)
    incrementing lcd so that, on return, lcd points to the first unused byte in codep. Note
    that this routine saves the result of previous calls until a new byte of code is produced,
    and only then increments lcd. An initializing call with isign=0 is required for each different
    array codep. The routine arcmak must have previously been called to initialize the code
    acode. A call with ich=acode%nch (as set in arcmak) has the reserved meaning "end
    of message."
INTEGER(I4B) :: ihi,j,ja,jh,jl,m
if (isign == 0) then
    Initialize enough digits of the upper and lower
    acode%jdif=acode%nradd-1
    bounds.
    acode%ilob(:)=0
    acode%iupb(:)=acode%nradd-1
    do j=NWK,1,-1
        acode%nc=j
        if (acode%jdif > acode%minint) RETURN
        acode%jdif=(acode%jdif+1)*acode%nradd-1
        Initialization complete.
    end do
    call nrerror('NWK too small in arcode')
else
    if (isign > 0) then
        If encoding, check for valid input character.
        if (ich > acode%nch .or. ich < 0) call nrerror('bad ich in arcode')
    else
        If decoding, locate the character ich by bi-
        ja=iuchar(codep(lcd))-acode%ilob(acode%nc)
        section.
        do j=acode%nc+1,NWK

```

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```

        ja=ja*acode%nrad+(ichar(codep(j+lcd-acode%nc))-acode%ilob(j))
    end do
    ich=0
    ihi=acode%nch+1
    do
        if (ihi-ich <= 1) exit
        m=(ich+ihi)/2
        if (ja >= jtry(acode%jdif,acode%ncumfq(m+1),acode%ncum)) then
            ich=m
        else
            ihi=m
        end if
    end do
    if (ich == acode%nch) RETURN          Detected end of message.
end if
    Following code is common for encoding and decoding. Convert character ich to a new
    subrange [ilob,iupb).
    jh=jtry(acode%jdif,acode%ncumfq(ich+2),acode%ncum)
    jl=jtry(acode%jdif,acode%ncumfq(ich+1),acode%ncum)
    acode%jdif=jh-jl
    call arcsun(acode%ilob,acode%iupb,jh,NWK,acode%nrad,acode%nc)
    How many leading digits to output (if encoding) or skip over?
    call arcsun(acode%ilob,acode%ilob,jl,NWK,acode%nrad,acode%nc)
    do j=acode%nc,NWK
        if (ich /= acode%nch .and. acode%iupb(j) /= acode%ilob(j)) exit
        if (acode%nc > size(codep)) codep=>reallocate(codep,2*size(codep))
        if (isign > 0) codep(lcd)=char(acode%ilob(j))
        lcd=lcd+1
    end do
    if (j > NWK) RETURN                  Ran out of message. Did someone forget to
    acode%nc=j                            encode a terminating ncd?
    j=0                                    How many digits to shift?
    do
        if (acode%jdif >= acode%minint) exit
        j=j+1
        acode%jdif=acode%jdif*acode%nrad
    end do
    if (acode%nc-j < 1) call nrerror('NWK too small in arcode')
    if (j /= 0) then                      Shift them.
        acode%iupb((acode%nc-j):(NWK-j))=acode%iupb(acode%nc:NWK)
        acode%ilob((acode%nc-j):(NWK-j))=acode%ilob(acode%nc:NWK)
    end if
    acode%nc=acode%nc-j
    acode%iupb((NWK-j+1):NWK)=0
    acode%ilob((NWK-j+1):NWK)=0
end if
CONTAINS
FUNCTION jtry(m,n,k)
USE nrtype
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: m,n,k
INTEGER(I4B) :: jtry
    Calculate (m*n)/k without overflow. Program efficiency can be improved by substituting an
    assembly language routine that does integer multiply to a double register.
    jtry=int((real(m,dp)*real(n,dp))/real(k,dp))
END FUNCTION jtry
SUBROUTINE arcsun(iin,iout,ja,nwk,nrad,nc)
USE nrtype
IMPLICIT NONE
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: iin
INTEGER(I4B), DIMENSION(:), INTENT(OUT) :: iout
INTEGER(I4B), INTENT(IN) :: nwk,nrad,nc
INTEGER(I4B), INTENT(INOUT) :: ja

```

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```

Add the integer ja to the radix nrad multiple-precision integer iin(nc..nwk). Return the
result in iout(nc..nwk).
INTEGER(I4B) :: j,jtmp,karry
karry=0
do j=nwk,nc+1,-1
  jtmp=ja
  ja=ja/nrad
  iout(j)=iin(j)+(jtmp-ja*nrad)+karry
  if (iout(j) >= nrad) then
    iout(j)=iout(j)-nrad
    karry=1
  else
    karry=0
  end if
end do
iout(nc)=iin(nc)+ja+karry
END SUBROUTINE arcsun
END SUBROUTINE arcode

```

\* \* \*

#### MODULE mpops

```

USE nrtype
INTEGER(I4B), PARAMETER :: NPAR_ICARRY=64
CONTAINS

SUBROUTINE icarry(karry, isum, nbits)
IMPLICIT NONE
INTEGER(I4B), INTENT(OUT) :: karry
  Perform deferred carry operation on an array isum of multiple-precision digits. Nonzero bits
  of higher order than nbits (typically 8) are carried to the next-lower (leftward) component
  of isum. The final (most leftward) carry value is returned as karry.
INTEGER(I2B), DIMENSION(:), INTENT(INOUT) :: isum
INTEGER(I4B), INTENT(IN) :: nbits
INTEGER(I4B) :: n,j
INTEGER(I2B), DIMENSION(size(isum)) :: ihi
INTEGER(I2B) :: mb,ihh
n=size(isum)
mb=ishft(1,nbits)-1           Make mask for low-order bits.
karry=0
if (n < NPAR_ICARRY ) then
  do j=n,2,-1                 Keep going until all carries have cascaded.
    ihh=ishft(isum(j),-nbits)
    if (ihh /= 0) then
      isum(j)=iand(isum(j),mb)
      isum(j-1)=isum(j-1)+ihh
    end if
  end do
  ihh=ishft(isum(1),-nbits)
  isum(1)=iand(isum(1),mb)
  karry=karry+ihh
else
  do
    ihi=ishft(isum,-nbits)    Get high bits.
    if (all(ihi == 0)) exit    Check if done.
    where (ihi /= 0) isum=iand(isum,mb)  Remove bits to be carried and add
    where (ihi(2:n) /= 0) isum(1:n-1)=isum(1:n-1)+ihi(2:n)  them to left.
    karry=karry+ihi(1)        Final carry.
  end do
end if
END SUBROUTINE icarry

```

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```

SUBROUTINE mpadd(w,u,v,n)
IMPLICIT NONE
CHARACTER(1), DIMENSION(:), INTENT(OUT) :: w
CHARACTER(1), DIMENSION(:), INTENT(IN) :: u,v
INTEGER(I4B), INTENT(IN) :: n
    Adds the unsigned radix 256 integers u(1:n) and v(1:n) yielding the unsigned integer
    w(1:n+1).
INTEGER(I2B), DIMENSION(n) :: isum
INTEGER(I4B) :: karry
isum=ichar(u(1:n))+ichar(v(1:n))
call icarry(karry,isum,8_I4B)
w(2:n+1)=char(isum)
w(1)=char(karry)
END SUBROUTINE mpadd

SUBROUTINE mpsub(is,w,u,v,n)
IMPLICIT NONE
INTEGER(I4B), INTENT(OUT) :: is
CHARACTER(1), DIMENSION(:), INTENT(OUT) :: w
CHARACTER(1), DIMENSION(:), INTENT(IN) :: u,v
INTEGER(I4B), INTENT(IN) :: n
    Subtracts the unsigned radix 256 integer v(1:n) from u(1:n) yielding the unsigned integer
    w(1:n). If the result is negative (wraps around), is is returned as -1; otherwise it is
    returned as 0.
INTEGER(I4B) :: karry
INTEGER(I2B), DIMENSION(n) :: isum
isum=255+ichar(u(1:n))-ichar(v(1:n))
isum(n)=isum(n)+1
call icarry(karry,isum,8_I4B)
w(1:n)=char(isum)
is=karry-1
END SUBROUTINE mpsub

SUBROUTINE mpsad(w,u,n,iv)
IMPLICIT NONE
CHARACTER(1), DIMENSION(:), INTENT(OUT) :: w
CHARACTER(1), DIMENSION(:), INTENT(IN) :: u
INTEGER(I4B), INTENT(IN) :: n,iv
    Short addition: The integer iv (in the range  $0 \leq iv \leq 255$ ) is added to the unsigned radix
    256 integer u(1:n), yielding w(1:n+1).
INTEGER(I4B) :: karry
INTEGER(I2B), DIMENSION(n) :: isum
isum=ichar(u(1:n))
isum(n)=isum(n)+iv
call icarry(karry,isum,8_I4B)
w(2:n+1)=char(isum)
w(1)=char(karry)
END SUBROUTINE mpsad

SUBROUTINE mpsmu(w,u,n,iv)
IMPLICIT NONE
CHARACTER(1), DIMENSION(:), INTENT(OUT) :: w
CHARACTER(1), DIMENSION(:), INTENT(IN) :: u
INTEGER(I4B), INTENT(IN) :: n,iv
    Short multiplication: The unsigned radix 256 integer u(1:n) is multiplied by the integer
    iv (in the range  $0 \leq iv \leq 255$ ), yielding w(1:n+1).
INTEGER(I4B) :: karry
INTEGER(I2B), DIMENSION(n) :: isum
isum=ichar(u(1:n))*iv
call icarry(karry,isum,8_I4B)
w(2:n+1)=char(isum)
w(1)=char(karry)
END SUBROUTINE mpsmu

SUBROUTINE mpneg(u,n)
IMPLICIT NONE

```

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```

CHARACTER(1), DIMENSION(:), INTENT(INOUT) :: u
INTEGER(I4B), INTENT(IN) :: n
    Ones-complement negate the unsigned radix 256 integer u(1:n).
INTEGER(I4B) :: karry
INTEGER(I2B), DIMENSION(n) :: isum
isum=255-ichar(u(1:n))
isum(n)=isum(n)+1
call icarry(karry,isum,8_I4B)
u(1:n)=char(isum)
END SUBROUTINE mpneg

SUBROUTINE mplsh(u,n)
IMPLICIT NONE
CHARACTER(1), DIMENSION(:), INTENT(INOUT) :: u
INTEGER(I4B), INTENT(IN) :: n
    Left shift u(2..n+1) onto u(1:n).
u(1:n)=u(2:n+1)
END SUBROUTINE mplsh

SUBROUTINE mpmov(u,v,n)
IMPLICIT NONE
CHARACTER(1), DIMENSION(:), INTENT(OUT) :: u
CHARACTER(1), DIMENSION(:), INTENT(IN) :: v
INTEGER(I4B), INTENT(IN) :: n
    Move v(1:n) onto u(1:n).
u(1:n)=v(1:n)
END SUBROUTINE mpmov

SUBROUTINE mpsdv(w,u,n,iv,ir)
IMPLICIT NONE
CHARACTER(1), DIMENSION(:), INTENT(OUT) :: w
CHARACTER(1), DIMENSION(:), INTENT(IN) :: u
INTEGER(I4B), INTENT(IN) :: n,iv
INTEGER(I4B), INTENT(OUT) :: ir
    Short division: The unsigned radix 256 integer u(1:n) is divided by the integer iv (in the
    range  $0 \leq iv \leq 255$ ), yielding a quotient w(1:n) and a remainder ir (with  $0 \leq ir \leq 255$ ).
    Note: Your Numerical Recipes authors don't know how to parallelize this routine in Fortran
    90!
INTEGER(I4B) :: i,j
ir=0
do j=1,n
    i=256*ir+ichar(u(j))
    w(j)=char(i/iv)
    ir=mod(i,iv)
end do
END SUBROUTINE mpsdv
END MODULE mpops

SUBROUTINE mpmul(w,u,v,n,m)
USE nrtype; USE nrutil, ONLY : nrerror
USE nr, ONLY : realft
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n,m
CHARACTER(1), DIMENSION(:), INTENT(IN) :: u,v
CHARACTER(1), DIMENSION(:), INTENT(OUT) :: w
! The logical dimensions are: CHARACTER(1) :: w(n+m),u(n),v(m)
REAL(DP), PARAMETER :: RX=256.0
    Uses fast Fourier transform to multiply the unsigned radix 256 integers u(1:n) and v(1:m),
    yielding a product w(1:n+m).
INTEGER(I4B) :: j,mn,nn
REAL(DP) :: cy,t
REAL(DP), DIMENSION(:), ALLOCATABLE :: a,b,tb
mn=max(m,n)
nn=1
    Find the smallest useable power of two for the transform.

```

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```

do
  if (nn >= mn) exit
  nn=nn+nn
end do
nn=nn+nn
allocate(a(nn),b(nn),tb((nn-1)/2))
a(1:n)=ichar(u(1:n))      Move U to a double-precision floating array.
a(n+1:nn)=0.0
b(1:m)=ichar(v(1:m))     Move V to a double-precision floating array.
b(m+1:nn)=0.0
call realft(a(1:nn),1)   Perform the convolution: First, the two Fourier trans-
call realft(b(1:nn),1)   forms.
b(1)=b(1)*a(1)          Then multiply the complex results (real and imaginary
b(2)=b(2)*a(2)          parts).
tb=b(3:nn:2)
b(3:nn:2)=tb*a(3:nn:2)-b(4:nn:2)*a(4:nn:2)
b(4:nn:2)=tb*a(4:nn:2)+b(4:nn:2)*a(3:nn:2)
call realft(b(1:nn),-1) Then do the inverse Fourier transform.
b(:)=b(:)/(nn/2)
cy=0.0                  Make a final pass to do all the carries.
do j=nn,1,-1
  t=b(j)+cy+0.5_dp      The 0.5 allows for roundoff error.
  b(j)=mod(t,RX)
  cy=int(t/RX)
end do
if (cy >= RX) call nrerror('mpmul: sanity check failed in fftmul')
w(1)=char(int(cy))      Copy answer to output.
w(2:(n+m))=char(int(b(1:(n+m-1))))
deallocate(a,b,tb)
END SUBROUTINE mpmul

SUBROUTINE mpinv(u,v,n,m)
USE nrtype; USE nrutil, ONLY : poly
USE nr, ONLY : mpmul
USE mpops, ONLY : mpmov,mpneg
IMPLICIT NONE
CHARACTER(1), DIMENSION(:), INTENT(OUT) :: u
CHARACTER(1), DIMENSION(:), INTENT(IN) :: v
INTEGER(I4B), INTENT(IN) :: n,m
INTEGER(I4B), PARAMETER :: MF=4
REAL(SP), PARAMETER :: BI=1.0_sp/256.0_sp
Character string v(1:m) is interpreted as a radix 256 number with the radix point after
(nonzero) v(1); u(1:n) is set to the most significant digits of its reciprocal, with the radix
point after u(1).
INTEGER(I4B) :: i,j,mm
REAL(SP) :: fu
CHARACTER(1), DIMENSION(:), ALLOCATABLE :: rr,s
allocate(rr(max(n,m)+n+1),s(n))
mm=min(MF,m)
fu=1.0_sp/poly(BI,real(ichar(v(:)),sp)) Use ordinary floating arithmetic to get an
do j=1,n                    initial approximation.
  i=int(fu)
  u(j)=char(i)
  fu=256.0_sp*(fu-i)
end do
do
  call mpmul(rr,u,v,n,m)
  call mpmov(s,rr(2:),n)
  call mpneg(s,n)
  s(1)=char(ichar(s(1))-254)
  call mpmul(rr,s,u,n,n)
  call mpmov(u,rr(2:),n)

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```

        if (all(ichar(s(2:n-1)) == 0)) exit      If fractional part of  $S$  is not zero, it has
    end do                                       not converged to 1.
    deallocate(rr,s)
END SUBROUTINE mpinv

```

```

SUBROUTINE mpdiv(q,r,u,v,n,m)
USE nrtype; USE nrutil, ONLY : nrerror
USE nr, ONLY : mpinv,mpmul
USE mpops, ONLY : mpsad,mpmov,mpsub
IMPLICIT NONE
CHARACTER(1), DIMENSION(:), INTENT(OUT) :: q,r
CHARACTER(1), DIMENSION(:), INTENT(IN)  :: u,v
! The logical dimensions are: CHARACTER(1) :: q(n-m+1),r(m),u(n),v(m)
INTEGER(I4B), INTENT(IN) :: n,m
    Divides unsigned radix 256 integers  $u(1:n)$  by  $v(1:m)$  (with  $m \leq n$  required), yielding a
    quotient  $q(1:n-m+1)$  and a remainder  $r(1:m)$ .
INTEGER(I4B), PARAMETER :: MACC=6
INTEGER(I4B) :: is
CHARACTER(1), DIMENSION(:), ALLOCATABLE, TARGET :: rr,s
CHARACTER(1), DIMENSION(:), POINTER :: rr2,s3
allocate(rr(2*(n+MACC)),s(2*(n+MACC)))
rr2=>rr(2:)
s3=>s(3:)
call mpinv(s,v,n+MACC,m)          Set  $S = 1/V$ .
call mpmul(rr,s,u,n+MACC,n)      Set  $Q = SU$ .
call mpsad(s,rr,n+n+MACC/2,1)
call mpmov(q,s3,n-m+1)
call mpmul(rr,q,v,n-m+1,m)       Multiply and subtract to get the remainder.
call mpsub(is,rr2,u,rr2,n)
if (is /= 0) call nrerror('MACC too small in mpdiv')
call mpmov(r,rr(n-m+2:),m)
deallocate(rr,s)
END SUBROUTINE mpdiv

```

```

SUBROUTINE mpsqrt(w,u,v,n,m)
USE nrtype; USE nrutil, ONLY : poly
USE nr, ONLY : mpmul
USE mpops, ONLY : mplsh,mpmov,mpneg,mpsdv
IMPLICIT NONE
CHARACTER(1), DIMENSION(:), INTENT(OUT) :: w,u
CHARACTER(1), DIMENSION(:), INTENT(IN)  :: v
INTEGER(I4B), INTENT(IN) :: n,m
INTEGER(I4B), PARAMETER :: MF=3
REAL(SP), PARAMETER :: BI=1.0_sp/256.0_sp
    Character string  $v(1:m)$  is interpreted as a radix 256 number with the radix point after
     $v(1)$ ;  $w(1:n)$  is set to its square root (radix point after  $w(1)$ ), and  $u(1:n)$  is set to the
    reciprocal thereof (radix point before  $u(1)$ ).  $w$  and  $u$  need not be distinct, in which case
    they are set to the square root.
INTEGER(I4B) :: i,ir,j,mm
REAL(SP) :: fu
CHARACTER(1), DIMENSION(:), ALLOCATABLE :: r,s
allocate(r(2*n),s(2*n))
mm=min(m,MF)
fu=1.0_sp/sqrt(poly(BI,real(ichar(v(:)),sp)))      Use ordinary floating arithmetic
do j=1,n                                           to get an initial approxima-
    i=int(fu)                                       tion.
    u(j)=char(i)
    fu=256.0_sp*(fu-i)
end do
do
    call mpmul(r,u,u,n,n)                          Iterate Newton's rule to convergence.
                                                    Construct  $S = (3 - VU^2)/2$ .

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```

call mplsh(r,n)
call mpmul(s,r,v,n,min(m,n))
call mplsh(s,n)
call mpneg(s,n)
s(1)=char(ichar(s(1))-253)
call mpsdv(s,s,n,2,ir)
if (any(ichar(s(2:n-1)) /= 0)) then
    If fractional part of  $S$  is not zero, it has not converged to 1.
    call mpmul(r,s,u,n,n)           Replace  $U$  by  $SU$ .
    call mpmov(u,r(2:),n)
    cycle
end if
call mpmul(r,u,v,n,min(m,n))       Get square root from reciprocal and return.
call mpmov(w,r(2:),n)
deallocate(r,s)
RETURN
end do
END SUBROUTINE mpsqrt

```

```

SUBROUTINE mp2dfr(a,s,n,m)
USE nrtype
USE mpops, ONLY : mplsh,mpsmu
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
INTEGER(I4B), INTENT(OUT) :: m
CHARACTER(1), DIMENSION(:), INTENT(INOUT) :: a
CHARACTER(1), DIMENSION(:), INTENT(OUT) :: s
INTEGER(I4B), PARAMETER :: IAZ=48
    Converts a radix 256 fraction a(1:n) (radix point before a(1)) to a decimal fraction
    represented as an ascii string s(1:m), where m is a returned value. The input array a(1:n)
    is destroyed. NOTE: For simplicity, this routine implements a slow ( $\propto N^2$ ) algorithm. Fast
    ( $\propto N \ln N$ ), more complicated, radix conversion algorithms do exist.
INTEGER(I4B) :: j
m=int(2.408_sp*n)
do j=1,m
    call mpsmu(a,a,n,10)
    s(j)=char(ichar(a(1))+IAZ)
    call mplsh(a,n)
end do
END SUBROUTINE mp2dfr

```

```

SUBROUTINE mppi(n)
USE nrtype
USE nr, ONLY : mp2dfr,mpinv,mpmul,mpsqr
USE mpops, ONLY : mpadd,mplsh,mpmov,mpsdv
IMPLICIT NONE
INTEGER(I4B), INTENT(IN) :: n
INTEGER(I4B), PARAMETER :: IAOFF=48
    Demonstrate multiple precision routines by calculating and printing the first n bytes of  $\pi$ .
INTEGER(I4B) :: ir,j,m
CHARACTER(1), DIMENSION(n) :: sx,sxi
CHARACTER(1), DIMENSION(2*n) :: t,y
CHARACTER(1), DIMENSION(3*n) :: s
CHARACTER(1), DIMENSION(n+1) :: x,bigpi
t(1)=char(2)           Set  $T = 2$ .
t(2:n)=char(0)
call mpsqr(x,x,t,n,n)   Set  $X_0 = \sqrt{2}$ .
call mpadd(bigpi,t,x,n) Set  $\pi_0 = 2 + \sqrt{2}$ .
call mplsh(bigpi,n)
call mpsqr(sx,sxi,x,n,n) Set  $Y_0 = 2^{1/4}$ .

```

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```

call mpmov(y,sx,n)
do
  call mpadd(x,sx,sxi,n)
  call mpsdv(x,x(2:),n,2,ir)
  call mpsqrt(sx,sxi,x,n,n)
  call mpmul(t,y,sx,n,n)
  call mpadd(t(2:),t(2:),sxi,n)
  x(1)=char(ichar(x(1))+1)
  y(1)=char(ichar(y(1))+1)
  call mpinv(s,y,n,n)
  call mpmul(y,t(3:),s,n,n)
  call mplsh(y,n)
  call mpmul(t,x,s,n,n)
  m=mod(255+ichar(t(2)),256)
  if (abs(ichar(t(n+1))-m) > 1 .or. any(ichar(t(3:n)) /= m)) then
    call mpmul(s,bigpi,t(2:),n,n)
    call mpmov(bigpi,s(2:),n)
    cycle
  end if
  write (*,*) 'pi='
  s(1)=char(ichar(bigpi(1))+IAOFF)
  s(2)='.'
  call mp2dfr(bigpi(2:),s(3:),n-1,m)
  Convert to decimal for printing. NOTE: The conversion routine, for this demonstration
  only, is a slow ( $\propto N^2$ ) algorithm. Fast ( $\propto N \ln N$ ), more complicated, radix conversion
  algorithms do exist.
  write (*,'(1x,64a1)') (s(j),j=1,m+1)
  RETURN
end do
END SUBROUTINE mppi

```

Set  $X_{i+1} = (X_i^{1/2} + X_i^{-1/2})/2$ .

Form the temporary  $T = Y_i X_{i+1}^{1/2} + X_{i+1}^{-1/2}$ .

Increment  $X_{i+1}$  and  $Y_i$  by 1.

Set  $Y_{i+1} = T/(Y_i + 1)$ .

Form temporary  $T = (X_{i+1} + 1)/(Y_i + 1)$ .

If  $T = 1$  then we have converged.

Set  $\pi_{i+1} = T\pi_i$ .

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## References

The references collected here are those of general usefulness, cited in this volume. For references to the material in Volume 1, see the References section of that volume.

A first group of references relates to the Fortran 90 language itself:

- Metcalf, M., and Reid, J. 1996, *Fortran 90/95 Explained* (Oxford: Oxford University Press).
- Kerrigan, J.F. 1993, *Migrating to Fortran 90* (Sebastopol, CA: O'Reilly).
- Brainerd, W.S., Goldberg, C.H., and Adams, J.C. 1996, *Programmer's Guide to Fortran 90*, 3rd ed. (New York: Springer-Verlag).

A second group of references relates to, or includes material on, parallel programming and algorithms:

- Akl, S.G. 1989, *The Design and Analysis of Parallel Algorithms* (Englewood Cliffs, NJ: Prentice Hall).
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# C1. Listing of Utility Modules (nrtype and nrutil)

## C1.1 Numerical Recipes Types (nrtype)

The file supplied as nrtype.f90 contains a single module named nrtype, which in turn contains definitions for a number of named constants (that is, PARAMETERS), and a couple of elementary derived data types used by the sparse matrix routines in this book. Of the named constants, by far the most important are those that define the KIND types of virtually all the variables used in this book: I4B, I2B, and I1B for integer variables, SP and DP for real variables (and SPC and DPC for the corresponding complex cases), and LGT for the default logical type.

### MODULE nrtype

Symbolic names for kind types of 4-, 2-, and 1-byte integers:

```
INTEGER, PARAMETER :: I4B = SELECTED_INT_KIND(9)
INTEGER, PARAMETER :: I2B = SELECTED_INT_KIND(4)
INTEGER, PARAMETER :: I1B = SELECTED_INT_KIND(2)
```

Symbolic names for kind types of single- and double-precision reals:

```
INTEGER, PARAMETER :: SP = KIND(1.0)
INTEGER, PARAMETER :: DP = KIND(1.0D0)
```

Symbolic names for kind types of single- and double-precision complex:

```
INTEGER, PARAMETER :: SPC = KIND((1.0,1.0))
INTEGER, PARAMETER :: DPC = KIND((1.0D0,1.0D0))
```

Symbolic name for kind type of default logical:

```
INTEGER, PARAMETER :: LGT = KIND(.true.)
```

Frequently used mathematical constants (with precision to spare):

```
REAL(SP), PARAMETER :: PI=3.141592653589793238462643383279502884197_sp
REAL(SP), PARAMETER :: PI02=1.57079632679489661923132169163975144209858_sp
REAL(SP), PARAMETER :: TWOPI=6.283185307179586476925286766559005768394_sp
REAL(SP), PARAMETER :: SQRT2=1.41421356237309504880168872420969807856967_sp
REAL(SP), PARAMETER :: EULER=0.5772156649015328606065120900824024310422_sp
REAL(DP), PARAMETER :: PI_D=3.141592653589793238462643383279502884197_dp
REAL(DP), PARAMETER :: PI02_D=1.57079632679489661923132169163975144209858_dp
REAL(DP), PARAMETER :: TWOPI_D=6.283185307179586476925286766559005768394_dp
```

Derived data types for sparse matrices, single and double precision (see use in Chapter B2):

```
TYPE sprs2_sp
  INTEGER(I4B) :: n,len
  REAL(SP), DIMENSION(:), POINTER :: val
  INTEGER(I4B), DIMENSION(:), POINTER :: irow
  INTEGER(I4B), DIMENSION(:), POINTER :: jcol
END TYPE sprs2_sp
TYPE sprs2_dp
  INTEGER(I4B) :: n,len
  REAL(DP), DIMENSION(:), POINTER :: val
```

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```

INTEGER(I4B), DIMENSION(:), POINTER :: irow
INTEGER(I4B), DIMENSION(:), POINTER :: jcol
END TYPE sprs2_dp
END MODULE nrtype

```

## About Converting to Higher Precision

You might hope that changing all the Numerical Recipes routines from single precision to double precision would be as simple as redefining the values of SP and DP in *nrtype*. Well . . . not quite.

Converting algorithms to a higher precision is not a purely mechanical task because of the distinction between “roundoff error” and “truncation error.” (Please see Volume 1, §1.2, if you are not familiar with these concepts.) While increasing the precision implied by the kind values SP and DP will indeed reduce a routine’s roundoff error, it will not reduce any truncation error that may be intrinsic to the algorithm. Sometimes, a routine contains “accuracy parameters” that can be adjusted to reduce the truncation error to the new, desired level. In other cases, however, the truncation error cannot be so easily reduced; then, a whole new algorithm is needed. Clearly such new algorithms are beyond the scope of a simple mechanical “conversion.”

If, despite these cautionary words, you want to proceed with converting some routines to a higher precision, here are some hints:

If your machine has a kind type that is distinct from, and has equal or greater precision than, the kind type that we use for DP, then, in *nrtype*, you can simply redefine DP to this new highest precision and redefine SP to what was previously DP. For example, DEC machines usually have a “quadruple precision” real type available, which can be used in this way. You should not need to make any further edits of *nrtype* or *nrutil*.

If, on the other hand, the kind type that we already use for DP is the highest precision available, then you must leave DP defined as it is, and redefine SP in *nrtype* to be this same kind type. Now, however, you will also have to edit *nrutil*, because some overloaded routines that were previously distinguishable (by the different kind types) will now be seen by the compiler as indistinguishable — and it will object strenuously. Simply delete all the “\_dp” function names from the list of overloaded procedures (i.e., from the MODULE PROCEDURE statements). Note that it is not necessary to delete the routines from the MODULE itself. Similarly, in the interface file *nr.f90* you must delete the “\_dp” interfaces, *except* for the *sprs* . . . routines. (Since they have TYPE(*sprs2\_dp*) or TYPE(*sprs2\_sp*), they are treated as distinct even though they have functionally equivalent kind types.)

Finally, the following table gives some suggestions for changing the accuracy parameters, or constants, in some of the routines. Please note that this table is not necessarily complete, and that higher-precision performance is not guaranteed for all the routines, *even if* you make all the changes indicated. The above edits, and these suggestions, do, however, work in the majority of cases.

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<i>In routine...</i>	<i>change...</i>	<i>to...</i>
beschb	NUSE1=5,NUSE2=5	NUSE1=7,NUSE2=8
bessi	IACC=40	IACC=200
bessik	EPS=1.0e-10 <sub>dp</sub>	EPS=epsilon(x)
bessj	IACC=40	IACC=160
bessjy	EPS=1.0e-10 <sub>dp</sub>	EPS=epsilon(x)
broydn	TOLF=1.0e-4 <sub>sp</sub> TOLMIN=1.0e-6 <sub>sp</sub>	TOLF=1.0e-8 <sub>sp</sub> TOLMIN=1.0e-12 <sub>sp</sub>
fdjac	EPS=1.0e-4 <sub>sp</sub>	EPS=1.0e-8 <sub>sp</sub>
frprmn	EPS=1.0e-10 <sub>sp</sub>	EPS=1.0e-18 <sub>sp</sub>
gauher	EPS=3.0e-13 <sub>dp</sub>	EPS=1.0e-14 <sub>dp</sub>
gaujac	EPS=3.0e-14 <sub>dp</sub>	EPS=1.0e-14 <sub>dp</sub>
gaulag	EPS=3.0e-13 <sub>dp</sub>	EPS=1.0e-14 <sub>dp</sub>
gauleg	EPS=3.0e-14 <sub>dp</sub>	EPS=1.0e-14 <sub>dp</sub>
hypgeo	EPS=1.0e-6 <sub>sp</sub>	EPS=1.0e-14 <sub>sp</sub>
linmin	TOL=1.0e-4 <sub>sp</sub>	TOL=1.0e-8 <sub>sp</sub>
newt	TOLF=1.0e-4 <sub>sp</sub> TOLMIN=1.0e-6 <sub>sp</sub>	TOLF=1.0e-8 <sub>sp</sub> TOLMIN=1.0e-12 <sub>sp</sub>
probks	EPS1=0.001 <sub>sp</sub> EPS2=1.0e-8 <sub>sp</sub>	EPS1=1.0e-6 <sub>sp</sub> EPS2=1.0e-16 <sub>sp</sub>
qromb	EPS=1.0e-6 <sub>sp</sub>	EPS=1.0e-10 <sub>sp</sub>
qromo	EPS=1.0e-6 <sub>sp</sub>	EPS=1.0e-10 <sub>sp</sub>
qroot	TINY=1.0e-6 <sub>sp</sub>	TINY=1.0e-14 <sub>sp</sub>
qsimp	EPS=1.0e-6 <sub>sp</sub>	EPS=1.0e-10 <sub>sp</sub>
qtrap	EPS=1.0e-6 <sub>sp</sub>	EPS=1.0e-10 <sub>sp</sub>
rc	ERRTOL=0.04 <sub>sp</sub>	ERRTOL=0.0012 <sub>sp</sub>
rd	ERRTOL=0.05 <sub>sp</sub>	ERRTOL=0.0015 <sub>sp</sub>
rf	ERRTOL=0.08 <sub>sp</sub>	ERRTOL=0.0025 <sub>sp</sub>
rj	ERRTOL=0.05 <sub>sp</sub>	ERRTOL=0.0015 <sub>sp</sub>
sfroid	conv=5.0e-6 <sub>sp</sub>	conv=1.0e-14 <sub>sp</sub>
shoot	EPS=1.0e-6 <sub>sp</sub>	EPS=1.0e-14 <sub>sp</sub>
shootf	EPS=1.0e-6 <sub>sp</sub>	EPS=1.0e-14 <sub>sp</sub>
simplx	EPS=1.0e-6 <sub>sp</sub>	EPS=1.0e-14 <sub>sp</sub>
sncndn	CA=0.0003 <sub>sp</sub>	CA=1.0e-8 <sub>sp</sub>
sor	EPS=1.0e-5 <sub>dp</sub>	EPS=1.0e-13 <sub>dp</sub>
sphfpt	DXX=1.0e-4 <sub>sp</sub>	DXX=1.0e-8 <sub>sp</sub>
sphoot	dx=1.0e-4 <sub>sp</sub>	dx=1.0e-8 <sub>sp</sub>
svdfit	TOL=1.0e-5 <sub>sp</sub>	TOL=1.0e-13 <sub>sp</sub>
zroots	EPS=1.0e-6 <sub>sp</sub>	EPS=1.0e-14 <sub>sp</sub>

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## C1.2 Numerical Recipes Utilities (*nrutil*)

The file supplied as `nrutil.f90` contains a single module named `nrutil`, which contains specific implementations for all the Numerical Recipes utility functions described in detail in Chapter 23.

The specific implementations given are something of a compromise between demonstrating parallel techniques (when they can be achieved in Fortran 90) and running efficiently on conventional, serial machines. The parameters at the beginning of the module (names beginning with `NPAR_`) are typically related to array lengths *below which* the implementations revert to serial operations. On a purely serial machine, these can be set to large values to suppress many parallel constructions.

The length and repetitiveness of the `nrutil.f90` file stems in large part from its extensive use of overloading. Indeed, the file would be even longer if we overloaded versions for all the applicable data types that each utility could, in principle, instantiate. The descriptions in Chapter 23 detail both the full set of intended data types and shapes for each routine, and also the types and shapes actually here implemented (which can also be gleaned by examining the file). The intended result of all this overloading is, in essence, to give the utility routines the desirable properties of many of the Fortran 90 intrinsic functions, namely, to be both *generic* (apply to many data types) and *elemental* (apply element-by-element to arbitrary shapes). Fortran 95's provision of user-defined elemental functions will reduce the multiplicity of overloading in some of our routines; unfortunately the necessity to overload for multiple data types will still be present.

Finally, it is worth reemphasizing the following point, already made in Chapter 23: The purpose of the `nrutil` utilities is to remove from the Numerical Recipes programs just those programming tasks and "idioms" whose efficient implementation is *most* hardware and compiler dependent, so as to allow for specific, efficient implementations on different machines. One should therefore not expect the utmost in efficiency from the general purpose, one-size-fits-all, implementation listed here.

Correspondingly, we would encourage the incorporation of efficient `nrutil` implementations, and/or comparable capabilities under different names, with as broad as possible a set of overloaded data types, in libraries associated with specific compilers or machines. In support of this goal, we have specifically put this Appendix C1, and the files `nrtype.f90` and `nrutil.f90`, into the public domain.

### MODULE `nrutil`

#### TABLE OF CONTENTS OF THE NRUTIL MODULE:

- routines that move data:
  - `array_copy`, `swap`, `reallocate`
- routines returning a location as an integer value
  - `ifirstloc`, `imaxloc`, `iminloc`
- routines for argument checking and error handling:
  - `assert`, `assert_eq`, `nrerror`
- routines relating to polynomials and recurrences
  - `arth`, `geop`, `cumsum`, `cumprod`, `poly`, `polyterm`, `zroots_unity`
- routines for "outer" operations on vectors
  - `outerand`, `outersum`, `outerdiff`, `outerprod`, `outerdiv`
- routines for scatter-with-combine
  - `scatter_add`, `scatter_max`
- routines for skew operations on matrices
  - `diagadd`, `diagmult`, `get_diag`, `put_diag`,

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```

        unit_matrix, lower_triangle, upper_triangle
miscellaneous routines
        vabs
USE nrtype
    Parameters for crossover from serial to parallel algorithms (these are used only within this
nrutil module):
IMPLICIT NONE
INTEGER(I4B), PARAMETER :: NPAR_ARTH=16,NPAR2_ARTH=8    Each NPAR2 must be ≤ the
INTEGER(I4B), PARAMETER :: NPAR_GEOP=4,NPAR2_GEOP=2    corresponding NPAR.
INTEGER(I4B), PARAMETER :: NPAR_CUMSUM=16
INTEGER(I4B), PARAMETER :: NPAR_CUMPROD=8
INTEGER(I4B), PARAMETER :: NPAR_POLY=8
INTEGER(I4B), PARAMETER :: NPAR_POLYTERM=8
    Next, generic interfaces for routines with overloaded versions. Naming conventions for ap-
    pended codes in the names of overloaded routines are as follows: r=real, d=double pre-
    cision, i=integer, c=complex, z=double-precision complex, h=character, l=logical. Any of
    r,d,i,c,z,h,l may be followed by v=vector or m=matrix (v,m suffixes are used only when
    needed to resolve ambiguities).
    Routines that move data:
INTERFACE array_copy
    MODULE PROCEDURE array_copy_r, array_copy_d, array_copy_i
END INTERFACE
INTERFACE swap
    MODULE PROCEDURE swap_i,swap_r,swap_rv,swap_c, &
        swap_cv,swap_cm,swap_z,swap_zv,swap_zm, &
        masked_swap_rs,masked_swap_rv,masked_swap_rm
END INTERFACE
INTERFACE reallocate
    MODULE PROCEDURE reallocate_rv,reallocate_rm,&
        reallocate_iv,reallocate_im,reallocate_hv
END INTERFACE
    Routines returning a location as an integer value (ifirstloc, iminloc are not currently over-
    loaded and so do not have a generic interface here):
INTERFACE imaxloc
    MODULE PROCEDURE imaxloc_r,imaxloc_i
END INTERFACE
    Routines for argument checking and error handling (nrerror is not currently overloaded):
INTERFACE assert
    MODULE PROCEDURE assert1,assert2,assert3,assert4,assert_v
END INTERFACE
INTERFACE assert_eq
    MODULE PROCEDURE assert_eq2,assert_eq3,assert_eq4,assert_eqn
END INTERFACE
    Routines relating to polynomials and recurrences (cumprod, zroots_unity are not currently
    overloaded):
INTERFACE arth
    MODULE PROCEDURE arth_r, arth_d, arth_i
END INTERFACE
INTERFACE geop
    MODULE PROCEDURE geop_r, geop_d, geop_i, geop_c, geop_dv
END INTERFACE
INTERFACE cumsum
    MODULE PROCEDURE cumsum_r,cumsum_i
END INTERFACE
INTERFACE poly
    MODULE PROCEDURE poly_rr,poly_rrv,poly_dd,poly_ddv,&
        poly_rc,poly_cc,poly_msk_rrv,poly_msk_ddv
END INTERFACE
INTERFACE poly_term
    MODULE PROCEDURE poly_term_rr,poly_term_cc
END INTERFACE
    Routines for “outer” operations on vectors (outerand, outersum, outerdiv are not currently
    overloaded):
INTERFACE outerprod

```

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```

MODULE PROCEDURE outerprod_r,outerprod_d
END INTERFACE
INTERFACE outerdiff
MODULE PROCEDURE outerdiff_r,outerdiff_d,outerdiff_i
END INTERFACE
Routines for scatter-with-combine, scatter_add, scatter_max:
INTERFACE scatter_add
MODULE PROCEDURE scatter_add_r,scatter_add_d
END INTERFACE
INTERFACE scatter_max
MODULE PROCEDURE scatter_max_r,scatter_max_d
END INTERFACE
Routines for skew operations on matrices (unit_matrix, lower_triangle, upper_triangle not
currently overloaded):
INTERFACE diagadd
MODULE PROCEDURE diagadd_rv,diagadd_r
END INTERFACE
INTERFACE diagmult
MODULE PROCEDURE diagmult_rv,diagmult_r
END INTERFACE
INTERFACE get_diag
MODULE PROCEDURE get_diag_rv, get_diag_dv
END INTERFACE
INTERFACE put_diag
MODULE PROCEDURE put_diag_rv, put_diag_r
END INTERFACE
Other routines (vabs is not currently overloaded):
CONTAINS
Routines that move data:
SUBROUTINE array_copy_r(src,dest,n_copied,n_not_copied)
Copy array where size of source not known in advance.
REAL(SP), DIMENSION(:), INTENT(IN) :: src
REAL(SP), DIMENSION(:), INTENT(OUT) :: dest
INTEGER(I4B), INTENT(OUT) :: n_copied, n_not_copied
n_copied=min(size(src),size(dest))
n_not_copied=size(src)-n_copied
dest(1:n_copied)=src(1:n_copied)
END SUBROUTINE array_copy_r

SUBROUTINE array_copy_d(src,dest,n_copied,n_not_copied)
REAL(DP), DIMENSION(:), INTENT(IN) :: src
REAL(DP), DIMENSION(:), INTENT(OUT) :: dest
INTEGER(I4B), INTENT(OUT) :: n_copied, n_not_copied
n_copied=min(size(src),size(dest))
n_not_copied=size(src)-n_copied
dest(1:n_copied)=src(1:n_copied)
END SUBROUTINE array_copy_d

SUBROUTINE array_copy_i(src,dest,n_copied,n_not_copied)
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: src
INTEGER(I4B), DIMENSION(:), INTENT(OUT) :: dest
INTEGER(I4B), INTENT(OUT) :: n_copied, n_not_copied
n_copied=min(size(src),size(dest))
n_not_copied=size(src)-n_copied
dest(1:n_copied)=src(1:n_copied)
END SUBROUTINE array_copy_i

SUBROUTINE swap_i(a,b)
Swap the contents of a and b.
INTEGER(I4B), INTENT(INOUT) :: a,b
INTEGER(I4B) :: dum
dum=a
a=b
b=dum
END SUBROUTINE swap_i

```

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```

SUBROUTINE swap_r(a,b)
REAL(SP), INTENT(INOUT) :: a,b
REAL(SP) :: dum
dum=a
a=b
b=dum
END SUBROUTINE swap_r

SUBROUTINE swap_rv(a,b)
REAL(SP), DIMENSION(:), INTENT(INOUT) :: a,b
REAL(SP), DIMENSION(SIZE(a)) :: dum
dum=a
a=b
b=dum
END SUBROUTINE swap_rv

SUBROUTINE swap_c(a,b)
COMPLEX(SPC), INTENT(INOUT) :: a,b
COMPLEX(SPC) :: dum
dum=a
a=b
b=dum
END SUBROUTINE swap_c

SUBROUTINE swap_cv(a,b)
COMPLEX(SPC), DIMENSION(:), INTENT(INOUT) :: a,b
COMPLEX(SPC), DIMENSION(SIZE(a)) :: dum
dum=a
a=b
b=dum
END SUBROUTINE swap_cv

SUBROUTINE swap_cm(a,b)
COMPLEX(SPC), DIMENSION(:,:), INTENT(INOUT) :: a,b
COMPLEX(SPC), DIMENSION(size(a,1),size(a,2)) :: dum
dum=a
a=b
b=dum
END SUBROUTINE swap_cm

SUBROUTINE swap_z(a,b)
COMPLEX(DPC), INTENT(INOUT) :: a,b
COMPLEX(DPC) :: dum
dum=a
a=b
b=dum
END SUBROUTINE swap_z

SUBROUTINE swap_zv(a,b)
COMPLEX(DPC), DIMENSION(:), INTENT(INOUT) :: a,b
COMPLEX(DPC), DIMENSION(SIZE(a)) :: dum
dum=a
a=b
b=dum
END SUBROUTINE swap_zv

SUBROUTINE swap_zm(a,b)
COMPLEX(DPC), DIMENSION(:,:), INTENT(INOUT) :: a,b
COMPLEX(DPC), DIMENSION(size(a,1),size(a,2)) :: dum
dum=a
a=b
b=dum
END SUBROUTINE swap_zm

SUBROUTINE masked_swap_rs(a,b,mask)
REAL(SP), INTENT(INOUT) :: a,b
LOGICAL(LGT), INTENT(IN) :: mask
REAL(SP) :: swp

```

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```

if (mask) then
  swp=a
  a=b
  b=swp
end if
END SUBROUTINE masked_swap_rs

SUBROUTINE masked_swap_rv(a,b,mask)
REAL(SP), DIMENSION(:), INTENT(INOUT) :: a,b
LOGICAL(LGT), DIMENSION(:), INTENT(IN) :: mask
REAL(SP), DIMENSION(size(a)) :: swp
where (mask)
  swp=a
  a=b
  b=swp
end where
END SUBROUTINE masked_swap_rv

SUBROUTINE masked_swap_rm(a,b,mask)
REAL(SP), DIMENSION(:, :), INTENT(INOUT) :: a,b
LOGICAL(LGT), DIMENSION(:, :), INTENT(IN) :: mask
REAL(SP), DIMENSION(size(a,1),size(a,2)) :: swp
where (mask)
  swp=a
  a=b
  b=swp
end where
END SUBROUTINE masked_swap_rm

FUNCTION reallocate_rv(p,n)
  Reallocate a pointer to a new size, preserving its previous contents.
REAL(SP), DIMENSION(:), POINTER :: p, reallocate_rv
INTEGER(I4B), INTENT(IN) :: n
INTEGER(I4B) :: nold,ierr
allocate(reallocate_rv(n),stat=ierr)
if (ierr /= 0) call &
  nrerror('reallocate_rv: problem in attempt to allocate memory')
if (.not. associated(p)) RETURN
nold=size(p)
reallocate_rv(1:min(nold,n))=p(1:min(nold,n))
deallocate(p)
END FUNCTION reallocate_rv

FUNCTION reallocate_iv(p,n)
INTEGER(I4B), DIMENSION(:), POINTER :: p, reallocate_iv
INTEGER(I4B), INTENT(IN) :: n
INTEGER(I4B) :: nold,ierr
allocate(reallocate_iv(n),stat=ierr)
if (ierr /= 0) call &
  nrerror('reallocate_iv: problem in attempt to allocate memory')
if (.not. associated(p)) RETURN
nold=size(p)
reallocate_iv(1:min(nold,n))=p(1:min(nold,n))
deallocate(p)
END FUNCTION reallocate_iv

FUNCTION reallocate_hv(p,n)
CHARACTER(1), DIMENSION(:), POINTER :: p, reallocate_hv
INTEGER(I4B), INTENT(IN) :: n
INTEGER(I4B) :: nold,ierr
allocate(reallocate_hv(n),stat=ierr)
if (ierr /= 0) call &
  nrerror('reallocate_hv: problem in attempt to allocate memory')
if (.not. associated(p)) RETURN
nold=size(p)
reallocate_hv(1:min(nold,n))=p(1:min(nold,n))

```

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```

deallocate(p)
END FUNCTION reallocate_hv

FUNCTION reallocate_rm(p,n,m)
REAL(SP), DIMENSION(:,:), POINTER :: p, reallocate_rm
INTEGER(I4B), INTENT(IN) :: n,m
INTEGER(I4B) :: nold,mold,ierr
allocate(reallocate_rm(n,m),stat=ierr)
if (ierr /= 0) call &
  nrerror('reallocate_rm: problem in attempt to allocate memory')
if (.not. associated(p)) RETURN
nold=size(p,1)
mold=size(p,2)
reallocate_rm(1:min(nold,n),1:min(mold,m))=&
  p(1:min(nold,n),1:min(mold,m))
deallocate(p)
END FUNCTION reallocate_rm

FUNCTION reallocate_im(p,n,m)
INTEGER(I4B), DIMENSION(:,:), POINTER :: p, reallocate_im
INTEGER(I4B), INTENT(IN) :: n,m
INTEGER(I4B) :: nold,mold,ierr
allocate(reallocate_im(n,m),stat=ierr)
if (ierr /= 0) call &
  nrerror('reallocate_im: problem in attempt to allocate memory')
if (.not. associated(p)) RETURN
nold=size(p,1)
mold=size(p,2)
reallocate_im(1:min(nold,n),1:min(mold,m))=&
  p(1:min(nold,n),1:min(mold,m))
deallocate(p)
END FUNCTION reallocate_im

```

Routines returning a location as an integer value:

```

FUNCTION ifirstloc(mask)
  Index of first occurrence of .true. in a logical vector.
  LOGICAL(LGT), DIMENSION(:), INTENT(IN) :: mask
  INTEGER(I4B) :: ifirstloc
  INTEGER(I4B), DIMENSION(1) :: loc
  loc=maxloc(merge(1,0,mask))
  ifirstloc=loc(1)
  if (.not. mask(ifirstloc)) ifirstloc=size(mask)+1
END FUNCTION ifirstloc

FUNCTION imaxloc_r(arr)
  Index of maxloc on an array.
  REAL(SP), DIMENSION(:), INTENT(IN) :: arr
  INTEGER(I4B) :: imaxloc_r
  INTEGER(I4B), DIMENSION(1) :: imax
  imax=maxloc(arr(:))
  imaxloc_r=imax(1)
END FUNCTION imaxloc_r

FUNCTION imaxloc_i(iarr)
  INTEGER(I4B), DIMENSION(:), INTENT(IN) :: iarr
  INTEGER(I4B), DIMENSION(1) :: imax
  INTEGER(I4B) :: imaxloc_i
  imax=maxloc(iarr(:))
  imaxloc_i=imax(1)
END FUNCTION imaxloc_i

FUNCTION iminloc(arr)
  Index of minloc on an array.
  REAL(SP), DIMENSION(:), INTENT(IN) :: arr
  INTEGER(I4B), DIMENSION(1) :: imin
  INTEGER(I4B) :: iminloc
  imin=minloc(arr(:))

```

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```

iminloc=imin(1)
END FUNCTION iminloc

  Routines for argument checking and error handling:
SUBROUTINE assert1(n1,string)
  Report and die if any logical is false (used for arg range checking).
CHARACTER(LEN=*), INTENT(IN) :: string
LOGICAL, INTENT(IN) :: n1
if (.not. n1) then
  write (*,*) 'nrerror: an assertion failed with this tag:', &
    string
  STOP 'program terminated by assert1'
end if
END SUBROUTINE assert1

SUBROUTINE assert2(n1,n2,string)
CHARACTER(LEN=*), INTENT(IN) :: string
LOGICAL, INTENT(IN) :: n1,n2
if (.not. (n1 .and. n2)) then
  write (*,*) 'nrerror: an assertion failed with this tag:', &
    string
  STOP 'program terminated by assert2'
end if
END SUBROUTINE assert2

SUBROUTINE assert3(n1,n2,n3,string)
CHARACTER(LEN=*), INTENT(IN) :: string
LOGICAL, INTENT(IN) :: n1,n2,n3
if (.not. (n1 .and. n2 .and. n3)) then
  write (*,*) 'nrerror: an assertion failed with this tag:', &
    string
  STOP 'program terminated by assert3'
end if
END SUBROUTINE assert3

SUBROUTINE assert4(n1,n2,n3,n4,string)
CHARACTER(LEN=*), INTENT(IN) :: string
LOGICAL, INTENT(IN) :: n1,n2,n3,n4
if (.not. (n1 .and. n2 .and. n3 .and. n4)) then
  write (*,*) 'nrerror: an assertion failed with this tag:', &
    string
  STOP 'program terminated by assert4'
end if
END SUBROUTINE assert4

SUBROUTINE assert_v(n,string)
CHARACTER(LEN=*), INTENT(IN) :: string
LOGICAL, DIMENSION(:), INTENT(IN) :: n
if (.not. all(n)) then
  write (*,*) 'nrerror: an assertion failed with this tag:', &
    string
  STOP 'program terminated by assert_v'
end if
END SUBROUTINE assert_v

FUNCTION assert_eq2(n1,n2,string)
  Report and die if integers not all equal (used for size checking).
CHARACTER(LEN=*), INTENT(IN) :: string
INTEGER, INTENT(IN) :: n1,n2
INTEGER :: assert_eq2
if (n1 == n2) then
  assert_eq2=n1
else
  write (*,*) 'nrerror: an assert_eq failed with this tag:', &
    string
  STOP 'program terminated by assert_eq2'
end if

```

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```

END FUNCTION assert_eq2

FUNCTION assert_eq3(n1,n2,n3,string)
CHARACTER(LEN=*), INTENT(IN) :: string
INTEGER, INTENT(IN) :: n1,n2,n3
INTEGER :: assert_eq3
if (n1 == n2 .and. n2 == n3) then
  assert_eq3=n1
else
  write (*,*) 'nrerror: an assert_eq failed with this tag:', &
    string
  STOP 'program terminated by assert_eq3'
end if
END FUNCTION assert_eq3

FUNCTION assert_eq4(n1,n2,n3,n4,string)
CHARACTER(LEN=*), INTENT(IN) :: string
INTEGER, INTENT(IN) :: n1,n2,n3,n4
INTEGER :: assert_eq4
if (n1 == n2 .and. n2 == n3 .and. n3 == n4) then
  assert_eq4=n1
else
  write (*,*) 'nrerror: an assert_eq failed with this tag:', &
    string
  STOP 'program terminated by assert_eq4'
end if
END FUNCTION assert_eq4

FUNCTION assert_eqn(nn,string)
CHARACTER(LEN=*), INTENT(IN) :: string
INTEGER, DIMENSION(:), INTENT(IN) :: nn
INTEGER :: assert_eqn
if (all(nn(2:) == nn(1))) then
  assert_eqn=nn(1)
else
  write (*,*) 'nrerror: an assert_eq failed with this tag:', &
    string
  STOP 'program terminated by assert_eqn'
end if
END FUNCTION assert_eqn

SUBROUTINE nrerror(string)
  Report a message, then die.
CHARACTER(LEN=*), INTENT(IN) :: string
write (*,*) 'nrerror: ',string
STOP 'program terminated by nrerror'
END SUBROUTINE nrerror

Routines relating to polynomials and recurrences:
FUNCTION arth_r(first,increment,n)
  Array function returning an arithmetic progression.
REAL(SP), INTENT(IN) :: first,increment
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), DIMENSION(n) :: arth_r
INTEGER(I4B) :: k,k2
REAL(SP) :: temp
if (n > 0) arth_r(1)=first
if (n <= NPAR_ARTH) then
  do k=2,n
    arth_r(k)=arth_r(k-1)+increment
  end do
else
  do k=2,NPAR2_ARTH
    arth_r(k)=arth_r(k-1)+increment
  end do
  temp=increment*NPAR2_ARTH
  k=NPAR2_ARTH

```

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```

do
  if (k >= n) exit
  k2=k+k
  arth_r(k+1:min(k2,n))=temp+arth_r(1:min(k,n-k))
  temp=temp+temp
  k=k2
end do
end if
END FUNCTION arth_r

FUNCTION arth_d(first,increment,n)
REAL(DP), INTENT(IN) :: first,increment
INTEGER(I4B), INTENT(IN) :: n
REAL(DP), DIMENSION(n) :: arth_d
INTEGER(I4B) :: k,k2
REAL(DP) :: temp
if (n > 0) arth_d(1)=first
if (n <= NPAR_ARTH) then
  do k=2,n
    arth_d(k)=arth_d(k-1)+increment
  end do
else
  do k=2,NPAR2_ARTH
    arth_d(k)=arth_d(k-1)+increment
  end do
  temp=increment*NPAR2_ARTH
  k=NPAR2_ARTH
  do
    if (k >= n) exit
    k2=k+k
    arth_d(k+1:min(k2,n))=temp+arth_d(1:min(k,n-k))
    temp=temp+temp
    k=k2
  end do
end if
END FUNCTION arth_d

FUNCTION arth_i(first,increment,n)
INTEGER(I4B), INTENT(IN) :: first,increment,n
INTEGER(I4B), DIMENSION(n) :: arth_i
INTEGER(I4B) :: k,k2,temp
if (n > 0) arth_i(1)=first
if (n <= NPAR_ARTH) then
  do k=2,n
    arth_i(k)=arth_i(k-1)+increment
  end do
else
  do k=2,NPAR2_ARTH
    arth_i(k)=arth_i(k-1)+increment
  end do
  temp=increment*NPAR2_ARTH
  k=NPAR2_ARTH
  do
    if (k >= n) exit
    k2=k+k
    arth_i(k+1:min(k2,n))=temp+arth_i(1:min(k,n-k))
    temp=temp+temp
    k=k2
  end do
end if
END FUNCTION arth_i

FUNCTION geop_r(first,factor,n)
  Array function returning a geometric progression.
REAL(SP), INTENT(IN) :: first,factor

```

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```

INTEGER(I4B), INTENT(IN) :: n
REAL(SP), DIMENSION(n) :: geop_r
INTEGER(I4B) :: k,k2
REAL(SP) :: temp
if (n > 0) geop_r(1)=first
if (n <= NPAR_GEOP) then
  do k=2,n
    geop_r(k)=geop_r(k-1)*factor
  end do
else
  do k=2,NPAR2_GEOP
    geop_r(k)=geop_r(k-1)*factor
  end do
  temp=factor**NPAR2_GEOP
  k=NPAR2_GEOP
  do
    if (k >= n) exit
    k2=k+k
    geop_r(k+1:min(k2,n))=temp*geop_r(1:min(k,n-k))
    temp=temp*temp
    k=k2
  end do
end if
END FUNCTION geop_r

FUNCTION geop_d(first,factor,n)
REAL(DP), INTENT(IN) :: first,factor
INTEGER(I4B), INTENT(IN) :: n
REAL(DP), DIMENSION(n) :: geop_d
INTEGER(I4B) :: k,k2
REAL(DP) :: temp
if (n > 0) geop_d(1)=first
if (n <= NPAR_GEOP) then
  do k=2,n
    geop_d(k)=geop_d(k-1)*factor
  end do
else
  do k=2,NPAR2_GEOP
    geop_d(k)=geop_d(k-1)*factor
  end do
  temp=factor**NPAR2_GEOP
  k=NPAR2_GEOP
  do
    if (k >= n) exit
    k2=k+k
    geop_d(k+1:min(k2,n))=temp*geop_d(1:min(k,n-k))
    temp=temp*temp
    k=k2
  end do
end if
END FUNCTION geop_d

FUNCTION geop_i(first,factor,n)
INTEGER(I4B), INTENT(IN) :: first,factor,n
INTEGER(I4B), DIMENSION(n) :: geop_i
INTEGER(I4B) :: k,k2,temp
if (n > 0) geop_i(1)=first
if (n <= NPAR_GEOP) then
  do k=2,n
    geop_i(k)=geop_i(k-1)*factor
  end do
else
  do k=2,NPAR2_GEOP
    geop_i(k)=geop_i(k-1)*factor
  end do

```

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```

temp=factor**NPAR2_GEOP
k=NPAR2_GEOP
do
  if (k >= n) exit
  k2=k+k
  geop_i(k+1:min(k2,n))=temp*geop_i(1:min(k,n-k))
  temp=temp*temp
  k=k2
end do
end if
END FUNCTION geop_i
FUNCTION geop_c(first,factor,n)
COMPLEX(SP), INTENT(IN) :: first,factor
INTEGER(I4B), INTENT(IN) :: n
COMPLEX(SP), DIMENSION(n) :: geop_c
INTEGER(I4B) :: k,k2
COMPLEX(SP) :: temp
if (n > 0) geop_c(1)=first
if (n <= NPAR_GEOP) then
  do k=2,n
    geop_c(k)=geop_c(k-1)*factor
  end do
else
  do k=2,NPAR2_GEOP
    geop_c(k)=geop_c(k-1)*factor
  end do
  temp=factor**NPAR2_GEOP
  k=NPAR2_GEOP
  do
    if (k >= n) exit
    k2=k+k
    geop_c(k+1:min(k2,n))=temp*geop_c(1:min(k,n-k))
    temp=temp*temp
    k=k2
  end do
end if
END FUNCTION geop_c
FUNCTION geop_dv(first,factor,n)
REAL(DP), DIMENSION(:), INTENT(IN) :: first,factor
INTEGER(I4B), INTENT(IN) :: n
REAL(DP), DIMENSION(size(first),n) :: geop_dv
INTEGER(I4B) :: k,k2
REAL(DP), DIMENSION(size(first)) :: temp
if (n > 0) geop_dv(:,1)=first(:)
if (n <= NPAR_GEOP) then
  do k=2,n
    geop_dv(:,k)=geop_dv(:,k-1)*factor(:)
  end do
else
  do k=2,NPAR2_GEOP
    geop_dv(:,k)=geop_dv(:,k-1)*factor(:)
  end do
  temp=factor**NPAR2_GEOP
  k=NPAR2_GEOP
  do
    if (k >= n) exit
    k2=k+k
    geop_dv(:,k+1:min(k2,n))=geop_dv(:,1:min(k,n-k))*&
      spread(temp,2,size(geop_dv(:,1:min(k,n-k)),2))
    temp=temp*temp
    k=k2
  end do
end if

```

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```

END FUNCTION geop_dv

RECURSIVE FUNCTION cumsum_r(arr,seed) RESULT(ans)
    Cumulative sum on an array, with optional additive seed.
    REAL(SP), DIMENSION(:), INTENT(IN) :: arr
    REAL(SP), OPTIONAL, INTENT(IN) :: seed
    REAL(SP), DIMENSION(size(arr)) :: ans
    INTEGER(I4B) :: n,j
    REAL(SP) :: sd
    n=size(arr)
    if (n == 0_i4b) RETURN
    sd=0.0_sp
    if (present(seed)) sd=seed
    ans(1)=arr(1)+sd
    if (n < NPAR_CUMSUM) then
        do j=2,n
            ans(j)=ans(j-1)+arr(j)
        end do
    else
        ans(2:n:2)=cumsum_r(arr(2:n:2)+arr(1:n-1:2),sd)
        ans(3:n:2)=ans(2:n-1:2)+arr(3:n:2)
    end if
END FUNCTION cumsum_r

RECURSIVE FUNCTION cumsum_i(arr,seed) RESULT(ans)
    INTEGER(I4B), DIMENSION(:), INTENT(IN) :: arr
    INTEGER(I4B), OPTIONAL, INTENT(IN) :: seed
    INTEGER(I4B), DIMENSION(size(arr)) :: ans
    INTEGER(I4B) :: n,j,sd
    n=size(arr)
    if (n == 0_i4b) RETURN
    sd=0_i4b
    if (present(seed)) sd=seed
    ans(1)=arr(1)+sd
    if (n < NPAR_CUMSUM) then
        do j=2,n
            ans(j)=ans(j-1)+arr(j)
        end do
    else
        ans(2:n:2)=cumsum_i(arr(2:n:2)+arr(1:n-1:2),sd)
        ans(3:n:2)=ans(2:n-1:2)+arr(3:n:2)
    end if
END FUNCTION cumsum_i

RECURSIVE FUNCTION cumprod(arr,seed) RESULT(ans)
    Cumulative product on an array, with optional multiplicative seed.
    REAL(SP), DIMENSION(:), INTENT(IN) :: arr
    REAL(SP), OPTIONAL, INTENT(IN) :: seed
    REAL(SP), DIMENSION(size(arr)) :: ans
    INTEGER(I4B) :: n,j
    REAL(SP) :: sd
    n=size(arr)
    if (n == 0_i4b) RETURN
    sd=1.0_sp
    if (present(seed)) sd=seed
    ans(1)=arr(1)*sd
    if (n < NPAR_CUMPROD) then
        do j=2,n
            ans(j)=ans(j-1)*arr(j)
        end do
    else
        ans(2:n:2)=cumprod(arr(2:n:2)*arr(1:n-1:2),sd)
        ans(3:n:2)=ans(2:n-1:2)*arr(3:n:2)
    end if
END FUNCTION cumprod

```

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```

FUNCTION poly_rr(x,coeffs)
  Polynomial evaluation.
  REAL(SP), INTENT(IN) :: x
  REAL(SP), DIMENSION(:), INTENT(IN) :: coeffs
  REAL(SP) :: poly_rr
  REAL(SP) :: pow
  REAL(SP), DIMENSION(:), ALLOCATABLE :: vec
  INTEGER(I4B) :: i,n,nn
  n=size(coeffs)
  if (n <= 0) then
    poly_rr=0.0_sp
  else if (n < NPAR_POLY) then
    poly_rr=coeffs(n)
    do i=n-1,1,-1
      poly_rr=x*poly_rr+coeffs(i)
    end do
  else
    allocate(vec(n+1))
    pow=x
    vec(1:n)=coeffs
    do
      vec(n+1)=0.0_sp
      nn=ishft(n+1,-1)
      vec(1:nn)=vec(1:n:2)+pow*vec(2:n+1:2)
      if (nn == 1) exit
      pow=pow*pow
      n=nn
    end do
    poly_rr=vec(1)
    deallocate(vec)
  end if
END FUNCTION poly_rr

FUNCTION poly_dd(x,coeffs)
  REAL(DP), INTENT(IN) :: x
  REAL(DP), DIMENSION(:), INTENT(IN) :: coeffs
  REAL(DP) :: poly_dd
  REAL(DP) :: pow
  REAL(DP), DIMENSION(:), ALLOCATABLE :: vec
  INTEGER(I4B) :: i,n,nn
  n=size(coeffs)
  if (n <= 0) then
    poly_dd=0.0_dp
  else if (n < NPAR_POLY) then
    poly_dd=coeffs(n)
    do i=n-1,1,-1
      poly_dd=x*poly_dd+coeffs(i)
    end do
  else
    allocate(vec(n+1))
    pow=x
    vec(1:n)=coeffs
    do
      vec(n+1)=0.0_dp
      nn=ishft(n+1,-1)
      vec(1:nn)=vec(1:n:2)+pow*vec(2:n+1:2)
      if (nn == 1) exit
      pow=pow*pow
      n=nn
    end do
    poly_dd=vec(1)
    deallocate(vec)
  end if
END FUNCTION poly_dd

```

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```

FUNCTION poly_rc(x,coeffs)
COMPLEX(SPC), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(IN) :: coeffs
COMPLEX(SPC) :: poly_rc
COMPLEX(SPC) :: pow
COMPLEX(SPC), DIMENSION(:), ALLOCATABLE :: vec
INTEGER(I4B) :: i,n,nn
n=size(coeffs)
if (n <= 0) then
  poly_rc=0.0_sp
else if (n < NPAR_POLY) then
  poly_rc=coeffs(n)
  do i=n-1,1,-1
    poly_rc=x*poly_rc+coeffs(i)
  end do
else
  allocate(vec(n+1))
  pow=x
  vec(1:n)=coeffs
  do
    vec(n+1)=0.0_sp
    nn=ishft(n+1,-1)
    vec(1:nn)=vec(1:n:2)+pow*vec(2:n+1:2)
    if (nn == 1) exit
    pow=pow*pow
    n=nn
  end do
  poly_rc=vec(1)
  deallocate(vec)
end if
END FUNCTION poly_rc

FUNCTION poly_cc(x,coeffs)
COMPLEX(SPC), INTENT(IN) :: x
COMPLEX(SPC), DIMENSION(:), INTENT(IN) :: coeffs
COMPLEX(SPC) :: poly_cc
COMPLEX(SPC) :: pow
COMPLEX(SPC), DIMENSION(:), ALLOCATABLE :: vec
INTEGER(I4B) :: i,n,nn
n=size(coeffs)
if (n <= 0) then
  poly_cc=0.0_sp
else if (n < NPAR_POLY) then
  poly_cc=coeffs(n)
  do i=n-1,1,-1
    poly_cc=x*poly_cc+coeffs(i)
  end do
else
  allocate(vec(n+1))
  pow=x
  vec(1:n)=coeffs
  do
    vec(n+1)=0.0_sp
    nn=ishft(n+1,-1)
    vec(1:nn)=vec(1:n:2)+pow*vec(2:n+1:2)
    if (nn == 1) exit
    pow=pow*pow
    n=nn
  end do
  poly_cc=vec(1)
  deallocate(vec)
end if
END FUNCTION poly_cc

FUNCTION poly_rrv(x,coeffs)

```

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```

REAL(SP), DIMENSION(:), INTENT(IN) :: coeffs,x
REAL(SP), DIMENSION(size(x)) :: poly_rrv
INTEGER(I4B) :: i,n,m
m=size(coeffs)
n=size(x)
if (m <= 0) then
  poly_rrv=0.0_sp
else if (m < n .or. m < NPAR_POLY) then
  poly_rrv=coeffs(m)
  do i=m-1,1,-1
    poly_rrv=x*poly_rrv+coeffs(i)
  end do
else
  do i=1,n
    poly_rrv(i)=poly_rr(x(i),coeffs)
  end do
end if
END FUNCTION poly_rrv

FUNCTION poly_ddv(x,coeffs)
REAL(DP), DIMENSION(:), INTENT(IN) :: coeffs,x
REAL(DP), DIMENSION(size(x)) :: poly_ddv
INTEGER(I4B) :: i,n,m
m=size(coeffs)
n=size(x)
if (m <= 0) then
  poly_ddv=0.0_dp
else if (m < n .or. m < NPAR_POLY) then
  poly_ddv=coeffs(m)
  do i=m-1,1,-1
    poly_ddv=x*poly_ddv+coeffs(i)
  end do
else
  do i=1,n
    poly_ddv(i)=poly_dd(x(i),coeffs)
  end do
end if
END FUNCTION poly_ddv

FUNCTION poly_msk_rrv(x,coeffs,mask)
REAL(SP), DIMENSION(:), INTENT(IN) :: coeffs,x
LOGICAL(LGT), DIMENSION(:), INTENT(IN) :: mask
REAL(SP), DIMENSION(size(x)) :: poly_msk_rrv
poly_msk_rrv=unpack(poly_rrv(pack(x,mask),coeffs),mask,0.0_sp)
END FUNCTION poly_msk_rrv

FUNCTION poly_msk_ddv(x,coeffs,mask)
REAL(DP), DIMENSION(:), INTENT(IN) :: coeffs,x
LOGICAL(LGT), DIMENSION(:), INTENT(IN) :: mask
REAL(DP), DIMENSION(size(x)) :: poly_msk_ddv
poly_msk_ddv=unpack(poly_ddv(pack(x,mask),coeffs),mask,0.0_dp)
END FUNCTION poly_msk_ddv

RECURSIVE FUNCTION poly_term_rr(a,b) RESULT(u)
  Tabulate cumulants of a polynomial.
REAL(SP), DIMENSION(:), INTENT(IN) :: a
REAL(SP), INTENT(IN) :: b
REAL(SP), DIMENSION(size(a)) :: u
INTEGER(I4B) :: n,j
n=size(a)
if (n <= 0) RETURN
u(1)=a(1)
if (n < NPAR_POLYTERM) then
  do j=2,n
    u(j)=a(j)+b*u(j-1)
  end do

```

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```

else
  u(2:n:2)=poly_term_rr(a(2:n:2)+a(1:n-1:2)*b,b*b)
  u(3:n:2)=a(3:n:2)+b*u(2:n-1:2)
end if
END FUNCTION poly_term_rr

RECURSIVE FUNCTION poly_term_cc(a,b) RESULT(u)
COMPLEX(SPC), DIMENSION(:), INTENT(IN) :: a
COMPLEX(SPC), INTENT(IN) :: b
COMPLEX(SPC), DIMENSION(size(a)) :: u
INTEGER(I4B) :: n,j
n=size(a)
if (n <= 0) RETURN
u(1)=a(1)
if (n < NPAR_POLYTERM) then
  do j=2,n
    u(j)=a(j)+b*u(j-1)
  end do
else
  u(2:n:2)=poly_term_cc(a(2:n:2)+a(1:n-1:2)*b,b*b)
  u(3:n:2)=a(3:n:2)+b*u(2:n-1:2)
end if
END FUNCTION poly_term_cc

FUNCTION zroots_unity(n,nn)
  Complex function returning nn powers of the nth root of unity.
  INTEGER(I4B), INTENT(IN) :: n,nn
  COMPLEX(SPC), DIMENSION(nn) :: zroots_unity
  INTEGER(I4B) :: k
  REAL(SP) :: theta
  zroots_unity(1)=1.0
  theta=TWOPI/n
  k=1
  do
    if (k >= nn) exit
    zroots_unity(k+1)=cplx(cos(k*theta),sin(k*theta),SPC)
    zroots_unity(k+2:min(2*k,nn))=zroots_unity(k+1)*&
      zroots_unity(2:min(k,nn-k))
    k=2*k
  end do
END FUNCTION zroots_unity

  Routines for "outer" operations on vectors. The order convention is: result(i,j) = first_operand(i)
  (op) second_operand(j).
FUNCTION outerprod_r(a,b)
REAL(SP), DIMENSION(:), INTENT(IN) :: a,b
REAL(SP), DIMENSION(size(a),size(b)) :: outerprod_r
outerprod_r = spread(a,dim=2,ncopies=size(b)) * &
  spread(b,dim=1,ncopies=size(a))
END FUNCTION outerprod_r

FUNCTION outerprod_d(a,b)
REAL(DP), DIMENSION(:), INTENT(IN) :: a,b
REAL(DP), DIMENSION(size(a),size(b)) :: outerprod_d
outerprod_d = spread(a,dim=2,ncopies=size(b)) * &
  spread(b,dim=1,ncopies=size(a))
END FUNCTION outerprod_d

FUNCTION outerdiv(a,b)
REAL(SP), DIMENSION(:), INTENT(IN) :: a,b
REAL(SP), DIMENSION(size(a),size(b)) :: outerdiv
outerdiv = spread(a,dim=2,ncopies=size(b)) / &
  spread(b,dim=1,ncopies=size(a))
END FUNCTION outerdiv

FUNCTION outersum(a,b)
REAL(SP), DIMENSION(:), INTENT(IN) :: a,b

```

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```

REAL(SP), DIMENSION(size(a),size(b)) :: outersum
outersum = spread(a,dim=2,ncopies=size(b)) + &
  spread(b,dim=1,ncopies=size(a))
END FUNCTION outersum

FUNCTION outerdiff_r(a,b)
REAL(SP), DIMENSION(:), INTENT(IN) :: a,b
REAL(SP), DIMENSION(size(a),size(b)) :: outerdiff_r
outersdiff_r = spread(a,dim=2,ncopies=size(b)) - &
  spread(b,dim=1,ncopies=size(a))
END FUNCTION outerdiff_r

FUNCTION outerdiff_d(a,b)
REAL(DP), DIMENSION(:), INTENT(IN) :: a,b
REAL(DP), DIMENSION(size(a),size(b)) :: outerdiff_d
outersdiff_d = spread(a,dim=2,ncopies=size(b)) - &
  spread(b,dim=1,ncopies=size(a))
END FUNCTION outerdiff_d

FUNCTION outerdiff_i(a,b)
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: a,b
INTEGER(I4B), DIMENSION(size(a),size(b)) :: outerdiff_i
outersdiff_i = spread(a,dim=2,ncopies=size(b)) - &
  spread(b,dim=1,ncopies=size(a))
END FUNCTION outerdiff_i

FUNCTION outerand(a,b)
LOGICAL(LGT), DIMENSION(:), INTENT(IN) :: a,b
LOGICAL(LGT), DIMENSION(size(a),size(b)) :: outerand
outerand = spread(a,dim=2,ncopies=size(b)) .and. &
  spread(b,dim=1,ncopies=size(a))
END FUNCTION outerand

  Routines for scatter-with-combine.
SUBROUTINE scatter_add_r(dest,source,dest_index)
REAL(SP), DIMENSION(:), INTENT(OUT) :: dest
REAL(SP), DIMENSION(:), INTENT(IN) :: source
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: dest_index
INTEGER(I4B) :: m,n,j,i
n=assert_eq2(size(source),size(dest_index),'scatter_add_r')
m=size(dest)
do j=1,n
  i=dest_index(j)
  if (i > 0 .and. i <= m) dest(i)=dest(i)+source(j)
end do
END SUBROUTINE scatter_add_r
SUBROUTINE scatter_add_d(dest,source,dest_index)
REAL(DP), DIMENSION(:), INTENT(OUT) :: dest
REAL(DP), DIMENSION(:), INTENT(IN) :: source
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: dest_index
INTEGER(I4B) :: m,n,j,i
n=assert_eq2(size(source),size(dest_index),'scatter_add_d')
m=size(dest)
do j=1,n
  i=dest_index(j)
  if (i > 0 .and. i <= m) dest(i)=dest(i)+source(j)
end do
END SUBROUTINE scatter_add_d
SUBROUTINE scatter_max_r(dest,source,dest_index)
REAL(SP), DIMENSION(:), INTENT(OUT) :: dest
REAL(SP), DIMENSION(:), INTENT(IN) :: source
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: dest_index
INTEGER(I4B) :: m,n,j,i
n=assert_eq2(size(source),size(dest_index),'scatter_max_r')
m=size(dest)
do j=1,n
  i=dest_index(j)

```

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```

        if (i > 0 .and. i <= m) dest(i)=max(dest(i),source(j))
    end do
END SUBROUTINE scatter_max_r
SUBROUTINE scatter_max_d(dest,source,dest_index)
REAL(DP), DIMENSION(:), INTENT(OUT) :: dest
REAL(DP), DIMENSION(:), INTENT(IN) :: source
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: dest_index
INTEGER(I4B) :: m,n,j,i
n=assert_eq2(size(source),size(dest_index),'scatter_max_d')
m=size(dest)
do j=1,n
    i=dest_index(j)
    if (i > 0 .and. i <= m) dest(i)=max(dest(i),source(j))
end do
END SUBROUTINE scatter_max_d

Routines for skew operations on matrices:
SUBROUTINE diagadd_rv(mat,diag)
    Adds vector or scalar diag to the diagonal of matrix mat.
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: mat
REAL(SP), DIMENSION(:), INTENT(IN) :: diag
INTEGER(I4B) :: j,n
n = assert_eq2(size(diag),min(size(mat,1),size(mat,2)),'diagadd_rv')
do j=1,n
    mat(j,j)=mat(j,j)+diag(j)
end do
END SUBROUTINE diagadd_rv

SUBROUTINE diagadd_r(mat,diag)
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: mat
REAL(SP), INTENT(IN) :: diag
INTEGER(I4B) :: j,n
n = min(size(mat,1),size(mat,2))
do j=1,n
    mat(j,j)=mat(j,j)+diag
end do
END SUBROUTINE diagadd_r

SUBROUTINE diagmult_rv(mat,diag)
    Multiplies vector or scalar diag into the diagonal of matrix mat.
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: mat
REAL(SP), DIMENSION(:), INTENT(IN) :: diag
INTEGER(I4B) :: j,n
n = assert_eq2(size(diag),min(size(mat,1),size(mat,2)),'diagmult_rv')
do j=1,n
    mat(j,j)=mat(j,j)*diag(j)
end do
END SUBROUTINE diagmult_rv

SUBROUTINE diagmult_r(mat,diag)
REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: mat
REAL(SP), INTENT(IN) :: diag
INTEGER(I4B) :: j,n
n = min(size(mat,1),size(mat,2))
do j=1,n
    mat(j,j)=mat(j,j)*diag
end do
END SUBROUTINE diagmult_r

FUNCTION get_diag_rv(mat)
    Return as a vector the diagonal of matrix mat.
REAL(SP), DIMENSION(:,:), INTENT(IN) :: mat
REAL(SP), DIMENSION(size(mat,1)) :: get_diag_rv
INTEGER(I4B) :: j
j=assert_eq2(size(mat,1),size(mat,2),'get_diag_rv')
do j=1,size(mat,1)
    get_diag_rv(j)=mat(j,j)

```

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```

end do
END FUNCTION get_diag_rv

FUNCTION get_diag_dv(mat)
REAL(DP), DIMENSION(:,,:), INTENT(IN) :: mat
REAL(DP), DIMENSION(size(mat,1)) :: get_diag_dv
INTEGER(I4B) :: j
j=assert_eq2(size(mat,1),size(mat,2),'get_diag_dv')
do j=1,size(mat,1)
    get_diag_dv(j)=mat(j,j)
end do
END FUNCTION get_diag_dv

SUBROUTINE put_diag_rv(diagv,mat)
    Set the diagonal of matrix mat to the values of a vector or scalar.
REAL(SP), DIMENSION(:), INTENT(IN) :: diagv
REAL(SP), DIMENSION(:,,:), INTENT(INOUT) :: mat
INTEGER(I4B) :: j,n
n=assert_eq2(size(diagv),min(size(mat,1),size(mat,2)),'put_diag_rv')
do j=1,n
    mat(j,j)=diagv(j)
end do
END SUBROUTINE put_diag_rv

SUBROUTINE put_diag_r(scal,mat)
REAL(SP), INTENT(IN) :: scal
REAL(SP), DIMENSION(:,,:), INTENT(INOUT) :: mat
INTEGER(I4B) :: j,n
n = min(size(mat,1),size(mat,2))
do j=1,n
    mat(j,j)=scal
end do
END SUBROUTINE put_diag_r

SUBROUTINE unit_matrix(mat)
    Set the matrix mat to be a unit matrix (if it is square).
REAL(SP), DIMENSION(:,,:), INTENT(OUT) :: mat
INTEGER(I4B) :: i,n
n=min(size(mat,1),size(mat,2))
mat(:,:)=0.0_sp
do i=1,n
    mat(i,i)=1.0_sp
end do
END SUBROUTINE unit_matrix

FUNCTION upper_triangle(j,k,extra)
    Return an upper triangular logical mask.
INTEGER(I4B), INTENT(IN) :: j,k
INTEGER(I4B), OPTIONAL, INTENT(IN) :: extra
LOGICAL(LGT), DIMENSION(j,k) :: upper_triangle
INTEGER(I4B) :: n
n=0
if (present(extra)) n=extra
upper_triangle=(outerdiff(arth_i(1,1,j),arth_i(1,1,k)) < n)
END FUNCTION upper_triangle

FUNCTION lower_triangle(j,k,extra)
    Return a lower triangular logical mask.
INTEGER(I4B), INTENT(IN) :: j,k
INTEGER(I4B), OPTIONAL, INTENT(IN) :: extra
LOGICAL(LGT), DIMENSION(j,k) :: lower_triangle
INTEGER(I4B) :: n
n=0
if (present(extra)) n=extra
lower_triangle=(outerdiff(arth_i(1,1,j),arth_i(1,1,k)) > -n)
END FUNCTION lower_triangle

```

Other routines:

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```
FUNCTION vabs(v)
    Return the length (ordinary  $L_2$  norm) of a vector.
    REAL(SP), DIMENSION(:), INTENT(IN) :: v
    REAL(SP) :: vabs
    vabs=sqrt(dot_product(v,v))
END FUNCTION vabs

END MODULE nrutil
```

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## C2. Alphabetical Listing of Explicit Interfaces

The file supplied as `nr.f90` contains explicit interfaces for all the Numerical Recipes routines (except those already in the module `nrutil`). The interfaces are in alphabetical order, by the generic interface name, if one exists, or by the specific routine name if there is no generic name.

The file `nr.f90` is normally invoked via a USE statement within a main program or subroutine that references a Numerical Recipes routine. See §21.1 for an example.

```
MODULE nr
INTERFACE
  SUBROUTINE airy(x,ai,bi,aip,bip)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP), INTENT(OUT) :: ai,bi,aip,bip
  END SUBROUTINE airy
END INTERFACE
INTERFACE
  SUBROUTINE amebsa(p,y,pb,yb,ftol,func,iter,temptr)
    USE nrtype
    INTEGER(I4B), INTENT(INOUT) :: iter
    REAL(SP), INTENT(INOUT) :: yb
    REAL(SP), INTENT(IN) :: ftol,temptr
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: y,pb
    REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: p
  INTERFACE
    FUNCTION func(x)
      USE nrtype
      REAL(SP), DIMENSION(:), INTENT(IN) :: x
      REAL(SP) :: func
    END FUNCTION func
  END INTERFACE
  END SUBROUTINE amebsa
END INTERFACE
INTERFACE
  SUBROUTINE amoeba(p,y,ftol,func,iter)
    USE nrtype
    INTEGER(I4B), INTENT(OUT) :: iter
    REAL(SP), INTENT(IN) :: ftol
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
    REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: p
  INTERFACE
    FUNCTION func(x)
      USE nrtype
      REAL(SP), DIMENSION(:), INTENT(IN) :: x
      REAL(SP) :: func
    END FUNCTION func
  END INTERFACE
END INTERFACE
```

```

END SUBROUTINE amoeba
END INTERFACE
INTERFACE
SUBROUTINE anneal(x,y,iorder)
USE nrtype
INTEGER(I4B), DIMENSION(:), INTENT(INOUT) :: iorder
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
END SUBROUTINE anneal
END INTERFACE
INTERFACE
SUBROUTINE asolve(b,x,itnsp)
USE nrtype
REAL(DP), DIMENSION(:), INTENT(IN) :: b
REAL(DP), DIMENSION(:), INTENT(OUT) :: x
INTEGER(I4B), INTENT(IN) :: itnsp
END SUBROUTINE asolve
END INTERFACE
INTERFACE
SUBROUTINE atimes(x,r,itnsp)
USE nrtype
REAL(DP), DIMENSION(:), INTENT(IN) :: x
REAL(DP), DIMENSION(:), INTENT(OUT) :: r
INTEGER(I4B), INTENT(IN) :: itnsp
END SUBROUTINE atimes
END INTERFACE
INTERFACE
SUBROUTINE avevar(data,ave,var)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: data
REAL(SP), INTENT(OUT) :: ave,var
END SUBROUTINE avevar
END INTERFACE
INTERFACE
SUBROUTINE balanc(a)
USE nrtype
REAL(SP), DIMENSION(:,,:), INTENT(INOUT) :: a
END SUBROUTINE balanc
END INTERFACE
INTERFACE
SUBROUTINE banbks(a,m1,m2,al,indx,b)
USE nrtype
INTEGER(I4B), INTENT(IN) :: m1,m2
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: indx
REAL(SP), DIMENSION(:,,:), INTENT(IN) :: a,al
REAL(SP), DIMENSION(:), INTENT(INOUT) :: b
END SUBROUTINE banbks
END INTERFACE
INTERFACE
SUBROUTINE bandec(a,m1,m2,al,indx,d)
USE nrtype
INTEGER(I4B), INTENT(IN) :: m1,m2
INTEGER(I4B), DIMENSION(:), INTENT(OUT) :: indx
REAL(SP), INTENT(OUT) :: d
REAL(SP), DIMENSION(:,,:), INTENT(INOUT) :: a
REAL(SP), DIMENSION(:,,:), INTENT(OUT) :: al
END SUBROUTINE bandec
END INTERFACE
INTERFACE
SUBROUTINE banmul(a,m1,m2,x,b)
USE nrtype
INTEGER(I4B), INTENT(IN) :: m1,m2
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(OUT) :: b
REAL(SP), DIMENSION(:,,:), INTENT(IN) :: a

```

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```

    END SUBROUTINE banmul
END INTERFACE
INTERFACE
  SUBROUTINE bcucof(y,y1,y2,y12,d1,d2,c)
    USE nrtype
    REAL(SP), INTENT(IN) :: d1,d2
    REAL(SP), DIMENSION(4), INTENT(IN) :: y,y1,y2,y12
    REAL(SP), DIMENSION(4,4), INTENT(OUT) :: c
  END SUBROUTINE bcucof
END INTERFACE
INTERFACE
  SUBROUTINE bcuint(y,y1,y2,y12,x1l,x1u,x2l,x2u,x1,x2,ansy,&
    ansy1,ansy2)
    USE nrtype
    REAL(SP), DIMENSION(4), INTENT(IN) :: y,y1,y2,y12
    REAL(SP), INTENT(IN) :: x1l,x1u,x2l,x2u,x1,x2
    REAL(SP), INTENT(OUT) :: ansy,ansy1,ansy2
  END SUBROUTINE bcuint
END INTERFACE
INTERFACE beschb
  SUBROUTINE beschb_s(x,gam1,gam2,gampl,gammi)
    USE nrtype
    REAL(DP), INTENT(IN) :: x
    REAL(DP), INTENT(OUT) :: gam1,gam2,gampl,gammi
  END SUBROUTINE beschb_s

  SUBROUTINE beschb_v(x,gam1,gam2,gampl,gammi)
    USE nrtype
    REAL(DP), DIMENSION(:), INTENT(IN) :: x
    REAL(DP), DIMENSION(:), INTENT(OUT) :: gam1,gam2,gampl,gammi
  END SUBROUTINE beschb_v
END INTERFACE
INTERFACE bessi
  FUNCTION bessi_s(n,x)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: bessi_s
  END FUNCTION bessi_s

  FUNCTION bessi_v(n,x)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: bessi_v
  END FUNCTION bessi_v
END INTERFACE
INTERFACE bessio
  FUNCTION bessio_s(x)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: bessio_s
  END FUNCTION bessio_s

  FUNCTION bessio_v(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: bessio_v
  END FUNCTION bessio_v
END INTERFACE
INTERFACE bessil
  FUNCTION bessil_s(x)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: bessil_s
  END FUNCTION bessil_s

```

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```

FUNCTION bess1_v(x)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: x
  REAL(SP), DIMENSION(size(x)) :: bess1_v
END FUNCTION bess1_v
END INTERFACE
INTERFACE
  SUBROUTINE bessik(x,xnu,ri,rk,rip,rkp)
    USE nrtype
    REAL(SP), INTENT(IN) :: x,xnu
    REAL(SP), INTENT(OUT) :: ri,rk,rip,rkp
  END SUBROUTINE bessik
END INTERFACE
INTERFACE bessj
  FUNCTION bessj_s(n,x)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: bessj_s
  END FUNCTION bessj_s

  FUNCTION bessj_v(n,x)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: bessj_v
  END FUNCTION bessj_v
END INTERFACE
INTERFACE bessj0
  FUNCTION bessj0_s(x)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: bessj0_s
  END FUNCTION bessj0_s

  FUNCTION bessj0_v(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: bessj0_v
  END FUNCTION bessj0_v
END INTERFACE
INTERFACE bessj1
  FUNCTION bessj1_s(x)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: bessj1_s
  END FUNCTION bessj1_s

  FUNCTION bessj1_v(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: bessj1_v
  END FUNCTION bessj1_v
END INTERFACE
INTERFACE bessjy
  SUBROUTINE bessjy_s(x,xnu,rj,ry,rjp,ryp)
    USE nrtype
    REAL(SP), INTENT(IN) :: x,xnu
    REAL(SP), INTENT(OUT) :: rj,ry,rjp,ryp
  END SUBROUTINE bessjy_s

  SUBROUTINE bessjy_v(x,xnu,rj,ry,rjp,ryp)
    USE nrtype
    REAL(SP), INTENT(IN) :: xnu
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(:), INTENT(OUT) :: rj,rjp,ry,ryp

```

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```

    END SUBROUTINE bessjy_v
END INTERFACE
INTERFACE bessk
  FUNCTION bessk_s(n,x)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: bessk_s
  END FUNCTION bessk_s

  FUNCTION bessk_v(n,x)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: bessk_v
  END FUNCTION bessk_v
END INTERFACE
INTERFACE bessk0
  FUNCTION bessk0_s(x)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: bessk0_s
  END FUNCTION bessk0_s

  FUNCTION bessk0_v(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: bessk0_v
  END FUNCTION bessk0_v
END INTERFACE
INTERFACE bessk1
  FUNCTION bessk1_s(x)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: bessk1_s
  END FUNCTION bessk1_s

  FUNCTION bessk1_v(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: bessk1_v
  END FUNCTION bessk1_v
END INTERFACE
INTERFACE bessy
  FUNCTION bessy_s(n,x)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: bessy_s
  END FUNCTION bessy_s

  FUNCTION bessy_v(n,x)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: bessy_v
  END FUNCTION bessy_v
END INTERFACE
INTERFACE bessy0
  FUNCTION bessy0_s(x)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: bessy0_s
  END FUNCTION bessy0_s

  FUNCTION bessy0_v(x)
    USE nrtype

```

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```

REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: bessy0_v
END FUNCTION bessy0_v
END INTERFACE
INTERFACE bessy1
FUNCTION bessy1_s(x)
USE nrtype
REAL(SP), INTENT(IN) :: x
REAL(SP) :: bessy1_s
END FUNCTION bessy1_s

FUNCTION bessy1_v(x)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: bessy1_v
END FUNCTION bessy1_v
END INTERFACE
INTERFACE beta
FUNCTION beta_s(z,w)
USE nrtype
REAL(SP), INTENT(IN) :: z,w
REAL(SP) :: beta_s
END FUNCTION beta_s

FUNCTION beta_v(z,w)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: z,w
REAL(SP), DIMENSION(size(z)) :: beta_v
END FUNCTION beta_v
END INTERFACE
INTERFACE betacf
FUNCTION betacf_s(a,b,x)
USE nrtype
REAL(SP), INTENT(IN) :: a,b,x
REAL(SP) :: betacf_s
END FUNCTION betacf_s

FUNCTION betacf_v(a,b,x)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: a,b,x
REAL(SP), DIMENSION(size(x)) :: betacf_v
END FUNCTION betacf_v
END INTERFACE
INTERFACE betai
FUNCTION betai_s(a,b,x)
USE nrtype
REAL(SP), INTENT(IN) :: a,b,x
REAL(SP) :: betai_s
END FUNCTION betai_s

FUNCTION betai_v(a,b,x)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: a,b,x
REAL(SP), DIMENSION(size(a)) :: betai_v
END FUNCTION betai_v
END INTERFACE
INTERFACE bico
FUNCTION bico_s(n,k)
USE nrtype
INTEGER(I4B), INTENT(IN) :: n,k
REAL(SP) :: bico_s
END FUNCTION bico_s

FUNCTION bico_v(n,k)
USE nrtype
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: n,k
REAL(SP), DIMENSION(size(n)) :: bico_v

```

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```

    END FUNCTION bico_v
END INTERFACE
INTERFACE
    FUNCTION bnldev(pp,n)
    USE nrtype
    REAL(SP), INTENT(IN) :: pp
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP) :: bnldev
    END FUNCTION bnldev
END INTERFACE
INTERFACE
    FUNCTION brent(ax,bx,cx,func,tol,xmin)
    USE nrtype
    REAL(SP), INTENT(IN) :: ax,bx,cx,tol
    REAL(SP), INTENT(OUT) :: xmin
    REAL(SP) :: brent
    INTERFACE
        FUNCTION func(x)
        USE nrtype
        REAL(SP), INTENT(IN) :: x
        REAL(SP) :: func
        END FUNCTION func
    END INTERFACE
    END FUNCTION brent
END INTERFACE
INTERFACE
    SUBROUTINE broydn(x,check)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: x
    LOGICAL(LGT), INTENT(OUT) :: check
    END SUBROUTINE broydn
END INTERFACE
INTERFACE
    SUBROUTINE bsstep(y,dydx,x,htry,eps,yscal,hdid,hnext,derivs)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
    REAL(SP), DIMENSION(:), INTENT(IN) :: dydx,yscal
    REAL(SP), INTENT(INOUT) :: x
    REAL(SP), INTENT(IN) :: htry,eps
    REAL(SP), INTENT(OUT) :: hdid,hnext
    INTERFACE
        SUBROUTINE derivs(x,y,dydx)
        USE nrtype
        REAL(SP), INTENT(IN) :: x
        REAL(SP), DIMENSION(:), INTENT(IN) :: y
        REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
        END SUBROUTINE derivs
    END INTERFACE
    END SUBROUTINE bsstep
END INTERFACE
INTERFACE
    SUBROUTINE caldat(julian,mm,id,iyyy)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: julian
    INTEGER(I4B), INTENT(OUT) :: mm,id,iyyy
    END SUBROUTINE caldat
END INTERFACE
INTERFACE
    FUNCTION chder(a,b,c)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,b
    REAL(SP), DIMENSION(:), INTENT(IN) :: c
    REAL(SP), DIMENSION(size(c)) :: chder
    END FUNCTION chder

```

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```

END INTERFACE
INTERFACE chebev
  FUNCTION chebev_s(a,b,c,x)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,b,x
    REAL(SP), DIMENSION(:), INTENT(IN) :: c
    REAL(SP) :: chebev_s
  END FUNCTION chebev_s

  FUNCTION chebev_v(a,b,c,x)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,b
    REAL(SP), DIMENSION(:), INTENT(IN) :: c,x
    REAL(SP), DIMENSION(size(x)) :: chebev_v
  END FUNCTION chebev_v
END INTERFACE
INTERFACE
  FUNCTION chebft(a,b,n,func)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,b
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP), DIMENSION(n) :: chebft
  INTERFACE
    FUNCTION func(x)
      USE nrtype
      REAL(SP), DIMENSION(:), INTENT(IN) :: x
      REAL(SP), DIMENSION(size(x)) :: func
    END FUNCTION func
  END INTERFACE
  END FUNCTION chebft
END INTERFACE
INTERFACE
  FUNCTION chebpc(c)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: c
    REAL(SP), DIMENSION(size(c)) :: chebpc
  END FUNCTION chebpc
END INTERFACE
INTERFACE
  FUNCTION chint(a,b,c)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,b
    REAL(SP), DIMENSION(:), INTENT(IN) :: c
    REAL(SP), DIMENSION(size(c)) :: chint
  END FUNCTION chint
END INTERFACE
INTERFACE
  SUBROUTINE choldc(a,p)
    USE nrtype
    REAL(SP), DIMENSION(:,.), INTENT(INOUT) :: a
    REAL(SP), DIMENSION(:), INTENT(OUT) :: p
  END SUBROUTINE choldc
END INTERFACE
INTERFACE
  SUBROUTINE cholsl(a,p,b,x)
    USE nrtype
    REAL(SP), DIMENSION(:,.), INTENT(IN) :: a
    REAL(SP), DIMENSION(:), INTENT(IN) :: p,b
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: x
  END SUBROUTINE cholsl
END INTERFACE
INTERFACE
  SUBROUTINE chsone(bins,ebins,knstrn,df,chsq,prob)
    USE nrtype

```

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```

    INTEGER(I4B), INTENT(IN) :: knstrn
    REAL(SP), INTENT(OUT) :: df,chsq,prob
    REAL(SP), DIMENSION(:), INTENT(IN) :: bins,ebins
    END SUBROUTINE chsone
END INTERFACE
INTERFACE
    SUBROUTINE chstwo(bins1,bins2,knstrn,df,chsq,prob)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: knstrn
    REAL(SP), INTENT(OUT) :: df,chsq,prob
    REAL(SP), DIMENSION(:), INTENT(IN) :: bins1,bins2
    END SUBROUTINE chstwo
END INTERFACE
INTERFACE
    SUBROUTINE cisi(x,ci,si)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP), INTENT(OUT) :: ci,si
    END SUBROUTINE cisi
END INTERFACE
INTERFACE
    SUBROUTINE cntab1(nn,chisq,df,prob,cramrv,ccc)
    USE nrtype
    INTEGER(I4B), DIMENSION(:,:), INTENT(IN) :: nn
    REAL(SP), INTENT(OUT) :: chisq,df,prob,cramrv,ccc
    END SUBROUTINE cntab1
END INTERFACE
INTERFACE
    SUBROUTINE cntab2(nn,h,hx,hy,hygx,hxgy,uygx,uxgy,uxy)
    USE nrtype
    INTEGER(I4B), DIMENSION(:,:), INTENT(IN) :: nn
    REAL(SP), INTENT(OUT) :: h,hx,hy,hygx,hxgy,uygx,uxgy,uxy
    END SUBROUTINE cntab2
END INTERFACE
INTERFACE
    FUNCTION convlv(data,respns,isign)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: data
    REAL(SP), DIMENSION(:), INTENT(IN) :: respns
    INTEGER(I4B), INTENT(IN) :: isign
    REAL(SP), DIMENSION(size(data)) :: convlv
    END FUNCTION convlv
END INTERFACE
INTERFACE
    FUNCTION correl(data1,data2)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2
    REAL(SP), DIMENSION(size(data1)) :: correl
    END FUNCTION correl
END INTERFACE
INTERFACE
    SUBROUTINE cosft1(y)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
    END SUBROUTINE cosft1
END INTERFACE
INTERFACE
    SUBROUTINE cosft2(y,isign)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
    INTEGER(I4B), INTENT(IN) :: isign
    END SUBROUTINE cosft2
END INTERFACE
INTERFACE

```

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```

SUBROUTINE covsrt(covar,maska)
  USE nrtype
  REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: covar
  LOGICAL(LGT), DIMENSION(:), INTENT(IN) :: maska
END SUBROUTINE covsrt
END INTERFACE
INTERFACE
  SUBROUTINE cyclic(a,b,c,alpha,beta,r,x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN):: a,b,c,r
    REAL(SP), INTENT(IN) :: alpha,beta
    REAL(SP), DIMENSION(:), INTENT(OUT):: x
  END SUBROUTINE cyclic
END INTERFACE
INTERFACE
  SUBROUTINE daub4(a,isign)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
    INTEGER(I4B), INTENT(IN) :: isign
  END SUBROUTINE daub4
END INTERFACE
INTERFACE dawson
  FUNCTION dawson_s(x)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: dawson_s
  END FUNCTION dawson_s

  FUNCTION dawson_v(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: dawson_v
  END FUNCTION dawson_v
END INTERFACE
INTERFACE
  FUNCTION dbrent(ax,bx,cx,func,dbrent_dfunc,tol,xmin)
    USE nrtype
    REAL(SP), INTENT(IN) :: ax,bx,cx,tol
    REAL(SP), INTENT(OUT) :: xmin
    REAL(SP) :: dbrent
  INTERFACE
    FUNCTION func(x)
      USE nrtype
      REAL(SP), INTENT(IN) :: x
      REAL(SP) :: func
    END FUNCTION func

    FUNCTION dbrent_dfunc(x)
      USE nrtype
      REAL(SP), INTENT(IN) :: x
      REAL(SP) :: dbrent_dfunc
    END FUNCTION dbrent_dfunc
  END INTERFACE
END FUNCTION dbrent
END INTERFACE
INTERFACE
  SUBROUTINE ddpoly(c,x,pd)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP), DIMENSION(:), INTENT(IN) :: c
    REAL(SP), DIMENSION(:), INTENT(OUT) :: pd
  END SUBROUTINE ddpoly
END INTERFACE
INTERFACE
  FUNCTION decchk(string,ch)

```

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```

USE nrtype
CHARACTER(1), DIMENSION(:), INTENT(IN) :: string
CHARACTER(1), INTENT(OUT) :: ch
LOGICAL(LGT) :: decchk
END FUNCTION decchk
END INTERFACE
INTERFACE
SUBROUTINE dfpmin(p,gtol,iter,fret,func,dfunc)
USE nrtype
INTEGER(I4B), INTENT(OUT) :: iter
REAL(SP), INTENT(IN) :: gtol
REAL(SP), INTENT(OUT) :: fret
REAL(SP), DIMENSION(:), INTENT(INOUT) :: p
INTERFACE
FUNCTION func(p)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: p
REAL(SP) :: func
END FUNCTION func

FUNCTION dfunc(p)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: p
REAL(SP), DIMENSION(size(p)) :: dfunc
END FUNCTION dfunc
END INTERFACE
END SUBROUTINE dfpmin
END INTERFACE
INTERFACE
FUNCTION dfridr(func,x,h,err)
USE nrtype
REAL(SP), INTENT(IN) :: x,h
REAL(SP), INTENT(OUT) :: err
REAL(SP) :: dfridr
INTERFACE
FUNCTION func(x)
USE nrtype
REAL(SP), INTENT(IN) :: x
REAL(SP) :: func
END FUNCTION func
END INTERFACE
END FUNCTION dfridr
END INTERFACE
INTERFACE
SUBROUTINE dftcor(w,delta,a,b,endpts,corre,corim,corfac)
USE nrtype
REAL(SP), INTENT(IN) :: w,delta,a,b
REAL(SP), INTENT(OUT) :: corre,corim,corfac
REAL(SP), DIMENSION(:), INTENT(IN) :: endpts
END SUBROUTINE dftcor
END INTERFACE
INTERFACE
SUBROUTINE dftint(func,a,b,w,cosint,sinint)
USE nrtype
REAL(SP), INTENT(IN) :: a,b,w
REAL(SP), INTENT(OUT) :: cosint,sinint
INTERFACE
FUNCTION func(x)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(size(x)) :: func
END FUNCTION func
END INTERFACE
END SUBROUTINE dftint

```

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```

END INTERFACE
INTERFACE
  SUBROUTINE difeq(k,k1,k2,jsf,is1,isf,indexv,s,y)
  USE nrtype
  INTEGER(I4B), INTENT(IN) :: is1,isf,jsf,k,k1,k2
  INTEGER(I4B), DIMENSION(:), INTENT(IN) :: indexv
  REAL(SP), DIMENSION(:,:), INTENT(OUT) :: s
  REAL(SP), DIMENSION(:,:), INTENT(IN) :: y
  END SUBROUTINE difeq
END INTERFACE
INTERFACE
  FUNCTION eclass(lista,listb,n)
  USE nrtype
  INTEGER(I4B), DIMENSION(:), INTENT(IN) :: lista,listb
  INTEGER(I4B), INTENT(IN) :: n
  INTEGER(I4B), DIMENSION(n) :: eclass
  END FUNCTION eclass
END INTERFACE
INTERFACE
  FUNCTION eclazz(equiv,n)
  USE nrtype
  INTERFACE
    FUNCTION equiv(i,j)
    USE nrtype
    LOGICAL(LGT) :: equiv
    INTEGER(I4B), INTENT(IN) :: i,j
    END FUNCTION equiv
  END INTERFACE
  INTEGER(I4B), INTENT(IN) :: n
  INTEGER(I4B), DIMENSION(n) :: eclazz
  END FUNCTION eclazz
END INTERFACE
INTERFACE
  FUNCTION ei(x)
  USE nrtype
  REAL(SP), INTENT(IN) :: x
  REAL(SP) :: ei
  END FUNCTION ei
END INTERFACE
INTERFACE
  SUBROUTINE eigsrt(d,v)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(INOUT) :: d
  REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: v
  END SUBROUTINE eigsrt
END INTERFACE
INTERFACE elle
  FUNCTION elle_s(phi,ak)
  USE nrtype
  REAL(SP), INTENT(IN) :: phi,ak
  REAL(SP) :: elle_s
  END FUNCTION elle_s

  FUNCTION elle_v(phi,ak)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: phi,ak
  REAL(SP), DIMENSION(size(phi)) :: elle_v
  END FUNCTION elle_v
END INTERFACE
INTERFACE ellf
  FUNCTION ellf_s(phi,ak)
  USE nrtype
  REAL(SP), INTENT(IN) :: phi,ak
  REAL(SP) :: ellf_s

```

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```

    END FUNCTION ellf_s
    FUNCTION ellf_v(phi,ak)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: phi,ak
    REAL(SP), DIMENSION(size(phi)) :: ellf_v
    END FUNCTION ellf_v
END INTERFACE
INTERFACE ellpi
    FUNCTION ellpi_s(phi,en,ak)
    USE nrtype
    REAL(SP), INTENT(IN) :: phi,en,ak
    REAL(SP) :: ellpi_s
    END FUNCTION ellpi_s

    FUNCTION ellpi_v(phi,en,ak)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: phi,en,ak
    REAL(SP), DIMENSION(size(phi)) :: ellpi_v
    END FUNCTION ellpi_v
END INTERFACE
INTERFACE
    SUBROUTINE elmhes(a)
    USE nrtype
    REAL(SP), DIMENSION(:,,:), INTENT(INOUT) :: a
    END SUBROUTINE elmhes
END INTERFACE
INTERFACE erf
    FUNCTION erf_s(x)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: erf_s
    END FUNCTION erf_s

    FUNCTION erf_v(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: erf_v
    END FUNCTION erf_v
END INTERFACE
INTERFACE erfc
    FUNCTION erfc_s(x)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: erfc_s
    END FUNCTION erfc_s

    FUNCTION erfc_v(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: erfc_v
    END FUNCTION erfc_v
END INTERFACE
INTERFACE erfcc
    FUNCTION erfcc_s(x)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: erfcc_s
    END FUNCTION erfcc_s

    FUNCTION erfcc_v(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: erfcc_v
    END FUNCTION erfcc_v
END INTERFACE
INTERFACE

```

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```

SUBROUTINE eulsum(sum,term,jterm)
  USE nrtype
  REAL(SP), INTENT(INOUT) :: sum
  REAL(SP), INTENT(IN) :: term
  INTEGER(I4B), INTENT(IN) :: jterm
END SUBROUTINE eulsum
END INTERFACE
INTERFACE
  FUNCTION evlmem(fdt,d,xms)
    USE nrtype
    REAL(SP), INTENT(IN) :: fdt,xms
    REAL(SP), DIMENSION(:), INTENT(IN) :: d
    REAL(SP) :: evlmem
  END FUNCTION evlmem
END INTERFACE
INTERFACE expdev
  SUBROUTINE expdev_s(harvest)
    USE nrtype
    REAL(SP), INTENT(OUT) :: harvest
  END SUBROUTINE expdev_s

  SUBROUTINE expdev_v(harvest)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(OUT) :: harvest
  END SUBROUTINE expdev_v
END INTERFACE
INTERFACE
  FUNCTION expint(n,x)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: expint
  END FUNCTION expint
END INTERFACE
INTERFACE factln
  FUNCTION factln_s(n)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP) :: factln_s
  END FUNCTION factln_s

  FUNCTION factln_v(n)
    USE nrtype
    INTEGER(I4B), DIMENSION(:), INTENT(IN) :: n
    REAL(SP), DIMENSION(size(n)) :: factln_v
  END FUNCTION factln_v
END INTERFACE
INTERFACE factrl
  FUNCTION factrl_s(n)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP) :: factrl_s
  END FUNCTION factrl_s

  FUNCTION factrl_v(n)
    USE nrtype
    INTEGER(I4B), DIMENSION(:), INTENT(IN) :: n
    REAL(SP), DIMENSION(size(n)) :: factrl_v
  END FUNCTION factrl_v
END INTERFACE
INTERFACE
  SUBROUTINE fasper(x,y,ofac,hifac,px,py,jmax,prob)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
    REAL(SP), INTENT(IN) :: ofac,hifac
    INTEGER(I4B), INTENT(OUT) :: jmax

```

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```

    REAL(SP), INTENT(OUT) :: prob
    REAL(SP), DIMENSION(:), POINTER :: px,py
  END SUBROUTINE fasper
END INTERFACE
INTERFACE
  SUBROUTINE fdjac(x,fvec,df)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: fvec
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: x
    REAL(SP), DIMENSION(:,.), INTENT(OUT) :: df
  END SUBROUTINE fdjac
END INTERFACE
INTERFACE
  SUBROUTINE fgauss(x,a,y,dyda)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x,a
    REAL(SP), DIMENSION(:), INTENT(OUT) :: y
    REAL(SP), DIMENSION(:,.), INTENT(OUT) :: dyda
  END SUBROUTINE fgauss
END INTERFACE
INTERFACE
  SUBROUTINE fit(x,y,a,b,siga,sigb,chi2,q,sig)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
    REAL(SP), INTENT(OUT) :: a,b,siga,sigb,chi2,q
    REAL(SP), DIMENSION(:), OPTIONAL, INTENT(IN) :: sig
  END SUBROUTINE fit
END INTERFACE
INTERFACE
  SUBROUTINE fitexy(x,y,sigx,sigy,a,b,siga,sigb,chi2,q)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,sigx,sigy
    REAL(SP), INTENT(OUT) :: a,b,siga,sigb,chi2,q
  END SUBROUTINE fitexy
END INTERFACE
INTERFACE
  SUBROUTINE fixrts(d)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: d
  END SUBROUTINE fixrts
END INTERFACE
INTERFACE
  FUNCTION fleg(x,n)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP), DIMENSION(n) :: fleg
  END FUNCTION fleg
END INTERFACE
INTERFACE
  SUBROUTINE flmoon(n,nph,jd,frac)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n,nph
    INTEGER(I4B), INTENT(OUT) :: jd
    REAL(SP), INTENT(OUT) :: frac
  END SUBROUTINE flmoon
END INTERFACE
INTERFACE
  SUBROUTINE four1
    SUBROUTINE four1_dp(data,isign)
      USE nrtype
      COMPLEX(DPC), DIMENSION(:), INTENT(INOUT) :: data
      INTEGER(I4B), INTENT(IN) :: isign
    END SUBROUTINE four1_dp
  END INTERFACE

```

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```

SUBROUTINE four1_sp(data,isign)
  USE nrtype
  COMPLEX(SPC), DIMENSION(:), INTENT(INOUT) :: data
  INTEGER(I4B), INTENT(IN) :: isign
END SUBROUTINE four1_sp
END INTERFACE
INTERFACE
  SUBROUTINE four1_alt(data,isign)
    USE nrtype
    COMPLEX(SPC), DIMENSION(:), INTENT(INOUT) :: data
    INTEGER(I4B), INTENT(IN) :: isign
  END SUBROUTINE four1_alt
END INTERFACE
INTERFACE
  SUBROUTINE four1_gather(data,isign)
    USE nrtype
    COMPLEX(SPC), DIMENSION(:), INTENT(INOUT) :: data
    INTEGER(I4B), INTENT(IN) :: isign
  END SUBROUTINE four1_gather
END INTERFACE
INTERFACE
  SUBROUTINE four2(data,isign)
    USE nrtype
    COMPLEX(SPC), DIMENSION(:,,:), INTENT(INOUT) :: data
    INTEGER(I4B), INTENT(IN) :: isign
  END SUBROUTINE four2
END INTERFACE
INTERFACE
  SUBROUTINE four2_alt(data,isign)
    USE nrtype
    COMPLEX(SPC), DIMENSION(:,,:), INTENT(INOUT) :: data
    INTEGER(I4B), INTENT(IN) :: isign
  END SUBROUTINE four2_alt
END INTERFACE
INTERFACE
  SUBROUTINE four3(data,isign)
    USE nrtype
    COMPLEX(SPC), DIMENSION(:, :, :), INTENT(INOUT) :: data
    INTEGER(I4B), INTENT(IN) :: isign
  END SUBROUTINE four3
END INTERFACE
INTERFACE
  SUBROUTINE four3_alt(data,isign)
    USE nrtype
    COMPLEX(SPC), DIMENSION(:, :, :), INTENT(INOUT) :: data
    INTEGER(I4B), INTENT(IN) :: isign
  END SUBROUTINE four3_alt
END INTERFACE
INTERFACE
  SUBROUTINE fourcol(data,isign)
    USE nrtype
    COMPLEX(SPC), DIMENSION(:, :, :), INTENT(INOUT) :: data
    INTEGER(I4B), INTENT(IN) :: isign
  END SUBROUTINE fourcol
END INTERFACE
INTERFACE
  SUBROUTINE fourcol_3d(data,isign)
    USE nrtype
    COMPLEX(SPC), DIMENSION(:, :, :), INTENT(INOUT) :: data
    INTEGER(I4B), INTENT(IN) :: isign
  END SUBROUTINE fourcol_3d
END INTERFACE
INTERFACE
  SUBROUTINE fourn_gather(data,nn,isign)

```

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```

    USE nrtype
    COMPLEX(SPC), DIMENSION(:), INTENT(INOUT) :: data
    INTEGER(I4B), DIMENSION(:), INTENT(IN) :: nn
    INTEGER(I4B), INTENT(IN) :: isign
    END SUBROUTINE fourn_gather
END INTERFACE
INTERFACE fourrow
SUBROUTINE fourrow_dp(data,isign)
    USE nrtype
    COMPLEX(DPC), DIMENSION(:,:), INTENT(INOUT) :: data
    INTEGER(I4B), INTENT(IN) :: isign
    END SUBROUTINE fourrow_dp

SUBROUTINE fourrow_sp(data,isign)
    USE nrtype
    COMPLEX(SPC), DIMENSION(:,:), INTENT(INOUT) :: data
    INTEGER(I4B), INTENT(IN) :: isign
    END SUBROUTINE fourrow_sp
END INTERFACE
INTERFACE
SUBROUTINE fourrow_3d(data,isign)
    USE nrtype
    COMPLEX(SPC), DIMENSION(:,:,:), INTENT(INOUT) :: data
    INTEGER(I4B), INTENT(IN) :: isign
    END SUBROUTINE fourrow_3d
END INTERFACE
INTERFACE
FUNCTION fpoly(x,n)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    INTEGER(I4B), INTENT(IN) :: n
    REAL(SP), DIMENSION(n) :: fpoly
    END FUNCTION fpoly
END INTERFACE
INTERFACE
SUBROUTINE fred2(a,b,t,f,w,g,ak)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,b
    REAL(SP), DIMENSION(:), INTENT(OUT) :: t,f,w
    INTERFACE
        FUNCTION g(t)
            USE nrtype
            REAL(SP), DIMENSION(:), INTENT(IN) :: t
            REAL(SP), DIMENSION(size(t)) :: g
            END FUNCTION g

        FUNCTION ak(t,s)
            USE nrtype
            REAL(SP), DIMENSION(:), INTENT(IN) :: t,s
            REAL(SP), DIMENSION(size(t),size(s)) :: ak
            END FUNCTION ak
    END INTERFACE
END SUBROUTINE fred2
END INTERFACE
INTERFACE
FUNCTION fredin(x,a,b,t,f,w,g,ak)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,b
    REAL(SP), DIMENSION(:), INTENT(IN) :: x,t,f,w
    REAL(SP), DIMENSION(size(x)) :: fredin
    INTERFACE
        FUNCTION g(t)
            USE nrtype
            REAL(SP), DIMENSION(:), INTENT(IN) :: t
            REAL(SP), DIMENSION(size(t)) :: g

```

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```

        END FUNCTION g
        FUNCTION ak(t,s)
        USE nrtype
        REAL(SP), DIMENSION(:), INTENT(IN) :: t,s
        REAL(SP), DIMENSION(size(t),size(s)) :: ak
        END FUNCTION ak
    END INTERFACE
    END FUNCTION fredin
END INTERFACE
INTERFACE
    SUBROUTINE frenel(x,s,c)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP), INTENT(OUT) :: s,c
    END SUBROUTINE frenel
END INTERFACE
INTERFACE
    SUBROUTINE frprmn(p,ftol,iter,fret)
    USE nrtype
    INTEGER(I4B), INTENT(OUT) :: iter
    REAL(SP), INTENT(IN) :: ftol
    REAL(SP), INTENT(OUT) :: fret
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: p
    END SUBROUTINE frprmn
END INTERFACE
INTERFACE
    SUBROUTINE fttest(data1,data2,f,prob)
    USE nrtype
    REAL(SP), INTENT(OUT) :: f,prob
    REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2
    END SUBROUTINE fttest
END INTERFACE
INTERFACE
    FUNCTION gamdev(ia)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: ia
    REAL(SP) :: gamdev
    END FUNCTION gamdev
END INTERFACE
INTERFACE gammln
    FUNCTION gammln_s(xx)
    USE nrtype
    REAL(SP), INTENT(IN) :: xx
    REAL(SP) :: gammln_s
    END FUNCTION gammln_s

    FUNCTION gammln_v(xx)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: xx
    REAL(SP), DIMENSION(size(xx)) :: gammln_v
    END FUNCTION gammln_v
END INTERFACE
INTERFACE gammp
    FUNCTION gammp_s(a,x)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,x
    REAL(SP) :: gammp_s
    END FUNCTION gammp_s

    FUNCTION gammp_v(a,x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: a,x
    REAL(SP), DIMENSION(size(a)) :: gammp_v
    END FUNCTION gammp_v
END INTERFACE

```

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```

INTERFACE gammq
  FUNCTION gammq_s(a,x)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,x
    REAL(SP) :: gammq_s
  END FUNCTION gammq_s

  FUNCTION gammq_v(a,x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: a,x
    REAL(SP), DIMENSION(size(a)) :: gammq_v
  END FUNCTION gammq_v
END INTERFACE
INTERFACE gasdev
  SUBROUTINE gasdev_s(harvest)
    USE nrtype
    REAL(SP), INTENT(OUT) :: harvest
  END SUBROUTINE gasdev_s

  SUBROUTINE gasdev_v(harvest)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(OUT) :: harvest
  END SUBROUTINE gasdev_v
END INTERFACE
INTERFACE
  SUBROUTINE gaucof(a,b,amu0,x,w)
    USE nrtype
    REAL(SP), INTENT(IN) :: amu0
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: a,b
    REAL(SP), DIMENSION(:), INTENT(OUT) :: x,w
  END SUBROUTINE gaucof
END INTERFACE
INTERFACE
  SUBROUTINE gauher(x,w)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(OUT) :: x,w
  END SUBROUTINE gauher
END INTERFACE
INTERFACE
  SUBROUTINE gaujac(x,w,alf,bet)
    USE nrtype
    REAL(SP), INTENT(IN) :: alf,bet
    REAL(SP), DIMENSION(:), INTENT(OUT) :: x,w
  END SUBROUTINE gaujac
END INTERFACE
INTERFACE
  SUBROUTINE gaulag(x,w,alf)
    USE nrtype
    REAL(SP), INTENT(IN) :: alf
    REAL(SP), DIMENSION(:), INTENT(OUT) :: x,w
  END SUBROUTINE gaulag
END INTERFACE
INTERFACE
  SUBROUTINE gauleg(x1,x2,x,w)
    USE nrtype
    REAL(SP), INTENT(IN) :: x1,x2
    REAL(SP), DIMENSION(:), INTENT(OUT) :: x,w
  END SUBROUTINE gauleg
END INTERFACE
INTERFACE
  SUBROUTINE gaussj(a,b)
    USE nrtype
    REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: a,b
  END SUBROUTINE gaussj
END INTERFACE

```

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```

INTERFACE gcf
  FUNCTION gcf_s(a,x,gln)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,x
    REAL(SP), OPTIONAL, INTENT(OUT) :: gln
    REAL(SP) :: gcf_s
  END FUNCTION gcf_s

  FUNCTION gcf_v(a,x,gln)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: a,x
    REAL(SP), DIMENSION(:), OPTIONAL, INTENT(OUT) :: gln
    REAL(SP), DIMENSION(size(a)) :: gcf_v
  END FUNCTION gcf_v
END INTERFACE
INTERFACE
  FUNCTION golden(ax,bx,cx,func,tol,xmin)
    USE nrtype
    REAL(SP), INTENT(IN) :: ax,bx,cx,tol
    REAL(SP), INTENT(OUT) :: xmin
    REAL(SP) :: golden
  INTERFACE
    FUNCTION func(x)
      USE nrtype
      REAL(SP), INTENT(IN) :: x
      REAL(SP) :: func
    END FUNCTION func
  END INTERFACE
END FUNCTION golden
END INTERFACE
INTERFACE gser
  FUNCTION gser_s(a,x,gln)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,x
    REAL(SP), OPTIONAL, INTENT(OUT) :: gln
    REAL(SP) :: gser_s
  END FUNCTION gser_s

  FUNCTION gser_v(a,x,gln)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: a,x
    REAL(SP), DIMENSION(:), OPTIONAL, INTENT(OUT) :: gln
    REAL(SP), DIMENSION(size(a)) :: gser_v
  END FUNCTION gser_v
END INTERFACE
INTERFACE
  SUBROUTINE hqr(a,wr,wi)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(OUT) :: wr,wi
    REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: a
  END SUBROUTINE hqr
END INTERFACE
INTERFACE
  SUBROUTINE hunt(xx,x,jlo)
    USE nrtype
    INTEGER(I4B), INTENT(INOUT) :: jlo
    REAL(SP), INTENT(IN) :: x
    REAL(SP), DIMENSION(:), INTENT(IN) :: xx
  END SUBROUTINE hunt
END INTERFACE
INTERFACE
  SUBROUTINE hypdrv(s,ry,rdyds)
    USE nrtype
    REAL(SP), INTENT(IN) :: s
    REAL(SP), DIMENSION(:), INTENT(IN) :: ry

```

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```

    REAL(SP), DIMENSION(:), INTENT(OUT) :: rdyds
  END SUBROUTINE hypdrv
END INTERFACE
INTERFACE
  FUNCTION hypgeo(a,b,c,z)
    USE nrtype
    COMPLEX(SPC), INTENT(IN) :: a,b,c,z
    COMPLEX(SPC) :: hypgeo
  END FUNCTION hypgeo
END INTERFACE
INTERFACE
  SUBROUTINE hypser(a,b,c,z,series,deriv)
    USE nrtype
    COMPLEX(SPC), INTENT(IN) :: a,b,c,z
    COMPLEX(SPC), INTENT(OUT) :: series,deriv
  END SUBROUTINE hypser
END INTERFACE
INTERFACE
  FUNCTION icrc(crc,buf,jinit,jrev)
    USE nrtype
    CHARACTER(1), DIMENSION(:), INTENT(IN) :: buf
    INTEGER(I2B), INTENT(IN) :: crc,jinit
    INTEGER(I4B), INTENT(IN) :: jrev
    INTEGER(I2B) :: icrc
  END FUNCTION icrc
END INTERFACE
INTERFACE
  FUNCTION igray(n,is)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n,is
    INTEGER(I4B) :: igray
  END FUNCTION igray
END INTERFACE
INTERFACE
  RECURSIVE SUBROUTINE index_bypack(arr,index,partial)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: arr
    INTEGER(I4B), DIMENSION(:), INTENT(INOUT) :: index
    INTEGER, OPTIONAL, INTENT(IN) :: partial
  END SUBROUTINE index_bypack
END INTERFACE
INTERFACE indexx
  SUBROUTINE indexx_sp(arr,index)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: arr
    INTEGER(I4B), DIMENSION(:), INTENT(OUT) :: index
  END SUBROUTINE indexx_sp
  SUBROUTINE indexx_i4b(iarr,index)
    USE nrtype
    INTEGER(I4B), DIMENSION(:), INTENT(IN) :: iarr
    INTEGER(I4B), DIMENSION(:), INTENT(OUT) :: index
  END SUBROUTINE indexx_i4b
END INTERFACE
INTERFACE
  FUNCTION interp(uc)
    USE nrtype
    REAL(DP), DIMENSION(:,:), INTENT(IN) :: uc
    REAL(DP), DIMENSION(2*size(uc,1)-1,2*size(uc,1)-1) :: interp
  END FUNCTION interp
END INTERFACE
INTERFACE
  FUNCTION rank(indx)
    USE nrtype
    INTEGER(I4B), DIMENSION(:), INTENT(IN) :: indx

```

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```

    INTEGER(I4B), DIMENSION(size(indx)) :: rank
  END FUNCTION rank
END INTERFACE
INTERFACE
  FUNCTION irbit1(iseed)
    USE nrtype
    INTEGER(I4B), INTENT(INOUT) :: iseed
    INTEGER(I4B) :: irbit1
  END FUNCTION irbit1
END INTERFACE
INTERFACE
  FUNCTION irbit2(iseed)
    USE nrtype
    INTEGER(I4B), INTENT(INOUT) :: iseed
    INTEGER(I4B) :: irbit2
  END FUNCTION irbit2
END INTERFACE
INTERFACE
  SUBROUTINE jacobi(a,d,v,nrot)
    USE nrtype
    INTEGER(I4B), INTENT(OUT) :: nrot
    REAL(SP), DIMENSION(:), INTENT(OUT) :: d
    REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: a
    REAL(SP), DIMENSION(:,:), INTENT(OUT) :: v
  END SUBROUTINE jacobi
END INTERFACE
INTERFACE
  SUBROUTINE jacobn(x,y,dfdx,dfdy)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP), DIMENSION(:), INTENT(IN) :: y
    REAL(SP), DIMENSION(:), INTENT(OUT) :: dfdx
    REAL(SP), DIMENSION(:,:), INTENT(OUT) :: dfdy
  END SUBROUTINE jacobn
END INTERFACE
INTERFACE
  FUNCTION julday(mm,id,iyyy)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: mm,id,iyyy
    INTEGER(I4B) :: julday
  END FUNCTION julday
END INTERFACE
INTERFACE
  SUBROUTINE kendl1(data1,data2,tau,z,prob)
    USE nrtype
    REAL(SP), INTENT(OUT) :: tau,z,prob
    REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2
  END SUBROUTINE kendl1
END INTERFACE
INTERFACE
  SUBROUTINE kendl2(tab,tau,z,prob)
    USE nrtype
    REAL(SP), DIMENSION(:,:), INTENT(IN) :: tab
    REAL(SP), INTENT(OUT) :: tau,z,prob
  END SUBROUTINE kendl2
END INTERFACE
INTERFACE
  FUNCTION kermom(y,m)
    USE nrtype
    REAL(DP), INTENT(IN) :: y
    INTEGER(I4B), INTENT(IN) :: m
    REAL(DP), DIMENSION(m) :: kermom
  END FUNCTION kermom
END INTERFACE

```

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```

INTERFACE
  SUBROUTINE ks2d1s(x1,y1,quadv1,d1,prob)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: x1,y1
  REAL(SP), INTENT(OUT) :: d1,prob
  INTERFACE
    SUBROUTINE quadv1(x,y,fa,fb,fc,fd)
    USE nrtype
    REAL(SP), INTENT(IN) :: x,y
    REAL(SP), INTENT(OUT) :: fa,fb,fc,fd
    END SUBROUTINE quadv1
  END INTERFACE
END SUBROUTINE ks2d1s
END INTERFACE
INTERFACE
  SUBROUTINE ks2d2s(x1,y1,x2,y2,d,prob)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: x1,y1,x2,y2
  REAL(SP), INTENT(OUT) :: d,prob
  END SUBROUTINE ks2d2s
END INTERFACE
INTERFACE
  SUBROUTINE ksone(data,func,d,prob)
  USE nrtype
  REAL(SP), INTENT(OUT) :: d,prob
  REAL(SP), DIMENSION(:), INTENT(INOUT) :: data
  INTERFACE
    FUNCTION func(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: func
    END FUNCTION func
  END INTERFACE
END SUBROUTINE ksone
END INTERFACE
INTERFACE
  SUBROUTINE kstwo(data1,data2,d,prob)
  USE nrtype
  REAL(SP), INTENT(OUT) :: d,prob
  REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2
  END SUBROUTINE kstwo
END INTERFACE
INTERFACE
  SUBROUTINE laguer(a,x,its)
  USE nrtype
  INTEGER(I4B), INTENT(OUT) :: its
  COMPLEX(SPC), INTENT(INOUT) :: x
  COMPLEX(SPC), DIMENSION(:), INTENT(IN) :: a
  END SUBROUTINE laguer
END INTERFACE
INTERFACE
  SUBROUTINE lfit(x,y,sig,a,maska,covar,chisq,funcs)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,sig
  REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
  LOGICAL(LGT), DIMENSION(:), INTENT(IN) :: maska
  REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: covar
  REAL(SP), INTENT(OUT) :: chisq
  INTERFACE
    SUBROUTINE funcs(x,arr)
    USE nrtype
    REAL(SP),INTENT(IN) :: x
    REAL(SP), DIMENSION(:), INTENT(OUT) :: arr
    END SUBROUTINE funcs
  END INTERFACE
END INTERFACE

```

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```

END INTERFACE
END SUBROUTINE lfit
END INTERFACE
INTERFACE
SUBROUTINE linbcg(b,x,itol,tol,itmax,iter,err)
USE nrtype
REAL(DP), DIMENSION(:), INTENT(IN) :: b
REAL(DP), DIMENSION(:), INTENT(INOUT) :: x
INTEGER(I4B), INTENT(IN) :: itol,itmax
REAL(DP), INTENT(IN) :: tol
INTEGER(I4B), INTENT(OUT) :: iter
REAL(DP), INTENT(OUT) :: err
END SUBROUTINE linbcg
END INTERFACE
INTERFACE
SUBROUTINE linmin(p,xi,fret)
USE nrtype
REAL(SP), INTENT(OUT) :: fret
REAL(SP), DIMENSION(:), TARGET, INTENT(INOUT) :: p,xi
END SUBROUTINE linmin
END INTERFACE
INTERFACE
SUBROUTINE lnsrch(xold,fold,g,p,x,f,stpmax,check,func)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: xold,g
REAL(SP), DIMENSION(:), INTENT(INOUT) :: p
REAL(SP), INTENT(IN) :: fold,stpmax
REAL(SP), DIMENSION(:), INTENT(OUT) :: x
REAL(SP), INTENT(OUT) :: f
LOGICAL(LGT), INTENT(OUT) :: check
INTERFACE
FUNCTION func(x)
USE nrtype
REAL(SP) :: func
REAL(SP), DIMENSION(:), INTENT(IN) :: x
END FUNCTION func
END INTERFACE
END SUBROUTINE lnsrch
END INTERFACE
INTERFACE
FUNCTION locate(xx,x)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: xx
REAL(SP), INTENT(IN) :: x
INTEGER(I4B) :: locate
END FUNCTION locate
END INTERFACE
INTERFACE
FUNCTION lop(u)
USE nrtype
REAL(DP), DIMENSION(:,.), INTENT(IN) :: u
REAL(DP), DIMENSION(size(u,1),size(u,1)) :: lop
END FUNCTION lop
END INTERFACE
INTERFACE
SUBROUTINE lubksb(a,indx,b)
USE nrtype
REAL(SP), DIMENSION(:,.), INTENT(IN) :: a
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: indx
REAL(SP), DIMENSION(:), INTENT(INOUT) :: b
END SUBROUTINE lubksb
END INTERFACE
INTERFACE
SUBROUTINE ludcmp(a,indx,d)

```

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```

    USE nrtype
    REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: a
    INTEGER(I4B), DIMENSION(:), INTENT(OUT) :: indx
    REAL(SP), INTENT(OUT) :: d
    END SUBROUTINE ludcmp
END INTERFACE
INTERFACE
    SUBROUTINE machar(ibeta,it,irnd,ngrd,machep,negep,iexp,minexp,&
        maxexp,eps,epsneg,xmin,xmax)
    USE nrtype
    INTEGER(I4B), INTENT(OUT) :: ibeta,iexp,irnd,it,machep,maxexp,&
        minexp,negep,ngrd
    REAL(SP), INTENT(OUT) :: eps,epsneg,xmax,xmin
    END SUBROUTINE machar
END INTERFACE
INTERFACE
    SUBROUTINE medfit(x,y,a,b,abdev)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
    REAL(SP), INTENT(OUT) :: a,b,abdev
    END SUBROUTINE medfit
END INTERFACE
INTERFACE
    SUBROUTINE memcof(data,xms,d)
    USE nrtype
    REAL(SP), INTENT(OUT) :: xms
    REAL(SP), DIMENSION(:), INTENT(IN) :: data
    REAL(SP), DIMENSION(:), INTENT(OUT) :: d
    END SUBROUTINE memcof
END INTERFACE
INTERFACE
    SUBROUTINE mgfas(u,maxcyc)
    USE nrtype
    REAL(DP), DIMENSION(:,:), INTENT(INOUT) :: u
    INTEGER(I4B), INTENT(IN) :: maxcyc
    END SUBROUTINE mgfas
END INTERFACE
INTERFACE
    SUBROUTINE mglin(u,ncycle)
    USE nrtype
    REAL(DP), DIMENSION(:,:), INTENT(INOUT) :: u
    INTEGER(I4B), INTENT(IN) :: ncycle
    END SUBROUTINE mglin
END INTERFACE
INTERFACE
    SUBROUTINE midexp(funk,aa,bb,s,n)
    USE nrtype
    REAL(SP), INTENT(IN) :: aa,bb
    REAL(SP), INTENT(INOUT) :: s
    INTEGER(I4B), INTENT(IN) :: n
    INTERFACE
        FUNCTION funk(x)
            USE nrtype
            REAL(SP), DIMENSION(:), INTENT(IN) :: x
            REAL(SP), DIMENSION(size(x)) :: funk
        END FUNCTION funk
    END INTERFACE
    END SUBROUTINE midexp
END INTERFACE
INTERFACE
    SUBROUTINE midinf(funk,aa,bb,s,n)
    USE nrtype
    REAL(SP), INTENT(IN) :: aa,bb
    REAL(SP), INTENT(INOUT) :: s

```

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```

INTEGER(I4B), INTENT(IN) :: n
INTERFACE
  FUNCTION funk(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: funk
  END FUNCTION funk
END INTERFACE
END SUBROUTINE midinf
END INTERFACE
INTERFACE
  SUBROUTINE midpnt(func,a,b,s,n)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,b
    REAL(SP), INTENT(INOUT) :: s
    INTEGER(I4B), INTENT(IN) :: n
  INTERFACE
    FUNCTION func(x)
      USE nrtype
      REAL(SP), DIMENSION(:), INTENT(IN) :: x
      REAL(SP), DIMENSION(size(x)) :: func
    END FUNCTION func
  END INTERFACE
END SUBROUTINE midpnt
END INTERFACE
INTERFACE
  SUBROUTINE midsql(func,aa,bb,s,n)
    USE nrtype
    REAL(SP), INTENT(IN) :: aa,bb
    REAL(SP), INTENT(INOUT) :: s
    INTEGER(I4B), INTENT(IN) :: n
  INTERFACE
    FUNCTION funk(x)
      USE nrtype
      REAL(SP), DIMENSION(:), INTENT(IN) :: x
      REAL(SP), DIMENSION(size(x)) :: funk
    END FUNCTION funk
  END INTERFACE
END SUBROUTINE midsql
END INTERFACE
INTERFACE
  SUBROUTINE midsqu(func,aa,bb,s,n)
    USE nrtype
    REAL(SP), INTENT(IN) :: aa,bb
    REAL(SP), INTENT(INOUT) :: s
    INTEGER(I4B), INTENT(IN) :: n
  INTERFACE
    FUNCTION funk(x)
      USE nrtype
      REAL(SP), DIMENSION(:), INTENT(IN) :: x
      REAL(SP), DIMENSION(size(x)) :: funk
    END FUNCTION funk
  END INTERFACE
END SUBROUTINE midsqu
END INTERFACE
INTERFACE
  RECURSIVE SUBROUTINE miser(func,regn,ndim,npts,dith,ave,var)
    USE nrtype
  INTERFACE
    FUNCTION func(x)
      USE nrtype
      REAL(SP) :: func
      REAL(SP), DIMENSION(:), INTENT(IN) :: x
    END FUNCTION func
  END INTERFACE

```

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```

END INTERFACE
REAL(SP), DIMENSION(:), INTENT(IN) :: regn
INTEGER(I4B), INTENT(IN) :: ndim,npts
REAL(SP), INTENT(IN) :: dith
REAL(SP), INTENT(OUT) :: ave,var
END SUBROUTINE miser
END INTERFACE
INTERFACE
SUBROUTINE mmid(y,dydx,xs,htot,nstep,yout,derivs)
USE nrtype
INTEGER(I4B), INTENT(IN) :: nstep
REAL(SP), INTENT(IN) :: xs,htot
REAL(SP), DIMENSION(:), INTENT(IN) :: y,dydx
REAL(SP), DIMENSION(:), INTENT(OUT) :: yout
INTERFACE
SUBROUTINE derivs(x,y,dydx)
USE nrtype
REAL(SP), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(IN) :: y
REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
END SUBROUTINE derivs
END INTERFACE
END SUBROUTINE mmid
END INTERFACE
INTERFACE
SUBROUTINE mnbrak(ax,bx,cx,fa,fb,fc,func)
USE nrtype
REAL(SP), INTENT(INOUT) :: ax,bx
REAL(SP), INTENT(OUT) :: cx,fa,fb,fc
INTERFACE
FUNCTION func(x)
USE nrtype
REAL(SP), INTENT(IN) :: x
REAL(SP) :: func
END FUNCTION func
END INTERFACE
END SUBROUTINE mnbrak
END INTERFACE
INTERFACE
SUBROUTINE mnnewt(ntrial,x,tolx,tolf,usrfun)
USE nrtype
INTEGER(I4B), INTENT(IN) :: ntrial
REAL(SP), INTENT(IN) :: tolx,tolf
REAL(SP), DIMENSION(:), INTENT(INOUT) :: x
INTERFACE
SUBROUTINE usrfun(x,fvec,fjac)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(OUT) :: fvec
REAL(SP), DIMENSION(:,:), INTENT(OUT) :: fjac
END SUBROUTINE usrfun
END INTERFACE
END SUBROUTINE mnnewt
END INTERFACE
INTERFACE
SUBROUTINE moment(data,ave,adev,sdev,var,skew,curt)
USE nrtype
REAL(SP), INTENT(OUT) :: ave,adev,sdev,var,skew,curt
REAL(SP), DIMENSION(:), INTENT(IN) :: data
END SUBROUTINE moment
END INTERFACE
INTERFACE
SUBROUTINE mp2dfr(a,s,n,m)
USE nrtype

```

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```

    INTEGER(I4B), INTENT(IN) :: n
    INTEGER(I4B), INTENT(OUT) :: m
    CHARACTER(1), DIMENSION(:), INTENT(INOUT) :: a
    CHARACTER(1), DIMENSION(:), INTENT(OUT) :: s
    END SUBROUTINE mp2dfr
END INTERFACE
INTERFACE
    SUBROUTINE mpdiv(q,r,u,v,n,m)
    USE nrtype
    CHARACTER(1), DIMENSION(:), INTENT(OUT) :: q,r
    CHARACTER(1), DIMENSION(:), INTENT(IN) :: u,v
    INTEGER(I4B), INTENT(IN) :: n,m
    END SUBROUTINE mpdiv
END INTERFACE
INTERFACE
    SUBROUTINE mpinv(u,v,n,m)
    USE nrtype
    CHARACTER(1), DIMENSION(:), INTENT(OUT) :: u
    CHARACTER(1), DIMENSION(:), INTENT(IN) :: v
    INTEGER(I4B), INTENT(IN) :: n,m
    END SUBROUTINE mpinv
END INTERFACE
INTERFACE
    SUBROUTINE mpmul(w,u,v,n,m)
    USE nrtype
    CHARACTER(1), DIMENSION(:), INTENT(IN) :: u,v
    CHARACTER(1), DIMENSION(:), INTENT(OUT) :: w
    INTEGER(I4B), INTENT(IN) :: n,m
    END SUBROUTINE mpmul
END INTERFACE
INTERFACE
    SUBROUTINE mppi(n)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n
    END SUBROUTINE mppi
END INTERFACE
INTERFACE
    SUBROUTINE mprove(a,alud,indx,b,x)
    USE nrtype
    REAL(SP), DIMENSION(:,), INTENT(IN) :: a,alud
    INTEGER(I4B), DIMENSION(:), INTENT(IN) :: indx
    REAL(SP), DIMENSION(:), INTENT(IN) :: b
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: x
    END SUBROUTINE mprove
END INTERFACE
INTERFACE
    SUBROUTINE mpsqrt(w,u,v,n,m)
    USE nrtype
    CHARACTER(1), DIMENSION(:), INTENT(OUT) :: w,u
    CHARACTER(1), DIMENSION(:), INTENT(IN) :: v
    INTEGER(I4B), INTENT(IN) :: n,m
    END SUBROUTINE mpsqrt
END INTERFACE
INTERFACE
    SUBROUTINE mrqcof(x,y,sig,a,maska,alpha,beta,chisq,funcs)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,a,sig
    REAL(SP), DIMENSION(:), INTENT(OUT) :: beta
    REAL(SP), DIMENSION(:,), INTENT(OUT) :: alpha
    REAL(SP), INTENT(OUT) :: chisq
    LOGICAL(LGT), DIMENSION(:), INTENT(IN) :: maska
    END SUBROUTINE mrqcof
    SUBROUTINE funcs(x,a,yfit,dyda)
    USE nrtype

```

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```

    REAL(SP), DIMENSION(:), INTENT(IN) :: x,a
    REAL(SP), DIMENSION(:), INTENT(OUT) :: yfit
    REAL(SP), DIMENSION(:,:), INTENT(OUT) :: dyda
    END SUBROUTINE funcs
END INTERFACE
END SUBROUTINE mrqcof
END INTERFACE
INTERFACE
SUBROUTINE mrqmin(x,y,sig,a,maska,covar,alpha,chisq,funcs,alamda)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,sig
REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
REAL(SP), DIMENSION(:,:), INTENT(OUT) :: covar,alpha
REAL(SP), INTENT(OUT) :: chisq
REAL(SP), INTENT(INOUT) :: alamda
LOGICAL(LGT), DIMENSION(:), INTENT(IN) :: maska
INTERFACE
    SUBROUTINE funcs(x,a,yfit,dyda)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x,a
    REAL(SP), DIMENSION(:), INTENT(OUT) :: yfit
    REAL(SP), DIMENSION(:,:), INTENT(OUT) :: dyda
    END SUBROUTINE funcs
END INTERFACE
END SUBROUTINE mrqmin
END INTERFACE
INTERFACE
SUBROUTINE newt(x,check)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(INOUT) :: x
LOGICAL(LGT), INTENT(OUT) :: check
END SUBROUTINE newt
END INTERFACE
INTERFACE
SUBROUTINE odeint(ystart,x1,x2,eps,h1,hmin,derivs,rkqs)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(INOUT) :: ystart
REAL(SP), INTENT(IN) :: x1,x2,eps,h1,hmin
INTERFACE
    SUBROUTINE derivs(x,y,dydx)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP), DIMENSION(:), INTENT(IN) :: y
    REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
    END SUBROUTINE derivs

    SUBROUTINE rkqs(y,dydx,x,htry,eps,yscal,hdid,hnext,derivs)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
    REAL(SP), DIMENSION(:), INTENT(IN) :: dydx,yscal
    REAL(SP), INTENT(INOUT) :: x
    REAL(SP), INTENT(IN) :: htry,eps
    REAL(SP), INTENT(OUT) :: hdid,hnext
    INTERFACE
        SUBROUTINE derivs(x,y,dydx)
        USE nrtype
        REAL(SP), INTENT(IN) :: x
        REAL(SP), DIMENSION(:), INTENT(IN) :: y
        REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
        END SUBROUTINE derivs
    END INTERFACE
END SUBROUTINE rkqs
END INTERFACE
END SUBROUTINE odeint

```

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```

END INTERFACE
INTERFACE
  SUBROUTINE orthog(anu,alpha,beta,a,b)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: anu,alpha,beta
  REAL(SP), DIMENSION(:), INTENT(OUT) :: a,b
  END SUBROUTINE orthog
END INTERFACE
INTERFACE
  SUBROUTINE pade(cof,resid)
  USE nrtype
  REAL(DP), DIMENSION(:), INTENT(INOUT) :: cof
  REAL(SP), INTENT(OUT) :: resid
  END SUBROUTINE pade
END INTERFACE
INTERFACE
  FUNCTION pccheb(d)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: d
  REAL(SP), DIMENSION(size(d)) :: pccheb
  END FUNCTION pccheb
END INTERFACE
INTERFACE
  SUBROUTINE pcshft(a,b,d)
  USE nrtype
  REAL(SP), INTENT(IN) :: a,b
  REAL(SP), DIMENSION(:), INTENT(INOUT) :: d
  END SUBROUTINE pcshft
END INTERFACE
INTERFACE
  SUBROUTINE pearsn(x,y,r,prob,z)
  USE nrtype
  REAL(SP), INTENT(OUT) :: r,prob,z
  REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
  END SUBROUTINE pearsn
END INTERFACE
INTERFACE
  SUBROUTINE period(x,y,ofac,hifac,px,py,jmax,prob)
  USE nrtype
  INTEGER(I4B), INTENT(OUT) :: jmax
  REAL(SP), INTENT(IN) :: ofac,hifac
  REAL(SP), INTENT(OUT) :: prob
  REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
  REAL(SP), DIMENSION(:), POINTER :: px,py
  END SUBROUTINE period
END INTERFACE
INTERFACE plgndr
  FUNCTION plgndr_s(l,m,x)
  USE nrtype
  INTEGER(I4B), INTENT(IN) :: l,m
  REAL(SP), INTENT(IN) :: x
  REAL(SP) :: plgndr_s
  END FUNCTION plgndr_s

  FUNCTION plgndr_v(l,m,x)
  USE nrtype
  INTEGER(I4B), INTENT(IN) :: l,m
  REAL(SP), DIMENSION(:), INTENT(IN) :: x
  REAL(SP), DIMENSION(size(x)) :: plgndr_v
  END FUNCTION plgndr_v
END INTERFACE
INTERFACE
  FUNCTION poidev(xm)
  USE nrtype

```

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```

    REAL(SP), INTENT(IN) :: xm
    REAL(SP) :: poidev
  END FUNCTION poidev
END INTERFACE
INTERFACE
  FUNCTION polcoe(x,y)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
  REAL(SP), DIMENSION(size(x)) :: polcoe
  END FUNCTION polcoe
END INTERFACE
INTERFACE
  FUNCTION polcof(xa,ya)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: xa,ya
  REAL(SP), DIMENSION(size(xa)) :: polcof
  END FUNCTION polcof
END INTERFACE
INTERFACE
  SUBROUTINE poldiv(u,v,q,r)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: u,v
  REAL(SP), DIMENSION(:), INTENT(OUT) :: q,r
  END SUBROUTINE poldiv
END INTERFACE
INTERFACE
  SUBROUTINE polin2(x1a,x2a,ya,x1,x2,y,dy)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: x1a,x2a
  REAL(SP), DIMENSION(:,:), INTENT(IN) :: ya
  REAL(SP), INTENT(IN) :: x1,x2
  REAL(SP), INTENT(OUT) :: y,dy
  END SUBROUTINE polin2
END INTERFACE
INTERFACE
  SUBROUTINE polint(xa,ya,x,y,dy)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: xa,ya
  REAL(SP), INTENT(IN) :: x
  REAL(SP), INTENT(OUT) :: y,dy
  END SUBROUTINE polint
END INTERFACE
INTERFACE
  SUBROUTINE powell(p,xi,ftol,iter,fret)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(INOUT) :: p
  REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: xi
  INTEGER(I4B), INTENT(OUT) :: iter
  REAL(SP), INTENT(IN) :: ftol
  REAL(SP), INTENT(OUT) :: fret
  END SUBROUTINE powell
END INTERFACE
INTERFACE
  FUNCTION predic(data,d,nfut)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: data,d
  INTEGER(I4B), INTENT(IN) :: nfut
  REAL(SP), DIMENSION(nfut) :: predic
  END FUNCTION predic
END INTERFACE
INTERFACE
  FUNCTION probks(alam)
  USE nrtype
  REAL(SP), INTENT(IN) :: alam

```

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```

    REAL(SP) :: probks
  END FUNCTION probks
END INTERFACE
INTERFACE psdes
  SUBROUTINE psdes_s(lword,rword)
    USE nrtype
    INTEGER(I4B), INTENT(INOUT) :: lword,rword
  END SUBROUTINE psdes_s

  SUBROUTINE psdes_v(lword,rword)
    USE nrtype
    INTEGER(I4B), DIMENSION(:), INTENT(INOUT) :: lword,rword
  END SUBROUTINE psdes_v
END INTERFACE
INTERFACE
  SUBROUTINE pwt(a,sign)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
    INTEGER(I4B), INTENT(IN) :: sign
  END SUBROUTINE pwt
END INTERFACE
INTERFACE
  SUBROUTINE pwtset(n)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n
  END SUBROUTINE pwtset
END INTERFACE
INTERFACE pythag
  FUNCTION pythag_dp(a,b)
    USE nrtype
    REAL(DP), INTENT(IN) :: a,b
    REAL(DP) :: pythag_dp
  END FUNCTION pythag_dp

  FUNCTION pythag_sp(a,b)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,b
    REAL(SP) :: pythag_sp
  END FUNCTION pythag_sp
END INTERFACE
INTERFACE
  SUBROUTINE pzextr(iest,xest,yest,yz,dy)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: iest
    REAL(SP), INTENT(IN) :: xest
    REAL(SP), DIMENSION(:), INTENT(IN) :: yest
    REAL(SP), DIMENSION(:), INTENT(OUT) :: yz,dy
  END SUBROUTINE pzextr
END INTERFACE
INTERFACE
  SUBROUTINE qrdcmp(a,c,d,sing)
    USE nrtype
    REAL(SP), DIMENSION(:,,:), INTENT(INOUT) :: a
    REAL(SP), DIMENSION(:), INTENT(OUT) :: c,d
    LOGICAL(LGT), INTENT(OUT) :: sing
  END SUBROUTINE qrdcmp
END INTERFACE
INTERFACE
  FUNCTION qromb(func,a,b)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,b
    REAL(SP) :: qromb
  INTERFACE
    FUNCTION func(x)
      USE nrtype

```

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```

        REAL(SP), DIMENSION(:), INTENT(IN) :: x
        REAL(SP), DIMENSION(size(x)) :: func
    END FUNCTION func
END INTERFACE
END FUNCTION qromb
END INTERFACE
INTERFACE
    FUNCTION qromo(func,a,b,choose)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,b
    REAL(SP) :: qromo
    INTERFACE
        FUNCTION func(x)
        USE nrtype
        REAL(SP), DIMENSION(:), INTENT(IN) :: x
        REAL(SP), DIMENSION(size(x)) :: func
        END FUNCTION func
    END INTERFACE
    INTERFACE
        SUBROUTINE choose(funk,aa,bb,s,n)
        USE nrtype
        REAL(SP), INTENT(IN) :: aa,bb
        REAL(SP), INTENT(INOUT) :: s
        INTEGER(I4B), INTENT(IN) :: n
        INTERFACE
            FUNCTION funk(x)
            USE nrtype
            REAL(SP), DIMENSION(:), INTENT(IN) :: x
            REAL(SP), DIMENSION(size(x)) :: funk
            END FUNCTION funk
        END INTERFACE
        END SUBROUTINE choose
    END INTERFACE
END FUNCTION qromo
END INTERFACE
INTERFACE
    SUBROUTINE qroot(p,b,c,eps)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: p
    REAL(SP), INTENT(INOUT) :: b,c
    REAL(SP), INTENT(IN) :: eps
    END SUBROUTINE qroot
END INTERFACE
INTERFACE
    SUBROUTINE qrsolv(a,c,d,b)
    USE nrtype
    REAL(SP), DIMENSION(:,.), INTENT(IN) :: a
    REAL(SP), DIMENSION(:), INTENT(IN) :: c,d
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: b
    END SUBROUTINE qrsolv
END INTERFACE
INTERFACE
    SUBROUTINE qrupdt(r,qt,u,v)
    USE nrtype
    REAL(SP), DIMENSION(:,.), INTENT(INOUT) :: r,qt
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: u
    REAL(SP), DIMENSION(:), INTENT(IN) :: v
    END SUBROUTINE qrupdt
END INTERFACE
INTERFACE
    FUNCTION qsimp(func,a,b)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,b
    REAL(SP) :: qsimp

```

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```

INTERFACE
  FUNCTION func(x)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x
    REAL(SP), DIMENSION(size(x)) :: func
  END FUNCTION func
END INTERFACE
END FUNCTION qsimp
END INTERFACE
INTERFACE
  FUNCTION qtrap(func,a,b)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,b
    REAL(SP) :: qtrap
    INTERFACE
      FUNCTION func(x)
        USE nrtype
        REAL(SP), DIMENSION(:), INTENT(IN) :: x
        REAL(SP), DIMENSION(size(x)) :: func
      END FUNCTION func
    END INTERFACE
  END FUNCTION qtrap
END INTERFACE
INTERFACE
  SUBROUTINE quadct(x,y,xx,yy,fa,fb,fc,fd)
    USE nrtype
    REAL(SP), INTENT(IN) :: x,y
    REAL(SP), DIMENSION(:), INTENT(IN) :: xx,yy
    REAL(SP), INTENT(OUT) :: fa,fb,fc,fd
  END SUBROUTINE quadct
END INTERFACE
INTERFACE
  SUBROUTINE quadmx(a)
    USE nrtype
    REAL(SP), DIMENSION(:,), INTENT(OUT) :: a
  END SUBROUTINE quadmx
END INTERFACE
INTERFACE
  SUBROUTINE quadvl(x,y,fa,fb,fc,fd)
    USE nrtype
    REAL(SP), INTENT(IN) :: x,y
    REAL(SP), INTENT(OUT) :: fa,fb,fc,fd
  END SUBROUTINE quadvl
END INTERFACE
INTERFACE
  FUNCTION ran(idum)
    INTEGER(selected_int_kind(9)), INTENT(INOUT) :: idum
    REAL :: ran
  END FUNCTION ran
END INTERFACE
INTERFACE ran0
  SUBROUTINE ran0_s(harvest)
    USE nrtype
    REAL(SP), INTENT(OUT) :: harvest
  END SUBROUTINE ran0_s

  SUBROUTINE ran0_v(harvest)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(OUT) :: harvest
  END SUBROUTINE ran0_v
END INTERFACE
INTERFACE ran1
  SUBROUTINE ran1_s(harvest)
    USE nrtype

```

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```

REAL(SP), INTENT(OUT) :: harvest
END SUBROUTINE ran1_s

SUBROUTINE ran1_v(harvest)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(OUT) :: harvest
END SUBROUTINE ran1_v
END INTERFACE
INTERFACE ran2
SUBROUTINE ran2_s(harvest)
USE nrtype
REAL(SP), INTENT(OUT) :: harvest
END SUBROUTINE ran2_s

SUBROUTINE ran2_v(harvest)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(OUT) :: harvest
END SUBROUTINE ran2_v
END INTERFACE
INTERFACE ran3
SUBROUTINE ran3_s(harvest)
USE nrtype
REAL(SP), INTENT(OUT) :: harvest
END SUBROUTINE ran3_s

SUBROUTINE ran3_v(harvest)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(OUT) :: harvest
END SUBROUTINE ran3_v
END INTERFACE
INTERFACE
SUBROUTINE ratint(xa,ya,x,y,dy)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: xa,ya
REAL(SP), INTENT(IN) :: x
REAL(SP), INTENT(OUT) :: y,dy
END SUBROUTINE ratint
END INTERFACE
INTERFACE
SUBROUTINE ratlsq(func,a,b,mm,kk,cof,dev)
USE nrtype
REAL(DP), INTENT(IN) :: a,b
INTEGER(I4B), INTENT(IN) :: mm,kk
REAL(DP), DIMENSION(:), INTENT(OUT) :: cof
REAL(DP), INTENT(OUT) :: dev
INTERFACE
FUNCTION func(x)
USE nrtype
REAL(DP), DIMENSION(:), INTENT(IN) :: x
REAL(DP), DIMENSION(size(x)) :: func
END FUNCTION func
END INTERFACE
END SUBROUTINE ratlsq
END INTERFACE
INTERFACE ratval
FUNCTION ratval_s(x,cof,mm,kk)
USE nrtype
REAL(DP), INTENT(IN) :: x
INTEGER(I4B), INTENT(IN) :: mm,kk
REAL(DP), DIMENSION(mm+kk+1), INTENT(IN) :: cof
REAL(DP) :: ratval_s
END FUNCTION ratval_s

FUNCTION ratval_v(x,cof,mm,kk)
USE nrtype
REAL(DP), DIMENSION(:), INTENT(IN) :: x

```

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```

    INTEGER(I4B), INTENT(IN) :: mm, kk
    REAL(DP), DIMENSION(mm+kk+1), INTENT(IN) :: cof
    REAL(DP), DIMENSION(size(x)) :: ratval_v
    END FUNCTION ratval_v
END INTERFACE
INTERFACE rc
    FUNCTION rc_s(x,y)
    USE nrtype
    REAL(SP), INTENT(IN) :: x,y
    REAL(SP) :: rc_s
    END FUNCTION rc_s

    FUNCTION rc_v(x,y)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
    REAL(SP), DIMENSION(size(x)) :: rc_v
    END FUNCTION rc_v
END INTERFACE
INTERFACE rd
    FUNCTION rd_s(x,y,z)
    USE nrtype
    REAL(SP), INTENT(IN) :: x,y,z
    REAL(SP) :: rd_s
    END FUNCTION rd_s

    FUNCTION rd_v(x,y,z)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,z
    REAL(SP), DIMENSION(size(x)) :: rd_v
    END FUNCTION rd_v
END INTERFACE
INTERFACE realft
    SUBROUTINE realft_dp(data, isign, zdata)
    USE nrtype
    REAL(DP), DIMENSION(:), INTENT(INOUT) :: data
    INTEGER(I4B), INTENT(IN) :: isign
    COMPLEX(DPC), DIMENSION(:), OPTIONAL, TARGET :: zdata
    END SUBROUTINE realft_dp

    SUBROUTINE realft_sp(data, isign, zdata)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: data
    INTEGER(I4B), INTENT(IN) :: isign
    COMPLEX(SPC), DIMENSION(:), OPTIONAL, TARGET :: zdata
    END SUBROUTINE realft_sp
END INTERFACE
INTERFACE
    RECURSIVE FUNCTION recur1(a,b) RESULT(u)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: a,b
    REAL(SP), DIMENSION(size(a)) :: u
    END FUNCTION recur1
END INTERFACE
INTERFACE
    FUNCTION recur2(a,b,c)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: a,b,c
    REAL(SP), DIMENSION(size(a)) :: recur2
    END FUNCTION recur2
END INTERFACE
INTERFACE
    SUBROUTINE relax(u,rhs)
    USE nrtype
    REAL(DP), DIMENSION(:,:), INTENT(INOUT) :: u
    REAL(DP), DIMENSION(:,:), INTENT(IN) :: rhs
    END SUBROUTINE relax

```

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```

END INTERFACE
INTERFACE
  SUBROUTINE relax2(u,rhs)
    USE nrtype
    REAL(DP), DIMENSION(:,:), INTENT(INOUT) :: u
    REAL(DP), DIMENSION(:,:), INTENT(IN) :: rhs
  END SUBROUTINE relax2
END INTERFACE
INTERFACE
FUNCTION resid(u,rhs)
  USE nrtype
  REAL(DP), DIMENSION(:,:), INTENT(IN) :: u,rhs
  REAL(DP), DIMENSION(size(u,1),size(u,1)) :: resid
END FUNCTION resid
END INTERFACE
INTERFACE rf
  FUNCTION rf_s(x,y,z)
    USE nrtype
    REAL(SP), INTENT(IN) :: x,y,z
    REAL(SP) :: rf_s
  END FUNCTION rf_s

  FUNCTION rf_v(x,y,z)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,z
    REAL(SP), DIMENSION(size(x)) :: rf_v
  END FUNCTION rf_v
END INTERFACE
INTERFACE rj
  FUNCTION rj_s(x,y,z,p)
    USE nrtype
    REAL(SP), INTENT(IN) :: x,y,z,p
    REAL(SP) :: rj_s
  END FUNCTION rj_s

  FUNCTION rj_v(x,y,z,p)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,z,p
    REAL(SP), DIMENSION(size(x)) :: rj_v
  END FUNCTION rj_v
END INTERFACE
INTERFACE
  SUBROUTINE rk4(y,dydx,x,h,yout,derivs)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: y,dydx
    REAL(SP), INTENT(IN) :: x,h
    REAL(SP), DIMENSION(:), INTENT(OUT) :: yout
  INTERFACE
    SUBROUTINE derivs(x,y,dydx)
      USE nrtype
      REAL(SP), INTENT(IN) :: x
      REAL(SP), DIMENSION(:), INTENT(IN) :: y
      REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
    END SUBROUTINE derivs
  END INTERFACE
END SUBROUTINE rk4
END INTERFACE
INTERFACE
  SUBROUTINE rkck(y,dydx,x,h,yout,yerr,derivs)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: y,dydx
    REAL(SP), INTENT(IN) :: x,h
    REAL(SP), DIMENSION(:), INTENT(OUT) :: yout,yerr
  INTERFACE
    SUBROUTINE derivs(x,y,dydx)

```

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```

        USE nrtype
        REAL(SP), INTENT(IN) :: x
        REAL(SP), DIMENSION(:), INTENT(IN) :: y
        REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
    END SUBROUTINE derivs
END INTERFACE
END SUBROUTINE rkck
END INTERFACE
INTERFACE
SUBROUTINE rk dumb(vstart,x1,x2,nstep,derivs)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: vstart
    REAL(SP), INTENT(IN) :: x1,x2
    INTEGER(I4B), INTENT(IN) :: nstep
    INTERFACE
        SUBROUTINE derivs(x,y,dydx)
            USE nrtype
            REAL(SP), INTENT(IN) :: x
            REAL(SP), DIMENSION(:), INTENT(IN) :: y
            REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
        END SUBROUTINE derivs
    END INTERFACE
END SUBROUTINE rk dumb
END INTERFACE
INTERFACE
SUBROUTINE rkqs(y,dydx,x,htry,eps,yscal,hdid,hnext,derivs)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
    REAL(SP), DIMENSION(:), INTENT(IN) :: dydx,yscal
    REAL(SP), INTENT(INOUT) :: x
    REAL(SP), INTENT(IN) :: htry,eps
    REAL(SP), INTENT(OUT) :: hdid,hnext
    INTERFACE
        SUBROUTINE derivs(x,y,dydx)
            USE nrtype
            REAL(SP), INTENT(IN) :: x
            REAL(SP), DIMENSION(:), INTENT(IN) :: y
            REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
        END SUBROUTINE derivs
    END INTERFACE
END SUBROUTINE rkqs
END INTERFACE
INTERFACE
SUBROUTINE rlft2(data,spec,specq,sign)
    USE nrtype
    REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: data
    COMPLEX(SPC), DIMENSION(:,:), INTENT(OUT) :: spec
    COMPLEX(SPC), DIMENSION(:), INTENT(OUT) :: specq
    INTEGER(I4B), INTENT(IN) :: sign
END SUBROUTINE rlft2
END INTERFACE
INTERFACE
SUBROUTINE rlft3(data,spec,specq,sign)
    USE nrtype
    REAL(SP), DIMENSION(:,:,:), INTENT(INOUT) :: data
    COMPLEX(SPC), DIMENSION(:,:,:), INTENT(OUT) :: spec
    COMPLEX(SPC), DIMENSION(:,:), INTENT(OUT) :: specq
    INTEGER(I4B), INTENT(IN) :: sign
END SUBROUTINE rlft3
END INTERFACE
INTERFACE
SUBROUTINE rotate(r,qt,i,a,b)
    USE nrtype
    REAL(SP), DIMENSION(:,:), TARGET, INTENT(INOUT) :: r,qt

```

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```

    INTEGER(I4B), INTENT(IN) :: i
    REAL(SP), INTENT(IN) :: a,b
    END SUBROUTINE rotate
END INTERFACE
INTERFACE
    SUBROUTINE rsolv(a,d,b)
    USE nrtype
    REAL(SP), DIMENSION(:,), INTENT(IN) :: a
    REAL(SP), DIMENSION(:), INTENT(IN) :: d
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: b
    END SUBROUTINE rsolv
END INTERFACE
INTERFACE
    FUNCTION rstrct(uf)
    USE nrtype
    REAL(DP), DIMENSION(:,), INTENT(IN) :: uf
    REAL(DP), DIMENSION((size(uf,1)+1)/2,(size(uf,1)+1)/2) :: rstrct
    END FUNCTION rstrct
END INTERFACE
INTERFACE
    FUNCTION rtbis(func,x1,x2,xacc)
    USE nrtype
    REAL(SP), INTENT(IN) :: x1,x2,xacc
    REAL(SP) :: rtbis
    INTERFACE
        FUNCTION func(x)
        USE nrtype
        REAL(SP), INTENT(IN) :: x
        REAL(SP) :: func
        END FUNCTION func
    END INTERFACE
    END FUNCTION rtbis
END INTERFACE
INTERFACE
    FUNCTION rtflsp(func,x1,x2,xacc)
    USE nrtype
    REAL(SP), INTENT(IN) :: x1,x2,xacc
    REAL(SP) :: rtflsp
    INTERFACE
        FUNCTION func(x)
        USE nrtype
        REAL(SP), INTENT(IN) :: x
        REAL(SP) :: func
        END FUNCTION func
    END INTERFACE
    END FUNCTION rtflsp
END INTERFACE
INTERFACE
    FUNCTION rtnewt(funcd,x1,x2,xacc)
    USE nrtype
    REAL(SP), INTENT(IN) :: x1,x2,xacc
    REAL(SP) :: rtnewt
    INTERFACE
        SUBROUTINE funcd(x,fval,fderiv)
        USE nrtype
        REAL(SP), INTENT(IN) :: x
        REAL(SP), INTENT(OUT) :: fval,fderiv
        END SUBROUTINE funcd
    END INTERFACE
    END FUNCTION rtnewt
END INTERFACE
INTERFACE
    FUNCTION rtsafe(funcd,x1,x2,xacc)
    USE nrtype

```

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```

REAL(SP), INTENT(IN) :: x1,x2,xacc
REAL(SP) :: rtsafe
INTERFACE
  SUBROUTINE funcd(x,fval,fderiv)
  USE nrtype
  REAL(SP), INTENT(IN) :: x
  REAL(SP), INTENT(OUT) :: fval,fderiv
  END SUBROUTINE funcd
END INTERFACE
END FUNCTION rtsafe
END INTERFACE
INTERFACE
  FUNCTION rtsec(func,x1,x2,xacc)
  USE nrtype
  REAL(SP), INTENT(IN) :: x1,x2,xacc
  REAL(SP) :: rtsec
  INTERFACE
    FUNCTION func(x)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: func
    END FUNCTION func
  END INTERFACE
END FUNCTION rtsec
END INTERFACE
INTERFACE
  SUBROUTINE rzextr(iest,xest,yest,yz,dy)
  USE nrtype
  INTEGER(I4B), INTENT(IN) :: iest
  REAL(SP), INTENT(IN) :: xest
  REAL(SP), DIMENSION(:), INTENT(IN) :: yest
  REAL(SP), DIMENSION(:), INTENT(OUT) :: yz,dy
  END SUBROUTINE rzextr
END INTERFACE
INTERFACE
  FUNCTION savgol(nl,nrr,ld,m)
  USE nrtype
  INTEGER(I4B), INTENT(IN) :: nl,nrr,ld,m
  REAL(SP), DIMENSION(nl+nrr+1) :: savgol
  END FUNCTION savgol
END INTERFACE
INTERFACE
  SUBROUTINE scrsho(func)
  USE nrtype
  INTERFACE
    FUNCTION func(x)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: func
    END FUNCTION func
  END INTERFACE
END SUBROUTINE scrsho
END INTERFACE
INTERFACE
  FUNCTION select(k,arr)
  USE nrtype
  INTEGER(I4B), INTENT(IN) :: k
  REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
  REAL(SP) :: select
  END FUNCTION select
END INTERFACE
INTERFACE
  FUNCTION select_bypack(k,arr)
  USE nrtype

```

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```

    INTEGER(I4B), INTENT(IN) :: k
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
    REAL(SP) :: select_bypack
    END FUNCTION select_bypack
END INTERFACE
INTERFACE
    SUBROUTINE select_heap(arr,heap)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: arr
    REAL(SP), DIMENSION(:), INTENT(OUT) :: heap
    END SUBROUTINE select_heap
END INTERFACE
INTERFACE
    FUNCTION select_inplace(k,arr)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: k
    REAL(SP), DIMENSION(:), INTENT(IN) :: arr
    REAL(SP) :: select_inplace
    END FUNCTION select_inplace
END INTERFACE
INTERFACE
    SUBROUTINE simplx(a,m1,m2,m3,icase,izrov,iposv)
    USE nrtype
    REAL(SP), DIMENSION(:,), INTENT(INOUT) :: a
    INTEGER(I4B), INTENT(IN) :: m1,m2,m3
    INTEGER(I4B), INTENT(OUT) :: icase
    INTEGER(I4B), DIMENSION(:), INTENT(OUT) :: izrov,iposv
    END SUBROUTINE simplx
END INTERFACE
INTERFACE
    SUBROUTINE simpr(y,dydx,dfdx,dfdy,xs,htot,nstep,yout,derivs)
    USE nrtype
    REAL(SP), INTENT(IN) :: xs,htot
    REAL(SP), DIMENSION(:), INTENT(IN) :: y,dydx,dfdx
    REAL(SP), DIMENSION(:,), INTENT(IN) :: dfdy
    INTEGER(I4B), INTENT(IN) :: nstep
    REAL(SP), DIMENSION(:), INTENT(OUT) :: yout
    INTERFACE
        SUBROUTINE derivs(x,y,dydx)
        USE nrtype
        REAL(SP), INTENT(IN) :: x
        REAL(SP), DIMENSION(:), INTENT(IN) :: y
        REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
        END SUBROUTINE derivs
    END INTERFACE
    END SUBROUTINE simpr
END INTERFACE
INTERFACE
    SUBROUTINE sinft(y)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
    END SUBROUTINE sinft
END INTERFACE
INTERFACE
    SUBROUTINE slvsm2(u,rhs)
    USE nrtype
    REAL(DP), DIMENSION(3,3), INTENT(OUT) :: u
    REAL(DP), DIMENSION(3,3), INTENT(IN) :: rhs
    END SUBROUTINE slvsm2
END INTERFACE
INTERFACE
    SUBROUTINE slvsml(u,rhs)
    USE nrtype
    REAL(DP), DIMENSION(3,3), INTENT(OUT) :: u

```

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```

    REAL(DP), DIMENSION(3,3), INTENT(IN) :: rhs
  END SUBROUTINE slvsml
END INTERFACE
INTERFACE
  SUBROUTINE sncndn(uu,emmc,sn,cn,dn)
    USE nrtype
    REAL(SP), INTENT(IN) :: uu,emmc
    REAL(SP), INTENT(OUT) :: sn,cn,dn
  END SUBROUTINE sncndn
END INTERFACE
INTERFACE
  FUNCTION snrm(sx,itol)
    USE nrtype
    REAL(DP), DIMENSION(:), INTENT(IN) :: sx
    INTEGER(I4B), INTENT(IN) :: itol
    REAL(DP) :: snrm
  END FUNCTION snrm
END INTERFACE
INTERFACE
  SUBROUTINE sobseq(x,init)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(OUT) :: x
    INTEGER(I4B), OPTIONAL, INTENT(IN) :: init
  END SUBROUTINE sobseq
END INTERFACE
INTERFACE
  SUBROUTINE solvde(itmax,conv,slowc,scalv,indexv,nb,y)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: itmax,nb
    REAL(SP), INTENT(IN) :: conv,slowc
    REAL(SP), DIMENSION(:), INTENT(IN) :: scalv
    INTEGER(I4B), DIMENSION(:), INTENT(IN) :: indexv
    REAL(SP), DIMENSION(:,:), INTENT(INOUT) :: y
  END SUBROUTINE solvde
END INTERFACE
INTERFACE
  SUBROUTINE sor(a,b,c,d,e,f,u,rjac)
    USE nrtype
    REAL(DP), DIMENSION(:,:), INTENT(IN) :: a,b,c,d,e,f
    REAL(DP), DIMENSION(:,:), INTENT(INOUT) :: u
    REAL(DP), INTENT(IN) :: rjac
  END SUBROUTINE sor
END INTERFACE
INTERFACE
  SUBROUTINE sort(arr)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
  END SUBROUTINE sort
END INTERFACE
INTERFACE
  SUBROUTINE sort2(arr,slave)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr,slave
  END SUBROUTINE sort2
END INTERFACE
INTERFACE
  SUBROUTINE sort3(arr,slave1,slave2)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr,slave1,slave2
  END SUBROUTINE sort3
END INTERFACE
INTERFACE
  SUBROUTINE sort_bypack(arr)
    USE nrtype

```

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```

    REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
  END SUBROUTINE sort_bypack
END INTERFACE
INTERFACE
  SUBROUTINE sort_byreshape(arr)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
  END SUBROUTINE sort_byreshape
END INTERFACE
INTERFACE
  SUBROUTINE sort_heap(arr)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
  END SUBROUTINE sort_heap
END INTERFACE
INTERFACE
  SUBROUTINE sort_pick(arr)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
  END SUBROUTINE sort_pick
END INTERFACE
INTERFACE
  SUBROUTINE sort_radix(arr)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
  END SUBROUTINE sort_radix
END INTERFACE
INTERFACE
  SUBROUTINE sort_shell(arr)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(INOUT) :: arr
  END SUBROUTINE sort_shell
END INTERFACE
INTERFACE
  SUBROUTINE spectrm(p,k,ovrlap,unit,n_window)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(OUT) :: p
  INTEGER(I4B), INTENT(IN) :: k
  LOGICAL(LGT), INTENT(IN) :: ovrlap
  INTEGER(I4B), OPTIONAL, INTENT(IN) :: n_window,unit
  END SUBROUTINE spectrm
END INTERFACE
INTERFACE
  SUBROUTINE spear(data1,data2,d,zd,probd,rs,probrs)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2
  REAL(SP), INTENT(OUT) :: d,zd,probd,rs,probrs
  END SUBROUTINE spear
END INTERFACE
INTERFACE sphbes
  SUBROUTINE sphbes_s(n,x,sj,sy,sjp,syp)
  USE nrtype
  INTEGER(I4B), INTENT(IN) :: n
  REAL(SP), INTENT(IN) :: x
  REAL(SP), INTENT(OUT) :: sj,sy,sjp,syp
  END SUBROUTINE sphbes_s

  SUBROUTINE sphbes_v(n,x,sj,sy,sjp,syp)
  USE nrtype
  INTEGER(I4B), INTENT(IN) :: n
  REAL(SP), DIMENSION(:), INTENT(IN) :: x
  REAL(SP), DIMENSION(:), INTENT(OUT) :: sj,sy,sjp,syp
  END SUBROUTINE sphbes_v
END INTERFACE

```

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```

INTERFACE
  SUBROUTINE splie2(x1a,x2a,ya,y2a)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: x1a,x2a
  REAL(SP), DIMENSION(:,), INTENT(IN) :: ya
  REAL(SP), DIMENSION(:,), INTENT(OUT) :: y2a
  END SUBROUTINE splie2
END INTERFACE
INTERFACE
  FUNCTION splin2(x1a,x2a,ya,y2a,x1,x2)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: x1a,x2a
  REAL(SP), DIMENSION(:,), INTENT(IN) :: ya,y2a
  REAL(SP), INTENT(IN) :: x1,x2
  REAL(SP) :: splin2
  END FUNCTION splin2
END INTERFACE
INTERFACE
  SUBROUTINE spline(x,y,yp1,ypn,y2)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: x,y
  REAL(SP), INTENT(IN) :: yp1,ypn
  REAL(SP), DIMENSION(:), INTENT(OUT) :: y2
  END SUBROUTINE spline
END INTERFACE
INTERFACE
  FUNCTION splint(xa,ya,y2a,x)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: xa,ya,y2a
  REAL(SP), INTENT(IN) :: x
  REAL(SP) :: splint
  END FUNCTION splint
END INTERFACE
INTERFACE sprsax
  SUBROUTINE sprsax_dp(sa,x,b)
  USE nrtype
  TYPE(sprs2_dp), INTENT(IN) :: sa
  REAL(DP), DIMENSION (:), INTENT(IN) :: x
  REAL(DP), DIMENSION (:), INTENT(OUT) :: b
  END SUBROUTINE sprsax_dp

  SUBROUTINE sprsax_sp(sa,x,b)
  USE nrtype
  TYPE(sprs2_sp), INTENT(IN) :: sa
  REAL(SP), DIMENSION (:), INTENT(IN) :: x
  REAL(SP), DIMENSION (:), INTENT(OUT) :: b
  END SUBROUTINE sprsax_sp
END INTERFACE
INTERFACE sprsdiag
  SUBROUTINE sprsdiag_dp(sa,b)
  USE nrtype
  TYPE(sprs2_dp), INTENT(IN) :: sa
  REAL(DP), DIMENSION (:), INTENT(OUT) :: b
  END SUBROUTINE sprsdiag_dp

  SUBROUTINE sprsdiag_sp(sa,b)
  USE nrtype
  TYPE(sprs2_sp), INTENT(IN) :: sa
  REAL(SP), DIMENSION (:), INTENT(OUT) :: b
  END SUBROUTINE sprsdiag_sp
END INTERFACE
INTERFACE sprsin
  SUBROUTINE sprsin_sp(a,thresh,sa)
  USE nrtype
  REAL(SP), DIMENSION(:,), INTENT(IN) :: a

```

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```

REAL(SP), INTENT(IN) :: thresh
TYPE(sprs2_sp), INTENT(OUT) :: sa
END SUBROUTINE sprsin_sp

SUBROUTINE sprsin_dp(a,thresh,sa)
USE nrtype
REAL(DP), DIMENSION(:,), INTENT(IN) :: a
REAL(DP), INTENT(IN) :: thresh
TYPE(sprs2_dp), INTENT(OUT) :: sa
END SUBROUTINE sprsin_dp
END INTERFACE
INTERFACE
SUBROUTINE sprstp(sa)
USE nrtype
TYPE(sprs2_sp), INTENT(INOUT) :: sa
END SUBROUTINE sprstp
END INTERFACE
INTERFACE sprstx
SUBROUTINE sprstx_dp(sa,x,b)
USE nrtype
TYPE(sprs2_dp), INTENT(IN) :: sa
REAL(DP), DIMENSION (:), INTENT(IN) :: x
REAL(DP), DIMENSION (:), INTENT(OUT) :: b
END SUBROUTINE sprstx_dp

SUBROUTINE sprstx_sp(sa,x,b)
USE nrtype
TYPE(sprs2_sp), INTENT(IN) :: sa
REAL(SP), DIMENSION (:), INTENT(IN) :: x
REAL(SP), DIMENSION (:), INTENT(OUT) :: b
END SUBROUTINE sprstx_sp
END INTERFACE
INTERFACE
SUBROUTINE stifbs(y,dydx,x,htry,eps,yscal,hdid,hnext,derivs)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
REAL(SP), DIMENSION(:), INTENT(IN) :: dydx,yscal
REAL(SP), INTENT(IN) :: htry,eps
REAL(SP), INTENT(INOUT) :: x
REAL(SP), INTENT(OUT) :: hdid,hnext
INTERFACE
SUBROUTINE derivs(x,y,dydx)
USE nrtype
REAL(SP), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(IN) :: y
REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
END SUBROUTINE derivs
END INTERFACE
END SUBROUTINE stifbs
END INTERFACE
INTERFACE
SUBROUTINE stiff(y,dydx,x,htry,eps,yscal,hdid,hnext,derivs)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(INOUT) :: y
REAL(SP), DIMENSION(:), INTENT(IN) :: dydx,yscal
REAL(SP), INTENT(INOUT) :: x
REAL(SP), INTENT(IN) :: htry,eps
REAL(SP), INTENT(OUT) :: hdid,hnext
INTERFACE
SUBROUTINE derivs(x,y,dydx)
USE nrtype
REAL(SP), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(IN) :: y
REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
END SUBROUTINE derivs

```

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```

END INTERFACE
END SUBROUTINE stiff
END INTERFACE
INTERFACE
SUBROUTINE stoerm(y,d2y,xs,htot,nstep,yout,derivs)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: y,d2y
REAL(SP), INTENT(IN) :: xs,htot
INTEGER(I4B), INTENT(IN) :: nstep
REAL(SP), DIMENSION(:), INTENT(OUT) :: yout
INTERFACE
SUBROUTINE derivs(x,y,dydx)
USE nrtype
REAL(SP), INTENT(IN) :: x
REAL(SP), DIMENSION(:), INTENT(IN) :: y
REAL(SP), DIMENSION(:), INTENT(OUT) :: dydx
END SUBROUTINE derivs
END INTERFACE
END SUBROUTINE stoerm
END INTERFACE
INTERFACE svbksb
SUBROUTINE svbksb_dp(u,w,v,b,x)
USE nrtype
REAL(DP), DIMENSION(:,.), INTENT(IN) :: u,v
REAL(DP), DIMENSION(:), INTENT(IN) :: w,b
REAL(DP), DIMENSION(:), INTENT(OUT) :: x
END SUBROUTINE svbksb_dp
SUBROUTINE svbksb_sp(u,w,v,b,x)
USE nrtype
REAL(SP), DIMENSION(:,.), INTENT(IN) :: u,v
REAL(SP), DIMENSION(:), INTENT(IN) :: w,b
REAL(SP), DIMENSION(:), INTENT(OUT) :: x
END SUBROUTINE svbksb_sp
END INTERFACE
INTERFACE svdcmp
SUBROUTINE svdcmp_dp(a,w,v)
USE nrtype
REAL(DP), DIMENSION(:,.), INTENT(INOUT) :: a
REAL(DP), DIMENSION(:), INTENT(OUT) :: w
REAL(DP), DIMENSION(:,.), INTENT(OUT) :: v
END SUBROUTINE svdcmp_dp
SUBROUTINE svdcmp_sp(a,w,v)
USE nrtype
REAL(SP), DIMENSION(:,.), INTENT(INOUT) :: a
REAL(SP), DIMENSION(:), INTENT(OUT) :: w
REAL(SP), DIMENSION(:,.), INTENT(OUT) :: v
END SUBROUTINE svdcmp_sp
END INTERFACE
INTERFACE
SUBROUTINE svdfit(x,y,sig,a,v,w,chisq,funcs)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(IN) :: x,y,sig
REAL(SP), DIMENSION(:), INTENT(OUT) :: a,w
REAL(SP), DIMENSION(:,.), INTENT(OUT) :: v
REAL(SP), INTENT(OUT) :: chisq
INTERFACE
FUNCTION funcs(x,n)
USE nrtype
REAL(SP), INTENT(IN) :: x
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), DIMENSION(n) :: funcs
END FUNCTION funcs
END INTERFACE
END INTERFACE

```

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```

    END SUBROUTINE svdfit
END INTERFACE
INTERFACE
  SUBROUTINE svdvar(v,w,cvm)
    USE nrtype
    REAL(SP), DIMENSION(:,,:), INTENT(IN) :: v
    REAL(SP), DIMENSION(:,), INTENT(IN) :: w
    REAL(SP), DIMENSION(:,,:), INTENT(OUT) :: cvm
  END SUBROUTINE svdvar
END INTERFACE
INTERFACE
  FUNCTION toeplz(r,y)
    USE nrtype
    REAL(SP), DIMENSION(:,), INTENT(IN) :: r,y
    REAL(SP), DIMENSION(size(y)) :: toeplz
  END FUNCTION toeplz
END INTERFACE
INTERFACE
  SUBROUTINE tptest(data1,data2,t,prob)
    USE nrtype
    REAL(SP), DIMENSION(:,), INTENT(IN) :: data1,data2
    REAL(SP), INTENT(OUT) :: t,prob
  END SUBROUTINE tptest
END INTERFACE
INTERFACE
  SUBROUTINE tqli(d,e,z)
    USE nrtype
    REAL(SP), DIMENSION(:,), INTENT(INOUT) :: d,e
    REAL(SP), DIMENSION(:,,:), OPTIONAL, INTENT(INOUT) :: z
  END SUBROUTINE tqli
END INTERFACE
INTERFACE
  SUBROUTINE trapzd(func,a,b,s,n)
    USE nrtype
    REAL(SP), INTENT(IN) :: a,b
    REAL(SP), INTENT(INOUT) :: s
    INTEGER(I4B), INTENT(IN) :: n
  INTERFACE
    FUNCTION func(x)
      USE nrtype
      REAL(SP), DIMENSION(:,), INTENT(IN) :: x
      REAL(SP), DIMENSION(size(x)) :: func
    END FUNCTION func
  END INTERFACE
END SUBROUTINE trapzd
END INTERFACE
INTERFACE
  SUBROUTINE tred2(a,d,e,novectors)
    USE nrtype
    REAL(SP), DIMENSION(:,,:), INTENT(INOUT) :: a
    REAL(SP), DIMENSION(:,), INTENT(OUT) :: d,e
    LOGICAL(LGT), OPTIONAL, INTENT(IN) :: novectors
  END SUBROUTINE tred2
END INTERFACE
! On a purely serial machine, for greater efficiency, remove
! the generic name tridag from the following interface,
! and put it on the next one after that.
INTERFACE tridag
  RECURSIVE SUBROUTINE tridag_par(a,b,c,r,u)
    USE nrtype
    REAL(SP), DIMENSION(:,), INTENT(IN) :: a,b,c,r
    REAL(SP), DIMENSION(:,), INTENT(OUT) :: u
  END SUBROUTINE tridag_par
END INTERFACE

```

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```

INTERFACE
  SUBROUTINE tridag_ser(a,b,c,r,u)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: a,b,c,r
  REAL(SP), DIMENSION(:), INTENT(OUT) :: u
  END SUBROUTINE tridag_ser
END INTERFACE
INTERFACE
  SUBROUTINE ttest(data1,data2,t,prob)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2
  REAL(SP), INTENT(OUT) :: t,prob
  END SUBROUTINE ttest
END INTERFACE
INTERFACE
  SUBROUTINE tutest(data1,data2,t,prob)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2
  REAL(SP), INTENT(OUT) :: t,prob
  END SUBROUTINE tutest
END INTERFACE
INTERFACE
  SUBROUTINE twofft(data1,data2,fft1,fft2)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: data1,data2
  COMPLEX(SPC), DIMENSION(:), INTENT(OUT) :: fft1,fft2
  END SUBROUTINE twofft
END INTERFACE
INTERFACE
  FUNCTION vander(x,q)
  USE nrtype
  REAL(DP), DIMENSION(:), INTENT(IN) :: x,q
  REAL(DP), DIMENSION(size(x)) :: vander
  END FUNCTION vander
END INTERFACE
INTERFACE
  SUBROUTINE vegas(region,func,init,ncall,itmx,nprn,tgral,sd,chi2a)
  USE nrtype
  REAL(SP), DIMENSION(:), INTENT(IN) :: region
  INTEGER(I4B), INTENT(IN) :: init,ncall,itmx,nprn
  REAL(SP), INTENT(OUT) :: tgral,sd,chi2a
  INTERFACE
    FUNCTION func(pt,wgt)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: pt
    REAL(SP), INTENT(IN) :: wgt
    REAL(SP) :: func
    END FUNCTION func
  END INTERFACE
  END SUBROUTINE vegas
END INTERFACE
INTERFACE
  SUBROUTINE voltra(t0,h,t,f,g,ak)
  USE nrtype
  REAL(SP), INTENT(IN) :: t0,h
  REAL(SP), DIMENSION(:), INTENT(OUT) :: t
  REAL(SP), DIMENSION(:,:), INTENT(OUT) :: f
  INTERFACE
    FUNCTION g(t)
    USE nrtype
    REAL(SP), INTENT(IN) :: t
    REAL(SP), DIMENSION(:), POINTER :: g
    END FUNCTION g
  END INTERFACE

```

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```

        FUNCTION ak(t,s)
        USE nrtype
        REAL(SP), INTENT(IN) :: t,s
        REAL(SP), DIMENSION(:,:), POINTER :: ak
        END FUNCTION ak
    END INTERFACE
END SUBROUTINE voltra
END INTERFACE
INTERFACE
SUBROUTINE wt1(a,isign,wtstep)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
INTEGER(I4B), INTENT(IN) :: isign
INTERFACE
    SUBROUTINE wtstep(a,isign)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
    INTEGER(I4B), INTENT(IN) :: isign
    END SUBROUTINE wtstep
END INTERFACE
END SUBROUTINE wt1
END INTERFACE
INTERFACE
SUBROUTINE wtn(a,nn,isign,wtstep)
USE nrtype
REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
INTEGER(I4B), DIMENSION(:), INTENT(IN) :: nn
INTEGER(I4B), INTENT(IN) :: isign
INTERFACE
    SUBROUTINE wtstep(a,isign)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(INOUT) :: a
    INTEGER(I4B), INTENT(IN) :: isign
    END SUBROUTINE wtstep
END INTERFACE
END SUBROUTINE wtn
END INTERFACE
INTERFACE
FUNCTION wwgths(n,h,kermom)
USE nrtype
INTEGER(I4B), INTENT(IN) :: n
REAL(SP), INTENT(IN) :: h
REAL(SP), DIMENSION(n) :: wwgths
INTERFACE
    FUNCTION kermom(y,m)
    USE nrtype
    REAL(DP), INTENT(IN) :: y
    INTEGER(I4B), INTENT(IN) :: m
    REAL(DP), DIMENSION(m) :: kermom
    END FUNCTION kermom
END INTERFACE
END FUNCTION wwgths
END INTERFACE
INTERFACE
SUBROUTINE zbrac(func,x1,x2,succes)
USE nrtype
REAL(SP), INTENT(INOUT) :: x1,x2
LOGICAL(LGT), INTENT(OUT) :: succes
INTERFACE
    FUNCTION func(x)
    USE nrtype
    REAL(SP), INTENT(IN) :: x
    REAL(SP) :: func
    END FUNCTION func

```

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```

    END INTERFACE
    END SUBROUTINE zbrac
END INTERFACE
INTERFACE
  SUBROUTINE zbrak(func,x1,x2,n,xb1,xb2,nb)
    USE nrtype
    INTEGER(I4B), INTENT(IN) :: n
    INTEGER(I4B), INTENT(OUT) :: nb
    REAL(SP), INTENT(IN) :: x1,x2
    REAL(SP), DIMENSION(:), POINTER :: xb1,xb2
    INTERFACE
      FUNCTION func(x)
        USE nrtype
        REAL(SP), INTENT(IN) :: x
        REAL(SP) :: func
      END FUNCTION func
    END INTERFACE
  END SUBROUTINE zbrak
END INTERFACE
INTERFACE
  FUNCTION zbrent(func,x1,x2,tol)
    USE nrtype
    REAL(SP), INTENT(IN) :: x1,x2,tol
    REAL(SP) :: zbrent
  END FUNCTION zbrent
END INTERFACE
INTERFACE
  SUBROUTINE zrhqr(a,rtr,rti)
    USE nrtype
    REAL(SP), DIMENSION(:), INTENT(IN) :: a
    REAL(SP), DIMENSION(:), INTENT(OUT) :: rtr,rti
  END SUBROUTINE zrhqr
END INTERFACE
INTERFACE
  FUNCTION zriddr(func,x1,x2,xacc)
    USE nrtype
    REAL(SP), INTENT(IN) :: x1,x2,xacc
    REAL(SP) :: zriddr
  END FUNCTION zriddr
END INTERFACE
INTERFACE
  SUBROUTINE zroots(a,roots,polish)
    USE nrtype
    COMPLEX(SPC), DIMENSION(:), INTENT(IN) :: a
    COMPLEX(SPC), DIMENSION(:), INTENT(OUT) :: roots
    LOGICAL(LGT), INTENT(IN) :: polish
  END SUBROUTINE zroots
END INTERFACE
END MODULE nr

```

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### C3. Index of Programs and Dependencies

The following table lists, in alphabetical order, all the routines in Volume 2 of *Numerical Recipes*. When a routine requires subsidiary routines, either from this book or else user-supplied, the full dependency tree is shown: A routine calls directly all routines to which it is connected by a solid line in the column immediately to its right; it calls indirectly the connected routines in all columns to its right. Typographical conventions: Routines from this book are in typewriter font (e.g., `eulsum`, `gamm1n`). The smaller, slanted font is used for the second and subsequent occurrences of a routine in a single dependency tree. (When you are getting routines from the *Numerical Recipes* machine-readable media or hypertext archives, you need specify names only in the larger, upright font.) User-supplied routines are indicated by the use of text font and square brackets, e.g., `[funcv]`. Consult the text for individual specifications of these routines. The right-hand side of the table lists chapter and page numbers for each program.

<code>airy</code>	└─ <code>bessik</code> ─┘	. . . . .	B6 (p. 1121)
	└─ <code>bessjy</code> ─┘	└─ <code>beschb</code> ─┘	└─ <code>chebev</code>
<code>amebsa</code>	└─ <code>ran1</code> ─┘	└─ <code>ran_state</code>	. . . . . B10 (p. 1222)
	└─ <code>[func]</code>		
<code>amoeba</code>	└─ <code>[func]</code>	. . . . .	B10 (p. 1208)
<code>anneal</code>	└─ <code>ran1</code> ─┘	└─ <code>ran_state</code>	. . . . . B10 (p. 1219)
<code>arcmak</code>	. . . . .		B20 (p. 1349)
<code>arcode</code>	└─ <code>arcmak</code>	. . . . .	B20 (p. 1350)
<code>avevar</code>	. . . . .		B14 (p. 1270)
<code>badluk</code>	└─ <code>julday</code> ─┘	. . . . .	B1 (p. 1011)
	└─ <code>flmoon</code>		
<code>balanc</code>	. . . . .		B11 (p. 1230)
<code>banbks</code>	. . . . .		B2 (p. 1021)
<code>bandec</code>	. . . . .		B2 (p. 1020)
<code>banmul</code>	. . . . .		B2 (p. 1019)
<code>bcucof</code>	. . . . .		B3 (p. 1049)
<code>bcuint</code>	└─ <code>bcucof</code>	. . . . .	B3 (p. 1050)
<code>beschb</code>	└─ <code>chebev</code>	. . . . .	B6 (p. 1118)



bessi — bessj0 . . . . .	B6 (p. 1114)
bessi0 . . . . .	B6 (p. 1109)
bessi1 . . . . .	B6 (p. 1111)
bessik — beschb — chebev . . . . .	B6 (p. 1118)
bessj — bessj0 . . . . .	B6 (p. 1106)
└─ bessj1	
bessj0 . . . . .	B6 (p. 1101)
bessj1 . . . . .	B6 (p. 1103)
bessjy — beschb — chebev . . . . .	B6 (p. 1115)
bessk — bessk0 — bessj0 . . . . .	B6 (p. 1113)
└─ bessk1 — bessj1	
bessk0 — bessj0 . . . . .	B6 (p. 1110)
bessk1 — bessj1 . . . . .	B6 (p. 1112)
bessy — bessy1 — bessj1 . . . . .	B6 (p. 1105)
└─ bessy0 — bessj0	
bessy0 — bessj0 . . . . .	B6 (p. 1102)
bessy1 — bessj1 . . . . .	B6 (p. 1104)
beta — gammln . . . . .	B6 (p. 1089)
betacf . . . . .	B6 (p. 1099)
betai — gammln . . . . .	B6 (p. 1098)
└─ betacf	
bico — factln — gammln . . . . .	B6 (p. 1087)
bnldev — ran1 — ran_state . . . . .	B7 (p. 1155)
└─ gammln	
brent — [func] . . . . .	B10 (p. 1204)
broydn — fmin . . . . .	B9 (p. 1199)
└─ fdjac — [funcv]	
└─ qrdcmp	
└─ grupdt — rotate	
└─ pythag	
└─ rsolv	
└─ lnsrch — fmin — [funcv]	
bsstep — mmid — [derivs] . . . . .	B16 (p. 1303)
└─ pzextr	
caldat . . . . .	B1 (p. 1013)
chder . . . . .	B5 (p. 1077)
chebev . . . . .	B5 (p. 1076)
chebft — [func] . . . . .	B5 (p. 1076)
chebpc . . . . .	B5 (p. 1078)
chint . . . . .	B5 (p. 1078)
chixy . . . . .	B15 (p. 1287)

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choldc		B2 (p. 1038)
chols1		B2 (p. 1039)
chsone	— gammq — $\left\{ \begin{array}{l} \text{gser} \\ \text{gcf} \end{array} \right. \text{— gammln}$	B14 (p. 1272)
chstwo	— gammq — $\left\{ \begin{array}{l} \text{gser} \\ \text{gcf} \end{array} \right. \text{— gammln}$	B14 (p. 1272)
cisi		B6 (p. 1125)
cntab1	— gammq — $\left\{ \begin{array}{l} \text{gser} \\ \text{gcf} \end{array} \right. \text{— gammln}$	B14 (p. 1275)
cntab2		B14 (p. 1275)
convlv	— realft — four1 — fourrow	B13 (p. 1253)
correl	— realft — four1 — fourrow	B13 (p. 1254)
cosft1	— realft — four1 — fourrow	B12 (p. 1245)
cosft2	— realft — four1 — fourrow	B12 (p. 1246)
covsrt		B15 (p. 1289)
cyclic	— tridag	B2 (p. 1030)
daub4		B13 (p. 1264)
dawson		B6 (p. 1127)
dbrent	$\left\{ \begin{array}{l} \text{[func]} \\ \text{[dfunc]} \end{array} \right.$	B10 (p. 1205)
ddpoly		B5 (p. 1071)
decchk		B20 (p. 1345)
dfpmin	$\left\{ \begin{array}{l} \text{[func]} \\ \text{[dfunc]} \\ \text{— lnsrch — [func]} \end{array} \right.$	B10 (p. 1215)
dfridr	— [func]	B5 (p. 1075)
dftcor		B13 (p. 1261)
dftint	$\left\{ \begin{array}{l} \text{[func]} \\ \text{— realft — four1 — fourrow} \\ \text{— polint} \\ \text{— dftcor} \end{array} \right.$	B13 (p. 1263)
difeq		B17 (p. 1320)
dlinmin	$\left\{ \begin{array}{l} \text{— mnbrak} \\ \text{— dbrent} \left\{ \begin{array}{l} \text{[func]} \\ \text{[dfunc]} \end{array} \right. \end{array} \right.$	B10 (p. 1212)
eclass		B8 (p. 1180)
eclazz	— [equiv]	B8 (p. 1180)
ei		B6 (p. 1097)
eigsrt		B11 (p. 1227)
elle	$\left\{ \begin{array}{l} \text{— rf} \\ \text{— rd} \end{array} \right.$	B6 (p. 1136)

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ellf — rf . . . . .	B6 (p. 1135)
ellpi — rf . . . . .	B6 (p. 1136)
└─ rj — rc	
└─ rf	
elmhes . . . . .	B11 (p. 1231)
erf — gammp — gser — gammln	B6 (p. 1094)
└─ gcf	
erfc — gammp — gser . . . . .	B6 (p. 1094)
└─ gcf — gammln	
└─ gammq — gser — gammln	
└─ gcf	
erfcc . . . . .	B6 (p. 1095)
eulsum . . . . .	B5 (p. 1070)
evlmem . . . . .	B13 (p. 1258)
expdev — ran1 — ran_state . . . . .	B7 (p. 1151)
expint . . . . .	B6 (p. 1096)
factln — gammln . . . . .	B6 (p. 1088)
factrl — gammln . . . . .	B6 (p. 1086)
fasper — avevar . . . . .	B13 (p. 1259)
└─ realft — four1 — fourrow	
fdjac — [funcv] . . . . .	B9 (p. 1197)
fgauss . . . . .	B15 (p. 1294)
fit — gammq — gser — gammln	B15 (p. 1285)
└─ gcf	
fitexy — avevar . . . . .	B15 (p. 1286)
└─ fit — gammq — gser — gammln	
└─ gcf	
└─ chixy	
└─ mnbrak	
└─ brent	
└─ gammq — gser — gammln	
└─ gcf	
└─ zbrent — chixy	
fixrts — roots — laguer . . . . .	B13 (p. 1257)
└─ indexx	
fleg . . . . .	B15 (p. 1291)
flmoon . . . . .	B1 (p. 1010)
fmin — [funcv] . . . . .	B9 (p. 1198)
four1 — fourrow . . . . .	B12 (p. 1239)
four1_alt — fourcol . . . . .	B12 (p. 1240)
four1_gather . . . . .	B12 (p. 1250)
four2 — fourrow . . . . .	B12 (p. 1241)

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four2_alt — fourcol . . . . .	B12 (p. 1242)
four3 — fourrow_3d . . . . .	B12 (p. 1246)
four3_alt — fourcol_3d . . . . .	B12 (p. 1247)
fourcol . . . . .	B12 (p. 1237)
fourcol_3d . . . . .	B12 (p. 1238)
fourn_gather . . . . .	B12 (p. 1251)
fourrow . . . . .	B12 (p. 1235)
fourrow_3d . . . . .	B12 (p. 1236)
fpoly . . . . .	B15 (p. 1291)
fred2 — gauleg . . . . .	B18 (p. 1325)
— [ak]	
— [g]	
— ludcmp	
— lubksb	
fredex — quadmx — wwgths — kermom . . . . .	B18 (p. 1331)
— ludcmp	
— lubksb	
fredin — [ak] . . . . .	B18 (p. 1326)
— [g]	
frenel . . . . .	B6 (p. 1123)
frprmn — [func] . . . . .	B10 (p. 1214)
— [dfunc]	
— linmin — mnbrak — brent — [func]	
ftest — avevar . . . . .	B14 (p. 1271)
— betai — gammln — betacf	
gamdev — ran1 — ran_state . . . . .	B7 (p. 1153)
gammln . . . . .	B6 (p. 1085)
gammp — gser — gammln . . . . .	B6 (p. 1089)
— gcf	
gammq — gser — gammln . . . . .	B6 (p. 1090)
— gcf	
gasdev — ran1 — ran_state . . . . .	B7 (p. 1152)
gaucof — tqli — pythag . . . . .	B4 (p. 1064)
— eigsrt	
gauher . . . . .	B4 (p. 1062)
gaujac — gammln . . . . .	B4 (p. 1063)
gaulag — gammln . . . . .	B4 (p. 1060)
gauleg . . . . .	B4 (p. 1059)
gaussj . . . . .	B2 (p. 1014)
gcf — gammln . . . . .	B6 (p. 1092)

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golden — [func]		B10 (p. 1202)
gser — gammln		B6 (p. 1090)
hqr		B11 (p. 1232)
hufdec — hufmak		B20 (p. 1349)
hufenc — hufmak		B20 (p. 1348)
hufmak		B20 (p. 1346)
hunt		B3 (p. 1046)
hypdrv		B6 (p. 1139)
hypgeo	hypser	B6 (p. 1138)
	odeint	
	bsstep	mmid
		pzextr
	hypdrv	
hypser		B6 (p. 1139)
icrc		B20 (p. 1344)
igray		B20 (p. 1344)
index_bypack		B8 (p. 1176)
indexx		B8 (p. 1173)
interp		B19 (p. 1337)
irbit1		B7 (p. 1159)
irbit2		B7 (p. 1160)
jacobi		B11 (p. 1225)
jacobn		B16 (p. 1309)
julday		B1 (p. 1011)
kendl1 — erfcc		B14 (p. 1279)
kendl2 — erfcc		B14 (p. 1279)
kermom		B18 (p. 1329)
ks2d1s	quadct	B14 (p. 1281)
	quadvl	
	pearsn — betai	gammln
		betacf
	probks	
ks2d2s	quadct	B14 (p. 1283)
	pearsn — betai	gammln
		betacf
	probks	
ksone	sort	B14 (p. 1273)
	[func]	
	probks	
kstwo	sort2	B14 (p. 1273)
	probks	
laguer		B9 (p. 1191)

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lfit	└─ [funcs]	. . . . .	B15 (p. 1288)
	└─ gaussj		
	└─ covsrt		
linbcg	└─ atimes	. . . . .	B2 (p. 1034)
	└─ snrm		
	└─ asolve		
linmin	└─ mnbrak	. . . . .	B10 (p. 1211)
	└─ brent	└─ [func]	
lnsrch	└─ [func]	. . . . .	B9 (p. 1195)
locate		. . . . .	B3 (p. 1045)
lop		. . . . .	B19 (p. 1342)
lubksb		. . . . .	B2 (p. 1017)
ludcmp		. . . . .	B2 (p. 1016)
machar		. . . . .	B20 (p. 1343)
medfit	└─ select	. . . . .	B15 (p. 1294)
memcof		. . . . .	B13 (p. 1256)
mgfas	└─ rstrct	. . . . .	B19 (p. 1339)
	└─ slvsm2		
	└─ interp		
	└─ relax2		
	└─ lop		
mglin	└─ rstrct	. . . . .	B19 (p. 1334)
	└─ slvsml		
	└─ interp		
	└─ relax		
	└─ resid		
midexp	└─ [funk]	. . . . .	B4 (p. 1058)
midinf	└─ [funk]	. . . . .	B4 (p. 1056)
midpnt	└─ [func]	. . . . .	B4 (p. 1054)
midsql	└─ [funk]	. . . . .	B4 (p. 1057)
midsqu	└─ [funk]	. . . . .	B4 (p. 1057)
miser	└─ ran1	└─ ran_state	. . . . .
	└─ [func]		B7 (p. 1164)
mmid	└─ [derivs]	. . . . .	B16 (p. 1302)
mnbrak	└─ [func]	. . . . .	B10 (p. 1201)
mnewt	└─ [usrfun]	. . . . .	B9 (p. 1194)
	└─ ludcmp		
	└─ lubksb		
moment		. . . . .	B14 (p. 1269)
mp2dfr	└─ mpops	. . . . .	B20 (p. 1357)

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mpdiv	<ul style="list-style-type: none"> <li>├── mpinv <ul style="list-style-type: none"> <li>├── mpmul — realft — four1 — fourrow</li> <li>└── mpops</li> </ul> </li> <li>└── mpmul — realft — four1 — fourrow <ul style="list-style-type: none"> <li>└── mpops</li> </ul> </li> </ul>	B20 (p. 1356)
mpinv	<ul style="list-style-type: none"> <li>├── mpmul — realft — four1 — fourrow</li> <li>└── mpops</li> </ul>	B20 (p. 1355)
mpmul	— realft — four1 — fourrow . . . . .	B20 (p. 1354)
mpops	. . . . .	B20 (p. 1352)
mppi	<ul style="list-style-type: none"> <li>├── mpsqrt <ul style="list-style-type: none"> <li>├── mpmul — realft — four1 — fourrow</li> <li>└── mpops</li> </ul> </li> <li>└── mpops</li> <li>└── mpmul — realft — four1 — fourrow</li> <li>└── mpinv — mpmul — realft — four1 — fourrow</li> <li>└── mp2dfr — mpops</li> </ul>	B20 (p. 1357)
mprove	— lubksb . . . . .	B2 (p. 1022)
mpsqrt	<ul style="list-style-type: none"> <li>├── mpmul — realft — four1 — fourrow</li> <li>└── mpops</li> </ul>	B20 (p. 1356)
mrqmin	<ul style="list-style-type: none"> <li>├── gaussj . . . . .</li> <li>└── covsrt <ul style="list-style-type: none"> <li>└── [funcs]</li> </ul> </li> </ul>	B15 (p. 1292)
newt	<ul style="list-style-type: none"> <li>├── fmin <ul style="list-style-type: none"> <li>└── [funcv]</li> </ul> </li> <li>├── fdjac <ul style="list-style-type: none"> <li>└── [funcv]</li> </ul> </li> <li>├── ludcmp</li> <li>├── lubksb</li> <li>└── lnsrch — fmin — [funcv]</li> </ul>	B9 (p. 1196)
odeint	<ul style="list-style-type: none"> <li>├── [derivs] . . . . .</li> <li>└── rkqs <ul style="list-style-type: none"> <li>└── [derivs]</li> <li>└── rkck — [derivs]</li> </ul> </li> </ul>	B16 (p. 1300)
orthog	. . . . .	B4 (p. 1064)
pade	<ul style="list-style-type: none"> <li>├── ludcmp . . . . .</li> <li>└── lubksb <ul style="list-style-type: none"> <li>└── mprove — lubksb</li> </ul> </li> </ul>	B5 (p. 1080)
pccheb	. . . . .	B5 (p. 1080)
pcshft	. . . . .	B5 (p. 1079)
pearsn	<ul style="list-style-type: none"> <li>├── betai <ul style="list-style-type: none"> <li>├── gammln . . . . .</li> <li>└── betacf</li> </ul> </li> </ul>	B14 (p. 1276)
period	— avevar . . . . .	B13 (p. 1258)
plgndr	. . . . .	B6 (p. 1122)
poidev	<ul style="list-style-type: none"> <li>├── ran1 — ran_state . . . . .</li> <li>└── gammln</li> </ul>	B7 (p. 1154)
polcoe	. . . . .	B3 (p. 1047)
polcof	— polint . . . . .	B3 (p. 1048)
poldiv	. . . . .	B5 (p. 1072)

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polin2 — polint . . . . .	B3 (p. 1049)
polint . . . . .	B3 (p. 1043)
powell — [func] . . . . .	B10 (p. 1210)
└─ linmin — mnbrak — brent — [func]	
predic . . . . .	B13 (p. 1257)
probks . . . . .	B14 (p. 1274)
psdes . . . . .	B7 (p. 1156)
pwt — pwtset . . . . .	B13 (p. 1266)
pwtset . . . . .	B13 (p. 1265)
pythag . . . . .	B2 (p. 1029)
pzextr . . . . .	B16 (p. 1305)
qrncmp . . . . .	B2 (p. 1039)
qromb — trapzd — [func] . . . . .	B4 (p. 1054)
└─ polint	
qromo — midpnt — [func] . . . . .	B4 (p. 1055)
└─ polint	
qroot — poldiv . . . . .	B9 (p. 1193)
qrsolv — rsolv . . . . .	B2 (p. 1040)
qrupdt — rotate . . . . .	B2 (p. 1041)
└─ pythag	
qsimp — trapzd — [func] . . . . .	B4 (p. 1053)
qtrap — trapzd — [func] . . . . .	B4 (p. 1053)
quad3d — polint . . . . .	B4 (p. 1065)
└─ [func]	
└─ [y1]	
└─ [y2]	
└─ [z1]	
└─ [z2]	
quadct . . . . .	B14 (p. 1282)
quadmx — wwgths — kermom . . . . .	B18 (p. 1330)
quadvl . . . . .	B14 (p. 1282)
ran . . . . .	B7 (p. 1142)
ran0 — ran_state . . . . .	B7 (p. 1148)
ran1 — ran_state . . . . .	B7 (p. 1149)
ran2 — ran_state . . . . .	B7 (p. 1150)
ran3 — ran_state . . . . .	B7 (p. 1158)
ran_state . . . . .	B7 (p. 1144)
rank . . . . .	B8 (p. 1176)
ratint . . . . .	B3 (p. 1043)

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ratlsq	└─ [func] . . . . .	B5 (p. 1081)
	└─ svdcmp ── pythag	
	└─ svbksb	
	└─ ratval	
ratval	. . . . .	B5 (p. 1072)
rc	. . . . .	B6 (p. 1134)
rd	. . . . .	B6 (p. 1130)
realft	─ four1 ── fourrow . . . . .	B12 (p. 1243)
recur1	. . . . .	B5 (p. 1073)
recur2	. . . . .	B5 (p. 1074)
relax	. . . . .	B19 (p. 1338)
relax2	. . . . .	B19 (p. 1341)
resid	. . . . .	B19 (p. 1338)
rf	. . . . .	B6 (p. 1128)
rj	└─ rc . . . . .	B6 (p. 1131)
	└─ rf	
rk4	─ [derivs] . . . . .	B16 (p. 1297)
rkck	─ [derivs] . . . . .	B16 (p. 1299)
rkdumb	└─ [derivs] . . . . .	B16 (p. 1297)
	└─ rk4 ── [derivs]	
rkqs	─ rkck ── [derivs] . . . . .	B16 (p. 1298)
rlft2	─ four2 ── fourrow . . . . .	B12 (p. 1248)
rlft3	─ four3 ── fourrow_3d . . . . .	B12 (p. 1249)
rotate	. . . . .	B2 (p. 1041)
rsolv	. . . . .	B2 (p. 1040)
rstrct	. . . . .	B19 (p. 1337)
rtbis	─ [func] . . . . .	B9 (p. 1184)
rtflsp	─ [func] . . . . .	B9 (p. 1185)
rtnewt	─ [funcd] . . . . .	B9 (p. 1189)
rtsafe	─ [funcd] . . . . .	B9 (p. 1190)
rtsec	─ [func] . . . . .	B9 (p. 1186)
rzextr	. . . . .	B16 (p. 1306)
savgol	└─ ludcmp . . . . .	B14 (p. 1283)
	└─ lubksb	
scrsho	─ [func] . . . . .	B9 (p. 1182)
select	. . . . .	B8 (p. 1177)
select_bypack	. . . . .	B8 (p. 1178)
select_heap	─ sort . . . . .	B8 (p. 1179)
select_inplace	─ select . . . . .	B8 (p. 1178)

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sfroid	└─ plgndr . . . . .	B17 (p. 1319)
	└─ solvde ── difeq	
shoot	└─ [load] . . . . .	B17 (p. 1314)
	└─ odeint ── [derivs]	
	└─ [score]	
	└─ rkqs ── rkck ── [derivs]	
shootf	└─ [load1] . . . . .	B17 (p. 1315)
	└─ odeint ── [derivs]	
	└─ [score]	
	└─ [load2]	
simplx	. . . . .	B10 (p. 1216)
simpr	└─ ludcmp . . . . .	B16 (p. 1310)
	└─ lubksb	
	└─ [derivs]	
sifft	─ realft ── four1 ── fourrow . . . . .	B12 (p. 1245)
slvsm2	. . . . .	B19 (p. 1342)
slvsm1	. . . . .	B19 (p. 1337)
sncndn	. . . . .	B6 (p. 1137)
snrm	. . . . .	B2 (p. 1036)
sobseq	. . . . .	B7 (p. 1160)
solvde	─ difeq . . . . .	B17 (p. 1316)
sor	. . . . .	B19 (p. 1332)
sort	. . . . .	B8 (p. 1169)
sort2	─ indexx . . . . .	B8 (p. 1170)
sort3	─ indexx . . . . .	B8 (p. 1175)
sort_bypack	. . . . .	B8 (p. 1171)
sort_byreshape	. . . . .	B8 (p. 1168)
sort_heap	. . . . .	B8 (p. 1171)
sort_pick	. . . . .	B8 (p. 1167)
sort_radix	. . . . .	B8 (p. 1172)
sort_shell	. . . . .	B8 (p. 1168)
spctrm	─ four1 ── fourrow . . . . .	B13 (p. 1254)
spear	└─ sort2 . . . . .	B14 (p. 1277)
	└─ erfcc	
	└─ betai ── gammln	
	└─ betacf	
sphbes	─ bessjy ── beschb ── chebev . . . . .	B6 (p. 1121)

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sphfpt	newt	fdjac	shootf (q.v.)	. . .	B17 (p. 1322)
		lnsrch	shootf (q.v.)		
		fmin			
		ludcmp			
		lubksb			
sphoot	newt	fdjac	shoot (q.v.)	. . . .	B17 (p. 1321)
		lnsrch	shoot (q.v.)		
		fmin			
		ludcmp			
		lubksb			
splie2	spline	tridag	. . . . .		B3 (p. 1050)
splin2	splint	locate	. . . . .		B3 (p. 1051)
	spline	tridag			
spline	tridag	. . . . .			B3 (p. 1044)
splint	locate	. . . . .			B3 (p. 1045)
sprsax	. . . . .				B2 (p. 1032)
sprsdia	. . . . .				B2 (p. 1033)
sprsin	. . . . .				B2 (p. 1031)
sprstp	. . . . .				B2 (p. 1033)
sprstx	. . . . .				B2 (p. 1032)
stifbs	jacobn	. . . . .			B16 (p. 1311)
	simpr	ludcmp			
		lubksb			
	pzextr				
stiff	jacobn	. . . . .			B16 (p. 1308)
	ludcmp				
	lubksb				
stoerm	[derivs]	. . . . .			B16 (p. 1307)
svbksb	. . . . .				B2 (p. 1022)
svdcmp	pythag	. . . . .			B2 (p. 1023)
svdfit	[funcs]	. . . . .			B15 (p. 1290)
	svdcmp	pythag			
	svbksb				
svdvar	. . . . .				B15 (p. 1290)
toeplz	. . . . .				B2 (p. 1038)
tptest	avevar	. . . . .			B14 (p. 1271)
	betai	gammln			
		betacf			
tqli	pythag	. . . . .			B11 (p. 1228)
trapzd	[func]	. . . . .			B4 (p. 1052)
tred2	. . . . .				B11 (p. 1227)
tridag	. . . . .				B2 (p. 1018)

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ttest	└─ avevar . . . . .	B14 (p. 1269)
	└─ betai └─ gammln	
	└─ betacf	
tutest	└─ avevar . . . . .	B14 (p. 1270)
	└─ betai └─ gammln	
	└─ betacf	
twofft	── four1 ── fourrow . . . . .	B12 (p. 1242)
vander	. . . . .	B2 (p. 1037)
vegas	└─ ran1 ── ran_state . . . . .	B7 (p. 1161)
	└─ [func]	
voltra	└─ [g] . . . . .	B18 (p. 1326)
	└─ [ak]	
	└─ ludcmp	
	└─ lubksb	
wt1	── daub4 . . . . .	B13 (p. 1264)
wtn	── daub4 . . . . .	B13 (p. 1267)
wghts	── kermom . . . . .	B18 (p. 1328)
zbrac	── [func] . . . . .	B9 (p. 1183)
zbrak	── [func] . . . . .	B9 (p. 1184)
zbrent	── [func] . . . . .	B9 (p. 1188)
zrhqr	└─ balanc . . . . .	B9 (p. 1193)
	└─ hqr	
	└─ indexx	
zriddr	── [func] . . . . .	B9 (p. 1187)
zroots	└─ laguer . . . . .	B9 (p. 1192)
	└─ indexx	

# General Index to Volumes 1 and 2

In this index, page numbers 1 through 934 refer to Volume 1, *Numerical Recipes in Fortran 77*, while page numbers 935 through 1446 refer to Volume 2, *Numerical Recipes in Fortran 90*. Front matter in Volume 1 is indicated by page numbers in the range 1/i through 1/xxxi, while front matter in Volume 2 is indicated 2/i through 2/xx.

- A**bstract data types 2/xiii, 1030
- Accelerated convergence of series 160ff., 1070
- Accuracy 19f.
  - achievable in minimization 392, 397, 404
  - achievable in root finding 346f.
  - contrasted with fidelity 832, 840
  - CPU different from memory 181
  - vs. stability 704, 729, 830, 844
- Accuracy parameters 1362f.
- Acknowledgments 1/xvi, 2/ix
- Ada 2/x
- Adams-Bashford-Moulton method 741
- Adams' stopping criterion 366
- Adaptive integration 123, 135, 703, 708ff., 720, 726, 731f., 737, 742ff., 788, 1298ff., 1303, 1308f.
  - Monte Carlo 306ff., 1161ff.
- Addition, multiple precision 907, 1353
- Addition theorem, elliptic integrals 255
- ADI (alternating direction implicit) method 847, 861f., 906
- Adjoint operator 867
- Adobe Illustrator 1/xvi, 2/xx
- Advective equation 826
- AGM (arithmetic geometric mean) 906
- Airy function 204, 234, 243f.
  - routine for 244f., 1121
- Aitken's delta squared process 160
- Aitken's interpolation algorithm 102
- Algol 2/x, 2/xiv
- Algorithms, non-numerical 881ff., 1343ff.
- Aliasing 495, 569
  - see also* Fourier transform
- all() intrinsic function 945, 948
- All-poles model 566
  - see also* Maximum entropy method (MEM)
- All-zeros model 566
  - see also* Periodogram
- Allocatable array 938, 941, 952ff., 1197, 1212, 1266, 1293, 1306, 1336
- allocate statement 938f., 941, 953f., 1197, 1266, 1293, 1306, 1336
- allocated() intrinsic function 938, 952ff., 1197, 1266, 1293
- Allocation status 938, 952ff., 961, 1197, 1266, 1293
- Alpha AXP 2/xix
- Alternating-direction implicit method (ADI) 847, 861f., 906
- Alternating series 160f., 1070
- Alternative extended Simpson's rule 128
- American National Standards Institute (ANSI) 2/x, 2/xiii
- Amoeba 403
  - see also* Simplex, method of Nelder and Mead
- Amplification factor 828, 830, 832, 840, 845f.
- Amplitude error 831
- Analog-to-digital converter 812, 886
- Analyticity 195
- Analyze/factorize/operate package 64, 824
- Anderson-Darling statistic 621
- Andrew's sine 697
- Annealing, method of simulated 387f., 436ff., 1219f.
  - assessment 447
  - for continuous variables 437, 443ff., 1222
  - schedule 438
  - thermodynamic analogy 437
  - traveling salesman problem 438ff., 1219ff.
- ANSI (American National Standards Institute) 2/x, 2/xiii
- Antonov-Saleev variant of Sobol' sequence 300, 1160
- any() intrinsic function 945, 948
- APL (computer language) 2/xi
- Apple 1/xxiii
  - Macintosh 2/xix, 4, 886
- Approximate inverse of matrix 49
- Approximation of functions 99, 1043
  - by Chebyshev polynomials 185f., 513, 1076ff.
  - Padé approximant 194ff., 1080f.
  - by rational functions 197ff., 1081f.
  - by wavelets 594f., 782
  - see also* Fitting
- Argument
  - keyword 2/xiv, 947f., 1341
  - optional 2/xiv, 947f., 1092, 1228, 1230, 1256, 1272, 1275, 1340
- Argument checking 994f., 1086, 1090, 1092, 1370f.

- Arithmetic  
 arbitrary precision 881, 906ff., 1352ff.  
 floating point 881, 1343  
 IEEE standard 276, 882, 1343  
 rounding 882, 1343  
 Arithmetic coding 881, 902ff., 1349ff.  
 Arithmetic-geometric mean (AGM) method 906  
 Arithmetic-if statement 2/xi  
 Arithmetic progression 971f., 996, 1072, 1127, 1365, 1371f.  
 Array 953ff.  
 allocatable 938, 941, 952ff., 1197, 1212, 1266, 1293, 1306, 1336  
 allocated with pointer 941  
 allocation 953  
 array manipulation functions 950  
 array sections 939, 941, 943ff.  
 of arrays 2/xii, 956, 1336  
 associated pointer 953f.  
 assumed-shape 942  
 automatic 938, 954, 1197, 1212, 1336  
 centered subarray of 113  
 conformable to a scalar 942f., 965, 1094  
 constructor 2/xii, 968, 971, 1022, 1052, 1055, 1127  
 copying 991, 1034, 1327f., 1365f.  
 cumulative product 997f., 1072, 1086, 1375  
 cumulative sum 997, 1280f., 1365, 1375  
 deallocation 938, 953f., 1197, 1266, 1293  
 disassociated pointer 953  
 extents 938, 949  
 in Fortran 90 941  
 increasing storage for 955, 1070, 1302  
 index loss 967f.  
 index table 1173ff.  
 indices 942  
 inquiry functions 948ff.  
 intrinsic procedures 2/xiii, 948ff.  
 of length 0 944  
 of length 1 949  
 location of first "true" 993, 1041, 1369  
 location of maximum value 993, 1015, 1017, 1365, 1369  
 location of minimum value 993, 1369f.  
 manipulation functions 950, 1247  
 masked swapping of elements in two arrays 1368  
 operations on 942, 949, 964ff., 969, 1026, 1040, 1050, 1200, 1326  
 outer product 949, 1076  
 parallel features 941ff., 964ff., 985  
 passing variable number of arguments to function 1022  
 of pointers forbidden 956, 1337  
 rank 938, 949  
 reallocation 955, 992, 1070f., 1365, 1368f.  
 reduction functions 948ff.  
 shape 938, 944, 949  
 size 938  
 skew sections 945, 985  
 stride 944  
 subscript bounds 942  
 subscript triplet 944  
 swapping elements of two arrays 991, 1015, 1365ff.  
 target 938  
 three-dimensional, in Fortran 90 1248  
 transformational functions 948ff.  
 unary and binary functions 949  
 undefined status 952ff., 961, 1266, 1293  
 zero-length 944  
 Array section 2/xiii, 943ff., 960  
 matches by shape 944  
 pointer alias 939, 944f., 1286, 1333  
 skew 2/xii, 945, 960, 985, 1284  
 vs. eoshift 1078  
 array\_copy() utility function 988, 991, 1034, 1153, 1278, 1328  
 arth() utility function 972, 974, 988, 996, 1072, 1086, 1127  
 replaces do-list 968  
 Artificial viscosity 831, 837  
 Ascending transformation, elliptic integrals 256  
 ASCII character set 6, 888, 896, 902  
 Assembly language 269  
 assert() utility function 988, 994, 1086, 1090, 1249  
 assert\_eq() utility function 988, 995, 1022  
 associated() intrinsic function 952f.  
 Associated Legendre polynomials 246ff., 764, 1122f., 1319  
 recurrence relation for 247  
 relation to Legendre polynomials 246  
 Association, measures of 604, 622ff., 1275  
 Assumed-shape array 942  
 Asymptotic series 161  
 exponential integral 218  
 Attenuation factors 583, 1261  
 Autocorrelation 492  
 in linear prediction 558  
 use of FFT 538f., 1254  
 Wiener-Khinchin theorem 492, 566f.  
 AUTODIN-II polynomial 890  
 Automatic array 938, 954, 1197, 1212, 1336  
 specifying size of 938, 954  
 Automatic deallocation 2/xv, 961  
 Autonomous differential equations 729f.  
 Autoregressive model (AR) *see* Maximum entropy method (MEM)  
 Average deviation of distribution 605, 1269  
 Averaging kernel, in Backus-Gilbert method 807
- B**acksubstitution 33ff., 39, 42, 92, 1017  
 in band diagonal matrix 46, 1021  
 in Cholesky decomposition 90, 1039  
 complex equations 41  
 direct for computing  $\mathbf{A}^{-1} \cdot \mathbf{B}$  40  
 with QR decomposition 93, 1040  
 relaxation solution of boundary value problems 755, 1316  
 in singular value decomposition 56, 1022f.  
 Backtracking 419  
 in quasi-Newton methods 376f., 1195  
 Backus-Gilbert method 806ff.  
 Backus, John 2/x  
 Backward deflation 363

- Bader-Deuffhard method 730, 735, 1310f.  
 Bairstow's method 364, 370, 1193  
 Balancing 476f., 1230f.  
 Band diagonal matrix 42ff., 1019  
   backsubstitution 46, 1021  
   LU decomposition 45, 1020  
   multiply by vector 44, 1019  
   storage 44, 1019  
 Band-pass filter 551, 554f.  
   wavelets 584, 592f.  
 Bandwidth limited function 495  
 Bank accounts, checksum for 894  
 Bar codes, checksum for 894  
 Bartlett window 547, 1254ff.  
 Base case, of recursive procedure 958  
 Base of representation 19, 882, 1343  
 BASIC, Numerical Recipes in 1, 2/x, 2/xviii  
 Basis functions in general linear least squares 665  
 Bayes' Theorem 810  
 Bayesian  
   approach to inverse problems 799, 810f., 816f.  
   contrasted with frequentist 810  
   vs. historic maximum entropy method 816f.  
   views on straight line fitting 664  
 Bays' shuffle 270  
 Bernoulli number 132  
 Bessel functions 223ff., 234ff., 936, 1101ff.  
   asymptotic form 223f., 229f.  
   complex 204  
   continued fraction 234, 239  
   double precision 223  
   fractional order 223, 234ff., 1115ff.  
   Miller's algorithm 175, 228, 1106  
   modified 229ff.  
   modified, fractional order 239ff.  
   modified, normalization formula 232, 240  
   modified, routines for 230ff., 1109ff.  
   normalization formula 175  
   parallel computation of 1107ff.  
   recurrence relation 172, 224, 232, 234  
   reflection formulas 236  
   reflection formulas, modified functions 241  
   routines for 225ff., 236ff., 1101ff.  
   routines for modified functions 241ff., 1118  
   series for  $J_\nu$  160, 223  
   series for  $K_\nu$  241  
   series for  $Y_\nu$  235  
   spherical 234, 245, 1121f.  
   turning point 234  
   Wronskian 234, 239  
 Best-fit parameters 650, 656, 660, 698, 1285ff.  
   *see also* Fitting  
 Beta function 206ff., 1089  
   incomplete *see* Incomplete beta function  
 BFGS algorithm *see* Broyden-Fletcher-Goldfarb-Shanno algorithm  
 Bias, of exponent 19  
 Bias, removal in linear prediction 563  
 Biconjugacy 77  
 Biconjugate gradient method  
   elliptic partial differential equations 824  
   preconditioning 78f., 824, 1037  
   for sparse system 77, 599, 1034ff.  
 Bicubic interpolation 118f., 1049f.  
 Bicubic spline 120f., 1050f.  
 Big-endian 293  
 Bilinear interpolation 117  
 Binary constant, initialization 959  
 Binomial coefficients 206ff., 1087f.  
   recurrences for 209  
 Binomial probability function 208  
   cumulative 222f.  
   deviates from 281, 285f., 1155  
 Binormal distribution 631, 690  
 Biorthogonality 77  
 Bisection 111, 359, 1045f.  
   compared to minimum bracketing 390ff.  
   minimum finding with derivatives 399  
   root finding 343, 346f., 352f., 390, 469, 1184f.  
 BISYNCH 890  
 Bit 18  
   manipulation functions *see* Bitwise logical functions  
   reversal in fast Fourier transform (FFT) 499f., 525  
 bit\_size() intrinsic function 951  
 Bitwise logical functions 2/xiii, 17, 287, 890f., 951  
 Block-by-block method 788  
 Block of statements 7  
 Bode's rule 126  
 Boltzmann probability distribution 437  
 Boltzmann's constant 437  
 Bootstrap method 686f.  
 Bordering method for Toeplitz matrix 85f.  
 Borwein and Borwein method for  $\pi$  906, 1357  
 Boundary 155f., 425f., 745  
 Boundary conditions  
   for differential equations 701f.  
   initial value problems 702  
   in multigrid method 868f.  
   partial differential equations 508, 819ff., 848ff.  
   for spheroidal harmonics 764  
   two-point boundary value problems 702, 745ff., 1314ff.  
 Boundary value problems *see* Differential equations; Elliptic partial differential equations; Two-point boundary value problems  
 Box-Muller algorithm for normal deviate 279f., 1152  
 Bracketing  
   of function minimum 343, 390ff., 402, 1201f.  
   of roots 341, 343ff., 353f., 362, 364, 369, 390, 1183f.  
 Branch cut, for hypergeometric function 203  
 Branching 9  
 Break iteration 14  
 Brenner, N.M. 500, 517

- Brent's method  
  minimization 389, 395ff., 660f., 1204ff., 1286  
  minimization, using derivative 389, 399, 1205  
  root finding 341, 349, 660f., 1188f., 1286  
Broadcast (parallel capability) 965ff.  
Broyden-Fletcher-Goldfarb-Shanno algorithm 390, 418ff., 1215  
Broyden's method 373, 382f., 386, 1199f.  
  singular Jacobian 386  
btest() intrinsic function 951  
Bubble sort 321, 1168  
Bugs 4  
  in compilers 1/xvii  
  how to report 1/iv, 2/iv  
Bulirsch-Stoer  
  algorithm for rational function interpolation 105f., 1043  
  method (differential equations) 202, 263, 702f., 706, 716, 718ff., 726, 740, 1138, 1303ff.  
  method (differential equations), stepsize control 719, 726  
  for second order equations 726, 1307  
Burg's LP algorithm 561, 1256  
Byte 18
- C** (programming language) 13, 2/viii  
  and case construct 1010  
  Numerical Recipes in 1, 2/x, 2/xviii  
C++ 1/xiv, 2/viii, 2/xvi, 7f.  
  class templates 1083, 1106  
Calendar algorithms 1f., 13ff., 1010ff.  
Calibration 653  
Capital letters in programs 3, 937  
Cards, sorting a hand of 321  
Carlson's elliptic integrals 255f., 1128ff.  
case construct 2/xiv, 1010  
  trapping errors 1036  
Cash-Karp parameters 710, 1299f.  
Cauchy probability distribution *see* Lorentzian probability distribution  
Cauchy problem for partial differential equations 818f.  
Cayley's representation of  $\exp(-iHt)$  844  
CCITT (Comité Consultatif International Télégraphique et Téléphonique) 889f., 901  
CCITT polynomial 889f.  
ceiling() intrinsic function 947  
Center of mass 295ff.  
Central limit theorem 652f.  
Central tendency, measures of 604ff., 1269  
Change of variable  
  in integration 137ff., 788, 1056ff.  
  in Monte Carlo integration 298  
  in probability distribution 279  
Character functions 952  
Character variables, in Fortran 90 1183  
Characteristic polynomial  
  digital filter 554  
  eigensystems 449, 469  
  linear prediction 559  
  matrix with a specified 368, 1193  
  of recurrence relation 175  
  Characteristics of partial differential equations 818  
Chebyshev acceleration in successive over-relaxation (SOR) 859f., 1332  
Chebyshev approximation 84, 124, 183, 184ff., 1076ff.  
  Clenshaw-Curtis quadrature 190  
  Clenshaw's recurrence formula 187, 1076  
  coefficients for 185f., 1076  
  contrasted with Padé approximation 195  
  derivative of approximated function 183, 189, 1077f.  
  economization of series 192f., 195, 1080  
  for error function 214, 1095  
  even function 188  
  and fast cosine transform 513  
  gamma functions 236, 1118  
  integral of approximated function 189, 1078  
  odd function 188  
  polynomial fits derived from 191, 1078  
  rational function 197ff., 1081f.  
  Remes exchange algorithm for filter 553  
Chebyshev polynomials 184ff., 1076ff.  
  continuous orthonormality 184  
  discrete orthonormality 185  
  explicit formulas for 184  
  formula for  $x^k$  in terms of 193, 1080  
Check digit 894, 1345f.  
Checksum 881, 888  
  cyclic redundancy (CRC) 888ff., 1344f.  
Cherry, sundae without a 809  
Chi-by-eye 651  
Chi-square fitting *see* Fitting; Least squares fitting  
Chi-square probability function 209ff., 215, 615, 654, 798, 1272  
  as boundary of confidence region 688f.  
  related to incomplete gamma function 215  
Chi-square test 614f.  
  for binned data 614f., 1272  
  chi-by-eye 651  
  and confidence limit estimation 688f.  
  for contingency table 623ff., 1275  
  degrees of freedom 615f.  
  for inverse problems 797  
  least squares fitting 653ff., 1285  
  nonlinear models 675ff., 1292  
  rule of thumb 655  
  for straight line fitting 655ff., 1285  
  for straight line fitting, errors in both coordinates 660, 1286ff.  
  for two binned data sets 616, 1272  
  unequal size samples 617  
Chip rate 290  
Chirp signal 556  
Cholesky decomposition 89f., 423, 455, 1038  
  backsubstitution 90, 1039  
  operation count 90  
  pivoting 90  
  solution of normal equations 668  
Circulant 585  
Class, data type 7  
Clenshaw-Curtis quadrature 124, 190, 512f.



- Clenshaw's recurrence formula 176f., 191, 1078  
 for Chebyshev polynomials 187, 1076  
 stability 176f.
- Clocking errors 891
- CM computers (Thinking Machines Inc.) 964
- CM Fortran 2/xv
- cn function 261, 1137f.
- Coarse-grid correction 864f.
- Coarse-to-fine operator 864, 1337
- Coding  
 arithmetic 902ff., 1349ff.  
 checksums 888, 1344  
 decoding a Huffman-encoded message 900, 1349  
 Huffman 896f., 1346ff.  
 run-length 901  
 variable length code 896, 1346ff.  
 Ziv-Lempel 896  
*see also* Arithmetic coding; Huffman coding
- Coefficients  
 binomial 208, 1087f.  
 for Gaussian quadrature 140ff., 1059ff.  
 for Gaussian quadrature, nonclassical weight function 151ff., 788f., 1064  
 for quadrature formulas 125ff., 789, 1328
- Cohen, Malcolm 2/xiv
- Column degeneracy 22
- Column operations on matrix 29, 31f.
- Column totals 624
- Combinatorial minimization *see* Annealing
- Comité Consultatif International Télégraphique et Téléphonique (CCITT) 889f., 901
- Common block  
 obsolescent 2/xif.  
 superseded by internal subprogram 957, 1067  
 superseded by module 940, 953, 1298, 1320, 1322, 1324, 1330
- Communication costs, in parallel processing 969, 981, 1250
- Communication theory, use in adaptive integration 721
- Communications protocol 888
- Comparison function for rejection method 281
- Compilers 964, 1364  
 CM Fortran 968  
 DEC (Digital Equipment Corp.) 2/viii  
 IBM (International Business Machines) 2/viii  
 Microsoft Fortran PowerStation 2/viii  
 NAG (Numerical Algorithms Group) 2/viii, 2/xiv  
 for parallel supercomputers 2/viii
- Complementary error function 1094f.  
*see* Error function
- Complete elliptic integral *see* Elliptic integrals
- Complex arithmetic 171f.  
 avoidance of in path integration 203  
 cubic equations 179f.  
 for linear equations 41  
 quadratic equations 178
- Complex error function 252
- Complex plane  
 fractal structure for Newton's rule 360f.  
 path integration for function evaluation 201ff., 263, 1138  
 poles in 105, 160, 202f., 206, 554, 566, 718f.
- Complex systems of linear equations 41f.
- Compression of data 596f.
- Concordant pair for Kendall's tau 637, 1281
- Condition number 53, 78
- Confidence level 687, 691ff.
- Confidence limits  
 bootstrap method 687f.  
 and chi-square 688f.  
 confidence region, confidence interval 687  
 on estimated model parameters 684ff.  
 by Monte Carlo simulation 684ff.  
 from singular value decomposition (SVD) 693f.
- Confluent hypergeometric function 204, 239
- Conformable arrays 942f., 1094
- Conjugate directions 408f., 414ff., 1210
- Conjugate gradient method  
 biconjugate 77, 1034  
 compared to variable metric method 418  
 elliptic partial differential equations 824  
 for minimization 390, 413ff., 804, 815, 1210, 1214  
 minimum residual method 78  
 preconditioner 78f., 1037  
 for sparse system 77ff., 599, 1034  
 and wavelets 599
- Conservative differential equations 726, 1307
- Constrained linear inversion method 799ff.
- Constrained linear optimization *see* Linear programming
- Constrained optimization 387
- Constraints, deterministic 804ff.
- Constraints, linear 423
- CONTAINS statement 954, 957, 1067, 1134, 1202
- Contingency coefficient C 625, 1275
- Contingency table 622ff., 638, 1275f.  
 statistics based on chi-square 623ff., 1275  
 statistics based on entropy 626ff., 1275f.
- Continued fraction 163ff.  
 Bessel functions 234  
 convergence criterion 165  
 equivalence transformation 166  
 evaluation 163ff.  
 evaluation along with normalization condition 240  
 even and odd parts 166, 211, 216  
 even part 249, 251  
 exponential integral 216  
 Fresnel integral 248f.  
 incomplete beta function 219f., 1099f.  
 incomplete gamma function 211, 1092f.  
 Lentz's method 165, 212  
 modified Lentz's method 165  
 Pincherle's theorem 175  
 ratio of Bessel functions 239  
 rational function approximation 164, 211, 219f.  
 recurrence for evaluating 164f.

- and recurrence relation 175
- sine and cosine integrals 250f.
- Steed's method 164f.
- tangent function 164
- typography for 163
- Continuous variable (statistics) 623
- Control structures 7ff., 2/xiv
  - bad 15
  - named 959, 1219, 1305
- Convergence
  - accelerated, for series 160ff., 1070
  - of algorithm for pi 906
  - criteria for 347, 392, 404, 483, 488, 679, 759
  - eigenvalues accelerated by shifting 470f.
  - golden ratio 349, 399
  - of golden section search 392f.
  - of Levenberg-Marquardt method 679
  - linear 346, 393
  - of QL method 470f.
  - quadratic 49, 351, 356, 409f., 419, 906
  - rate 346f., 353, 356
  - recurrence relation 175
  - of Ridders' method 351
  - series vs. continued fraction 163f.
  - and spectral radius 856ff., 862
- Conversion intrinsic functions 946f.
- Convex sets, use in inverse problems 804
- Convolution
  - denoted by asterisk 492
  - finite impulse response (FIR) 531
  - of functions 492, 503f.
  - of large data sets 536f.
  - for multiple precision arithmetic 909, 1354
  - multiplication as 909, 1354
  - necessity for optimal filtering 535
  - overlap-add method 537
  - overlap-save method 536f.
  - and polynomial interpolation 113
  - relation to wavelet transform 585
  - theorem 492, 531ff., 546
  - theorem, discrete 531ff.
  - treatment of end effects 533
  - use of FFT 523, 531ff., 1253
  - wraparound problem 533
- Cooley-Tukey FFT algorithm 503, 1250
  - parallel version 1239f.
- Co-processor, floating point 886
- Copyright rules 1/xx, 2/xix
- Cornwell-Evans algorithm 816
- Corporate promotion ladder 328
- Corrected two-pass algorithm 607, 1269
- Correction, in multigrid method 863
- Correlation coefficient (linear) 630ff., 1276
- Correlation function 492
  - autocorrelation 492, 539, 558
  - and Fourier transforms 492
  - theorem 492, 538
  - treatment of end effects 538f.
  - using FFT 538f., 1254
  - Wiener-Khinchin theorem 492, 566f.
- Correlation, statistical 603f., 622
  - Kendall's tau 634, 637ff., 1279
  - linear correlation coefficient 630ff., 658, 1276
  - linear related to least square fitting 630, 658
  - nonparametric or rank statistical 633ff., 1277
  - among parameters in a fit 657, 667, 670
  - in random number generators 268
  - Spearman rank-order coefficient 634f., 1277
  - sum squared difference of ranks 634, 1277
- Cosine function, recurrence 172
- Cosine integral 248, 250ff., 1125f.
  - continued fraction 250
  - routine for 251f., 1125
  - series 250
- Cosine transform *see* Fast Fourier transform (FFT); Fourier transform
- Coulomb wave function 204, 234
- count() intrinsic function 948
- Courant condition 829, 832ff., 836
  - multidimensional 846
- Courant-Friedrichs-Lewy stability criterion *see* Courant condition
- Covariance
  - a priori 700
  - in general linear least squares 667, 671, 1288ff.
  - matrix, by Cholesky decomposition 91, 667
  - matrix, of errors 796, 808
  - matrix, is inverse of Hessian matrix 679
  - matrix, when it is meaningful 690ff.
  - in nonlinear models 679, 681, 1292
  - relation to chi-square 690ff.
  - from singular value decomposition (SVD) 693f.
  - in straight line fitting 657
- cpu\_time() intrinsic function (Fortran 95) 961
- CR method *see* Cyclic reduction (CR)
- Cramer's V 625, 1275
- Crank-Nicholson method 840, 844, 846
- Cray computers 964
- CRC (cyclic redundancy check) 888ff., 1344f.
- CRC-12 890
- CRC-16 polynomial 890
- CRC-CCITT 890
- Creativity, essay on 9
- Critical (Nyquist) sampling 494, 543
- Cross (denotes matrix outer product) 66
- Crosstabulation analysis 623
  - see also* Contingency table
- Crout's algorithm 36ff., 45, 1017
- cshift() intrinsic function 950
  - communication bottleneck 969
- Cubic equations 178ff., 360
- Cubic spline interpolation 107ff., 1044f.
  - see also* Spline
- cumprod() utility function 974, 988, 997, 1072, 1086
- cumsum() utility function 974, 989, 997, 1280, 1305
- Cumulant, of a polynomial 977, 999, 1071f., 1192

- Cumulative binomial distribution 222f.  
 Cumulative Poisson function 214  
   related to incomplete gamma function 214  
 Curvature matrix *see* Hessian matrix  
 cycle statement 959, 1219  
 Cycle, in multigrid method 865  
 Cyclic Jacobi method 459, 1225  
 Cyclic reduction (CR) 848f., 852ff.  
   linear recurrences 974  
   tridiagonal systems 976, 1018  
 Cyclic redundancy check (CRC) 888ff., 1344f.  
 Cyclic tridiagonal systems 67, 1030
- D.C.** (direct current) 492  
 Danielson-Lanczos lemma 498f., 525, 1235ff.  
 DAP Fortran 2/xi  
 Data  
   assigning keys to 889  
   continuous vs. binned 614  
   entropy 626ff., 896, 1275  
   essay on 603  
   fitting 650ff., 1285ff.  
   fraudulent 655  
   glitches in 653  
   iid (independent and identically distributed) 686  
   modeling 650ff., 1285ff.  
   serial port 892  
   smoothing 604, 644ff., 1283f.  
   statistical tests 603ff., 1269ff.  
   unevenly or irregularly sampled 569, 574, 648f., 1258ff.  
   use of CRCs in manipulating 889  
   windowing 545ff., 1254  
   *see also* Statistical tests  
 Data compression 596f., 881  
   arithmetic coding 902ff., 1349ff.  
   cosine transform 513  
   Huffman coding 896f., 902, 1346ff.  
   linear predictive coding (LPC) 563ff.  
   lossless 896  
 Data Encryption Standard (DES) 290ff., 1144, 1147f., 1156ff.  
 Data hiding 956ff., 1209, 1293, 1296  
 Data parallelism 941, 964ff., 985  
 DATA statement 959  
   for binary, octal, hexadecimal constants 959  
   repeat count feature 959  
   superseded by initialization expression 943, 959, 1127  
 Data type 18, 936  
   accuracy parameters 1362f.  
   character 1183  
   derived 2/xiii, 937, 1030, 1336, 1346  
   derived, for array of arrays 956, 1336  
   derived, initialization 2/xv  
   derived, for Numerical Recipes 1361  
   derived, storage allocation 955  
   DP (double precision) 1361f.  
   DPC (double precision complex) 1361  
   I1B (1 byte integer) 1361  
   I2B (2 byte integer) 1361  
   I4B (4 byte integer) 1361  
   intrinsic 937  
   LGT (default logical type) 1361  
   nrtype.f90 1361f.  
   passing complex as real 1140  
   SP (single precision) 1361f.  
   SPC (single precision complex) 1361  
   user-defined 1346  
 DAUB4 584ff., 588, 590f., 594, 1264f.  
 DAUB6 586  
 DAUB12 598  
 DAUB20 590f., 1265  
 Daubechies wavelet coefficients 584ff., 588, 590f., 594, 598, 1264ff.  
 Davidson-Fletcher-Powell algorithm 390, 418ff., 1215  
 Dawson's integral 252ff., 600, 1127f.  
   approximation for 252f.  
   routine for 253f., 1127  
 dble() intrinsic function (deprecated) 947  
 deallocate statement 938f., 953f., 1197, 1266, 1293  
 Deallocation, of allocatable array 938, 953f., 1197, 1266, 1293  
 Debugging 8  
 DEC (Digital Equipment Corp.) 1/xxiii, 2/xix, 886  
   Alpha AXP 2/viii  
   Fortran 90 compiler 2/viii  
   quadruple precision option 1362  
   VAX 4  
 Decomposition *see* Cholesky decomposition; LU decomposition; QR decomposition; Singular value decomposition (SVD)  
 Deconvolution 535, 540, 1253  
   *see also* Convolution; Fast Fourier transform (FFT); Fourier transform  
 Defect, in multigrid method 863  
 Deferred approach to the limit *see* Richardson's deferred approach to the limit  
 Deflation  
   of matrix 471  
   of polynomials 362ff., 370f., 977  
 Degeneracy of linear algebraic equations 22, 53, 57, 670  
 Degenerate kernel 785  
 Degenerate minimization principle 795  
 Degrees of freedom 615f., 654, 691  
 Dekker, T.J. 353  
 Demonstration programs 3, 936  
 Deprecated features  
   common block 2/xif., 940, 953, 957, 1067, 1298, 1320, 1322, 1324, 1330  
   dble() intrinsic function 947  
   EQUIVALENCE statement 2/xif., 1161, 1286  
   statement function 1057, 1256  
 Derivatives  
   computation via Chebyshev approximation 183, 189, 1077f.  
   computation via Savitzky-Golay filters 183, 645  
   matrix of first partial *see* Jacobian determinant  
   matrix of second partial *see* Hessian matrix

- numerical computation 180ff., 379, 645, 732, 750, 771, 1075, 1197, 1309  
of polynomial 167, 978, 1071f.  
use in optimization 388f., 399, 1205ff.
- Derived data type *see* Data type, derived
- DES *see* Data Encryption Standard
- Descending transformation, elliptic integrals 256
- Descent direction 376, 382, 419
- Descriptive statistics 603ff., 1269ff.  
*see also* Statistical tests
- Design matrix 645, 665, 795, 801, 1082
- Determinant 25, 41
- Deviate, random *see* Random deviate
- DFP algorithm *see* Davidon-Fletcher-Powell algorithm
- diagadd() utility function 985, 989, 1004
- diagmult() utility function 985, 989, 1004, 1294
- Diagonal dominance 43, 679, 780, 856
- Difference equations, finite *see* Finite difference equations (FDEs)
- Difference operator 161
- Differential equations 701ff., 1297ff.  
accuracy vs. stability 704, 729  
Adams-Bashforth-Moulton schemes 741  
adaptive stepsize control 703, 708ff., 719, 726, 731, 737, 742f., 1298ff., 1303ff., 1308f., 1311ff.  
algebraically difficult sets 763  
backward Euler's method 729  
Bader-Deuffhard method for stiff 730, 735, 1310f.  
boundary conditions 701f., 745ff., 749, 751f., 771, 1314ff.  
Bulirsch-Stoer method 202, 263, 702, 706, 716, 718ff., 740, 1138, 1303  
Bulirsch-Stoer method for conservative equations 726, 1307  
comparison of methods 702f., 739f., 743  
conservative 726, 1307  
danger of too small stepsize 714  
eigenvalue problem 748, 764ff., 770ff., 1319ff.  
embedded Runge-Kutta method 709f., 731, 1298, 1308  
equivalence of multistep and multivalued methods 743  
Euler's method 702, 704, 728f.  
forward Euler's method 728  
free boundary problem 748, 776  
high-order implicit methods 730ff., 1308ff.  
implicit differencing 729, 740, 1308  
initial value problems 702  
internal boundary conditions 775ff.  
internal singular points 775ff.  
interpolation on right-hand sides 111  
Kaps-Rentrop method for stiff 730, 1308  
local extrapolation 709  
modified midpoint method 716f., 719, 1302f.  
multistep methods 740ff.  
multivalued methods 740  
order of method 704f., 719  
path integration for function evaluation 201ff., 263, 1138  
predictor-corrector methods 702, 730, 740ff.  
reduction to first-order sets 701, 745  
relaxation method 746f., 753ff., 1316ff.  
relaxation method, example of 764ff., 1319ff.  
r.h.s. independent of  $x$  729f.  
Rosenbrock methods for stiff 730, 1308f.  
Runge-Kutta method 702, 704ff., 708ff., 731, 740, 1297f., 1308  
Runge-Kutta method, high-order 705, 1297  
Runge-Kutta-Fehlberg method 709ff., 1298  
scaling stepsize to required accuracy 709  
second order 726, 1307  
semi-implicit differencing 730  
semi-implicit Euler method 730, 735f.  
semi-implicit extrapolation method 730, 735f., 1311ff.  
semi-implicit midpoint rule 735f., 1310f.  
shooting method 746, 749ff., 1314ff.  
shooting method, example 770ff., 1321ff.  
similarity to Volterra integral equations 786  
singular points 718f., 751, 775ff., 1315f., 1323ff.  
step doubling 708f.  
stepsize control 703, 708ff., 719, 726, 731, 737, 742f., 1298, 1303ff., 1308f.  
stiff 703, 727ff., 1308ff.  
stiff methods compared 739  
Stoermer's rule 726, 1307  
*see also* Partial differential equations; Two-point boundary value problems
- Diffusion equation 818, 838ff., 855  
Crank-Nicholson method 840, 844, 846  
Forward Time Centered Space (FTCS) 839ff., 855  
implicit differencing 840  
multidimensional 846
- Digamma function 216
- Digital filtering *see* Filter
- Dihedral group  $D_5$  894
- dim optional argument 948
- Dimensional expansion 965ff.
- Dimensions (units) 678
- Diminishing increment sort 322, 1168
- Dirac delta function 284, 780
- Direct method *see* Periodogram
- Direct methods for linear algebraic equations 26, 1014
- Direct product *see* Outer product of matrices
- Direction of largest decrease 410f.
- Direction numbers, Sobol's sequence 300
- Direction-set methods for minimization 389, 406f., 1210ff.
- Dirichlet boundary conditions 820, 840, 850, 856, 858
- Disclaimer of warranty 1/xx, 2/xvii
- Discordant pair for Kendall's tau 637, 1281
- Discrete convolution theorem 531ff.

- Discrete Fourier transform (DFT) 495ff., 1235ff.  
 as approximate continuous transform 497  
*see also* Fast Fourier transform (FFT)
- Discrete optimization 436ff., 1219ff.
- Discriminant 178, 457
- Diskettes  
 are ANSI standard 3  
 how to order 1/xxi, 2/xvii
- Dispersion 831
- DISPO *see* Savitzky-Golay filters
- Dissipation, numerical 830
- Divergent series 161
- Divide and conquer algorithm 1226, 1229
- Division  
 complex 171  
 multiple precision 910f., 1356  
 of polynomials 169, 362, 370, 1072
- dn function 261, 1137f.
- Do-list, implied 968, 971, 1127
- Do-loop 2/xiv
- Do-until iteration 14
- Do-while iteration 13
- Dogleg step methods 386
- Domain of integration 155f.
- Dominant solution of recurrence relation 174
- Dot (denotes matrix multiplication) 23
- dot-product() intrinsic function 945, 949, 969, 1216
- Double exponential error distribution 696
- Double precision  
 converting to 1362  
 as refuge of scoundrels 882  
 use in iterative improvement 47, 1022
- Double root 341
- Downhill simplex method *see* Simplex, method of Nelder and Mead
- DP, defined 937
- Driver programs 3
- Dual viewpoint, in multigrid method 875
- Duplication theorem, elliptic integrals 256
- DWT (discrete wavelet transform) *see* Wavelet transform
- Dynamical allocation of storage 2/xiii, 869, 938, 941f., 953ff., 1327, 1336  
 garbage collection 956  
 increasing 955, 1070, 1302
- E**ardley, D.M. 338
- EBCDIC 890
- Economization of power series 192f., 195, 1080
- Eigensystems 449ff., 1225ff.  
 balancing matrix 476f., 1230f.  
 bounds on eigenvalues 50  
 calculation of few eigenvalues 454, 488  
 canned routines 454f.  
 characteristic polynomial 449, 469  
 completeness 450  
 defective 450, 476, 489  
 deflation 471  
 degenerate eigenvalues 449ff.  
 elimination method 453, 478, 1231  
 factorization method 453  
 fast Givens reduction 463  
 generalized eigenproblem 455  
 Givens reduction 462f.  
 Hermitian matrix 475  
 Hessenberg matrix 453, 470, 476ff., 488, 1232  
 Householder transformation 453, 462ff., 469, 473, 475, 478, 1227f., 1231  
 ill-conditioned eigenvalues 477  
 implicit shifts 472ff., 1228f.  
 and integral equations 779, 785  
 invariance under similarity transform 452  
 inverse iteration 455, 469, 476, 487ff., 1230  
 Jacobi transformation 453, 456ff., 462, 475, 489, 1225f.  
 left eigenvalues 451  
 list of tasks 454f.  
 multiple eigenvalues 489  
 nonlinear 455  
 nonsymmetric matrix 476ff., 1230ff.  
 operation count of balancing 476  
 operation count of Givens reduction 463  
 operation count of Householder reduction 467  
 operation count of inverse iteration 488  
 operation count of Jacobi method 460  
 operation count of QL method 470, 473  
 operation count of QR method for Hessenberg matrices 484  
 operation count of reduction to Hessenberg form 479  
 orthogonality 450  
 parallel algorithms 1226, 1229  
 polynomial roots and 368, 1193  
 QL method 469ff., 475, 488f.  
 QL method with implicit shifts 472ff., 1228f.  
 QR method 52, 453, 456, 469ff., 1228  
 QR method for Hessenberg matrices 480ff., 1232ff.  
 real, symmetric matrix 150, 467, 785, 1225, 1228  
 reduction to Hessenberg form 478f., 1231  
 right eigenvalues 451  
 shifting eigenvalues 449, 470f., 480  
 special matrices 454  
 termination criterion 484, 488  
 tridiagonal matrix 453, 469ff., 488, 1228
- Eigenvalue and eigenvector, defined 449
- Eigenvalue problem for differential equations 748, 764ff., 770ff., 1319ff.
- Eigenvalues and polynomial root finding 368, 1193
- EISPACK 454, 475
- Electromagnetic potential 519
- ELEMENTAL attribute (Fortran 95) 961, 1084
- Elemental functions 2/xiii, 2/xv, 940, 942, 946f., 961, 986, 1015, 1083, 1097f.
- Elimination *see* Gaussian elimination
- Ellipse in confidence limit estimation 688
- Elliptic integrals 254ff., 906  
 addition theorem 255

- Carlson's forms and algorithms 255f., 1128ff.  
 Cauchy principal value 256f.  
 duplication theorem 256  
 Legendre 254ff., 260f., 1135ff.  
 routines for 257ff., 1128ff.  
 symmetric form 255  
 Weierstrass 255  
 Elliptic partial differential equations 818, 1332ff.  
   alternating-direction implicit method (ADI) 861f., 906  
   analyze/factorize/operate package 824  
   biconjugate gradient method 824  
   boundary conditions 820  
   comparison of rapid methods 854  
   conjugate gradient method 824  
   cyclic reduction 848f., 852ff.  
   Fourier analysis and cyclic reduction (FACR) 848ff., 854  
   Gauss-Seidel method 855, 864ff., 876, 1338, 1341  
   incomplete Cholesky conjugate gradient method (ICCG) 824  
   Jacobi's method 855f., 864  
   matrix methods 824  
   multigrid method 824, 862ff., 1009, 1334ff.  
   rapid (Fourier) method 824, 848ff.  
   relaxation method 823, 854ff., 1332  
   strongly implicit procedure 824  
   successive over-relaxation (SOR) 857ff., 862, 866, 1332  
 elsewhere construct 943  
 Emacs, GNU 1/xvi  
 Embedded Runge-Kutta method 709f., 731, 1298, 1308  
 Encapsulation, in programs 7  
 Encryption 290, 1156  
 enddo statement 12, 17  
 Entropy 896  
   of data 626ff., 811, 1275  
 EOM (end of message) 902  
 eoshift() intrinsic function 950  
   communication bottleneck 969  
   vector shift argument 1019f.  
   vs. array section 1078  
 epsilon() intrinsic function 951, 1189  
 Equality constraints 423  
 Equations  
   cubic 178ff., 360  
   normal (fitting) 645, 666ff., 800, 1288  
   quadratic 20, 178  
   *see also* Differential equations; Partial differential equations; Root finding  
 Equivalence classes 337f., 1180  
 EQUIVALENCE statement 2/xif., 1161, 1286  
 Equivalence transformation 166  
 Error  
   checksums for preventing 891  
   clocking 891  
   double exponential distribution 696  
   local truncation 875  
   Lorentzian distribution 696f.  
   in multigrid method 863  
   nonnormal 653, 690, 694ff.  
   relative truncation 875  
   roundoff 180f., 881, 1362  
   series, advantage of an even 132f., 717, 1362  
   systematic vs. statistical 653, 1362  
   truncation 20f., 180, 399, 709, 881, 1362  
   varieties found by check digits 895  
   varieties of, in PDEs 831ff.  
   *see also* Roundoff error  
 Error function 213f., 601, 1094f.  
   approximating via sampling theorem 601  
   Chebyshev approximation 214, 1095  
   complex 252  
   for Fisher's z-transformation 632, 1276  
   relation to Dawson's integral 252, 1127  
   relation to Fresnel integrals 248  
   relation to incomplete gamma function 213  
   routine for 214, 1094  
   for significance of correlation 631, 1276  
   for sum squared difference of ranks 635, 1277  
 Error handling in programs 2/xii, 2/xvi, 3, 994f., 1036, 1370f.  
 Estimation of parameters *see* Fitting; Maximum likelihood estimate  
 Estimation of power spectrum 542ff., 565ff., 1254ff., 1258  
 Euler equation (fluid flow) 831  
 Euler-Maclaurin summation formula 132, 135  
 Euler's constant 216ff., 250  
 Euler's method for differential equations 702, 704, 728f.  
 Euler's transformation 160f., 1070  
   generalized form 162f.  
 Evaluation of functions *see* Function  
 Even and odd parts, of continued fraction 166, 211, 216  
 Even parity 888  
 Exception handling in programs *see* Error handling in programs  
 exit statement 959, 1219  
 Explicit differencing 827  
 Exponent in floating point format 19, 882, 1343  
 exponent intrinsic function 1107  
 Exponential deviate 278, 1151f.  
 Exponential integral 215ff., 1096f.  
   asymptotic expansion 218  
   continued fraction 216  
   recurrence relation 172  
   related to incomplete gamma function 215  
   relation to cosine integral 250  
   routine for  $Ei(x)$  218, 1097  
   routine for  $E_n(x)$  217, 1096  
   series 216  
 Exponential probability distribution 570  
 Extended midpoint rule 124f., 129f., 135, 1054f.  
 Extended Simpson's rule 128, 788, 790  
 Extended Simpson's three-eighths rule 789  
 Extended trapezoidal rule 125, 127, 130ff., 135, 786, 1052ff., 1326  
   roundoff error 132  
 Extirpolation (so-called) 574, 1261

- Extrapolation 99ff.  
 in Bulirsch-Stoer method 718ff., 726, 1305ff.  
 differential equations 702  
 by linear prediction 557ff., 1256f.  
 local 709  
 maximum entropy method as type of 567  
 polynomial 724, 726, 740, 1305f.  
 rational function 718ff., 726, 1306f.  
 relation to interpolation 101  
 for Romberg integration 134  
*see also* Interpolation
- Extremization *see* Minimization
- F**-distribution probability function 222
- F-test for differences of variances 611, 613, 1271
- FACR *see* Fourier analysis and cyclic reduction (FACR)
- Facsimile standard 901
- Factorial  
 double (denoted “!!”) 247  
 evaluation of 159, 1072, 1086  
 relation to gamma function 206  
 routine for 207f., 1086ff.
- False position 347ff., 1185f.
- Family tree 338
- FAS (full approximation storage algorithm) 874, 1339ff.
- Fast Fourier transform (FFT) 498ff., 881, 981, 1235f.  
 alternative algorithms 503f.  
 as approximation to continuous transform 497  
 Bartlett window 547, 1254  
 bit reversal 499f., 525  
 and Clenshaw-Curtis quadrature 190  
 column-parallel algorithm 981, 1237ff.  
 communication bottleneck 969, 981, 1250  
 convolution 503f., 523, 531ff., 909, 1253, 1354  
 convolution of large data sets 536f.  
 Cooley-Tukey algorithm 503, 1250  
 Cooley-Tukey algorithm, parallel 1239f.  
 correlation 538f., 1254  
 cosine transform 190, 511ff., 851, 1245f.  
 cosine transform, second form 513, 852, 1246  
 Danielson-Lanczos lemma 498f., 525  
 data sets not a power of 2 503  
 data smoothing 645  
 data windowing 545ff., 1254  
 decimation-in-frequency algorithm 503  
 decimation-in-time algorithm 503  
 discrete autocorrelation 539, 1254  
 discrete convolution theorem 531ff.  
 discrete correlation theorem 538  
 at double frequency 575  
 effect of caching 982  
 endpoint corrections 578f., 1261ff.  
 external storage 525  
 figures of merit for data windows 548  
 filtering 551ff.  
 FIR filter 553  
 four-step framework 983, 1239  
 Fourier integrals 577ff., 1261  
 Fourier integrals, infinite range 583  
 Hamming window 547  
 Hann window 547  
 history 498  
 IIR filter 553ff.  
 image processing 803, 805  
 integrals using 124  
 inverse of cosine transform 512ff.  
 inverse of sine transform 511  
 large data sets 525  
 leakage 544  
 memory-local algorithm 528  
 multidimensional 515ff., 1236f., 1241, 1246, 1251  
 for multiple precision arithmetic 906  
 for multiple precision multiplication 909, 1354  
 number-theoretic transforms 503f.  
 operation count 498  
 optimal (Wiener) filtering 539ff., 558  
 order of storage in 501  
 parallel algorithms 981ff., 1235ff.  
 partial differential equations 824, 848ff.  
 Parzen window 547  
 periodicity of 497  
 periodogram 543ff., 566  
 power spectrum estimation 542ff., 1254ff.  
 for quadrature 124  
 of real data in 2D and 3D 519ff., 1248f.  
 of real functions 504ff., 519ff., 1242f., 1248f.  
 related algorithms 503f.  
 row-parallel algorithm 981, 1235f.  
 Sande-Tukey algorithm 503  
 sine transform 508ff., 850, 1245  
 Singleton’s algorithm 525  
 six-step framework 983, 1240  
 square window 546, 1254  
 timing 982  
 treatment of end effects in convolution 533  
 treatment of end effects in correlation 538f.  
 Tukey’s trick for frequency doubling 575  
 use in smoothing data 645  
 used for Lomb periodogram 574, 1259  
 variance of power spectrum estimate 544f., 549  
 virtual memory machine 528  
 Welch window 547, 1254  
 Winograd algorithms 503  
*see also* Discrete Fourier transform (DFT);  
 Fourier transform; Spectral density
- Faure sequence 300
- Fax (facsimile) Group 3 standard 901
- Feasible vector 424
- FFT *see* Fast Fourier transform (FFT)
- Field, in data record 329
- Figure-of-merit function 650
- Filon’s method 583
- Filter 551ff.  
 acausal 552  
 bilinear transformation method 554  
 causal 552, 644

- characteristic polynomial 554  
 data smoothing 644f., 1283f.  
 digital 551ff.  
 DISPO 644  
 by fast Fourier transform (FFT) 523, 551ff.  
 finite impulse response (FIR) 531, 552  
 homogeneous modes of 554  
 infinite impulse response (IIR) 552ff., 566  
 Kalman 700  
 linear 552ff.  
 low-pass for smoothing 644ff., 1283f.  
 nonrecursive 552  
 optimal (Wiener) 535, 539ff., 558, 644  
 quadrature mirror 585, 593  
 realizable 552, 554f.  
 recursive 552ff., 566  
 Remes exchange algorithm 553  
 Savitzky-Golay 183, 644ff., 1283f.  
 stability of 554f.  
 in the time domain 551ff.  
 Fine-to-coarse operator 864, 1337  
 Finite difference equations (FDEs) 753, 763, 774  
   alternating-direction implicit method (ADI) 847, 861f.  
   art not science 829  
   Cayley's form for unitary operator 844  
   Courant condition 829, 832ff., 836  
   Courant condition (multidimensional) 846  
   Crank-Nicholson method 840, 844, 846  
   eigenmodes of 827f.  
   explicit vs. implicit schemes 827  
   forward Euler 826f.  
   Forward Time Centered Space (FTCS) 827ff., 839ff., 843, 855  
   implicit scheme 840  
   Lax method 828ff., 836  
   Lax method (multidimensional) 845f.  
   mesh drifting instability 834f.  
   numerical derivatives 181  
   partial differential equations 821ff.  
   in relaxation methods 753ff.  
   staggered leapfrog method 833f.  
   two-step Lax-Wendroff method 835ff.  
   upwind differencing 832f., 837  
   *see also* Partial differential equations  
 Finite element methods, partial differential equations 824  
 Finite impulse response (FIR) 531  
 Finkelstein, S. 1/xvi, 2/ix  
 FIR (finite impulse response) filter 552  
 Fisher's z-transformation 631f., 1276  
 Fitting 650ff., 1285ff.  
   basis functions 665  
   by Chebyshev approximation 185f., 1076  
   chi-square 653ff., 1285ff.  
   confidence levels related to chi-square values 691ff.  
   confidence levels from singular value decomposition (SVD) 693f.  
   confidence limits on fitted parameters 684ff.  
   covariance matrix not always meaningful 651, 690  
   degeneracy of parameters 674  
   an exponential 674  
   freezing parameters in 668, 700  
   Gaussians, a sum of 682, 1294  
   general linear least squares 665ff., 1288, 1290f.  
   Kalman filter 700  
   K-S test, caution regarding 621f.  
   least squares 651ff., 1285  
   Legendre polynomials 674, 1291f.  
   Levenberg-Marquardt method 678ff., 816, 1292f.  
   linear regression 655ff., 1285ff.  
   maximum likelihood estimation 652f., 694ff.  
   Monte Carlo simulation 622, 654, 684ff.  
   multidimensional 675  
   nonlinear models 675ff., 1292f.  
   nonlinear models, advanced methods 683  
   nonlinear problems that are linear 674  
   nonnormal errors 656, 690, 694ff.  
   polynomial 83, 114, 191, 645, 665, 674, 1078, 1291  
   by rational Chebyshev approximation 197ff., 1081f.  
   robust methods 694ff., 1294  
   of sharp spectral features 566  
   standard (probable) errors on fitted parameters 657f., 661, 667, 671, 684ff., 1285f., 1288, 1290  
   straight line 655ff., 667f., 698, 1285ff., 1294ff.  
   straight line, errors in both coordinates 660ff., 1286ff.  
   *see also* Error; Least squares fitting; Maximum likelihood estimate; Robust estimation  
 Five-point difference star 867  
 Fixed point format 18  
 Fletcher-Powell algorithm *see* Davidon-Fletcher-Powell algorithm  
 Fletcher-Reeves algorithm 390, 414ff., 1214  
 Floating point co-processor 886  
 Floating point format 18ff., 882, 1343  
   care in numerical derivatives 181  
   IEEE 276, 882, 1343  
 floor() intrinsic function 948  
 Flux-conservative initial value problems 825ff.  
 FMG (full multigrid method) 863, 868, 1334ff.  
 FOR iteration 9f., 12  
 forall statement 2/xii, 2/xv, 960, 964, 986  
   access to associated index 968  
   skew array sections 985, 1007  
 Formats of numbers 18ff., 882, 1343  
 Fortran 9  
   arithmetic-if statement 2/xi  
   COMMON block 2/xif., 953, 957  
   deprecated features 2/xif., 947, 1057, 1161, 1256, 1286  
   dynamical allocation of storage 869, 1336  
   EQUIVALENCE statement 2/xif., 1161, 1286  
   evolution of 2/xivff.  
   exception handling 2/xii, 2/xvi  
   filenames 935  
   Fortran 2000 (planned) 2/xvi



- Fortran 95 2/xv, 945, 947, 1084, 1100, 1364  
HPF (High-Performance Fortran) 2/xvf.  
Numerical Recipes in 2/x, 2/xvii, 1  
obsolescent features 2/xif.  
side effects 960  
*see also* Fortran 90
- Fortran D 2/xv
- Fortran 77 1/xix  
bit manipulation functions 17  
hexadecimal constants 17
- Fortran 8x 2/xi, 2/xiii
- Fortran 90 3  
abstract data types 2/xiii, 1030  
all() intrinsic function 945, 948  
allocatable array 938, 941, 953ff., 1197, 1212, 1266, 1293, 1306, 1336  
allocate statement 938f., 941, 953f., 1197, 1266, 1293, 1306, 1336  
allocated() intrinsic function 938, 952ff., 1197, 1266, 1293  
any() intrinsic function 945, 948  
array allocation and deallocation 953  
array of arrays 2/xii, 956, 1336  
array constructor 2/xii, 968, 971, 1022, 1052, 1055, 1127  
array constructor with implied do-list 968, 971  
array extents 938, 949  
array features 941ff., 953ff.  
array intrinsic procedures 2/xiii, 948ff.  
array of length 0 944  
array of length 1 949  
array manipulation functions 950  
array parallel operations 964f.  
array rank 938, 949  
array reallocation 955  
array section 2/xiif., 2/xiii, 939, 941ff., 960, 1078, 1284, 1286, 1333  
array shape 938, 949  
array size 938, 942  
array transpose 981f.  
array unary and binary functions 949  
associated() intrinsic function 952f.  
associated pointer 953f.  
assumed-shape array 942  
automatic array 938, 954, 1197, 1212, 1336  
backwards-compatibility 935, 946  
bit manipulation functions 2/xiii, 951  
bit\_size() intrinsic function 951  
broadcasts 965f.  
btest() intrinsic function 951  
case construct 1010, 1036  
case insensitive 937  
ceiling() intrinsic function 947  
character functions 952  
character variables 1183  
cmplx function 1125  
communication bottlenecks 969, 981, 1250  
compatibility with Fortran 77 935, 946  
compilers 2/viii, 2/xiv, 1364  
compiling 936  
conformable arrays 942f., 1094
- CONTAINS statement 954, 957, 985, 1067, 1134, 1202  
control structure 2/xiv, 959, 1219, 1305  
conversion elemental functions 946  
count() intrinsic function 948  
cshift() intrinsic function 950, 969  
cycle statement 959, 1219  
data hiding 956ff., 1209  
data parallelism 964  
DATA statement 959  
data types 937, 1336, 1346, 1361  
deallocate statement 938f., 953f., 1197, 1266, 1293  
deallocating array 938, 953f., 1197, 1266, 1293  
defined types 956  
deprecated features 947, 1057, 1161, 1256, 1286  
derived types 937, 955  
dimensional expansion 965ff.  
do-loop 2/xiv  
dot\_product() intrinsic function 945, 949, 969, 1216  
dynamical allocation of storage 2/xiii, 938, 941f., 953ff., 1327, 1336  
elemental functions 940, 942, 946f., 951, 1015, 1083, 1364  
elsewhere construct 943  
eoshift() intrinsic function 950, 969, 1019f., 1078  
epsilon() intrinsic function 951, 1189  
evolution 2/xivff., 959, 987f.  
example 936  
exit statement 959, 1219  
exponent() intrinsic function 1107  
floor() intrinsic function 948  
Fortran tip icon 1009  
garbage collection 956  
gather-scatter operations 2/xiif., 969, 981, 984, 1002, 1032, 1034, 1250  
generic interface 2/xiii, 1083  
generic procedures 939, 1015, 1083, 1094, 1096, 1364  
global variables 955, 957, 1210  
history 2/xff.  
huge() intrinsic function 951  
iand() intrinsic function 951  
ibclr() intrinsic function 951  
ibits() intrinsic function 951  
ibset() intrinsic function 951  
ieor() intrinsic function 951  
IMPLICIT NONE statement 2/xiv, 936  
implied do-list 968, 971, 1127  
index loss 967f.  
initialization expression 943, 959, 1012, 1127  
inquiry functions 948  
integer model 1144, 1149, 1156  
INTENT attribute 1072, 1092  
interface 939, 942, 1067, 1084, 1384  
internal subprogram 2/xii, 2/xiv, 957, 1057, 1067, 1202f., 1256, 1302  
interprocessor communication 969, 981, 1250  
intrinsic data types 937

- intrinsic procedures 939, 945ff., 987, 1016  
 ior() intrinsic function 951  
 ishft() intrinsic function 951  
 ishftc() intrinsic function 951  
 ISO (International Standards Organization)  
   2/xf., 2/xiiif.  
 keyword argument 2/xiv, 947f., 1341  
 kind() intrinsic function 951  
 KIND parameter 937, 946, 1125, 1144,  
   1192, 1254, 1261, 1284, 1361  
 language features 935ff.  
 lbound() intrinsic function 949  
 lexical comparison 952  
 linear algebra 969f., 1000ff., 1018f., 1026,  
   1040, 1200, 1326  
 linear recurrence 971, 988  
 linking 936  
 literal constant 937, 1361  
 logo for tips 2/viii, 1009  
 mask 948, 967f., 1006f., 1038, 1102,  
   1200, 1226, 1305, 1333f., 1368, 1378,  
   1382  
 matmul() intrinsic function 945, 949, 969,  
   1026, 1040, 1050, 1076, 1200, 1216,  
   1290, 1326  
 maxexponent() intrinsic function 1107  
 maxloc() intrinsic function 949, 961,  
   992f., 1015  
 maxval() intrinsic function 945, 948, 961,  
   1016, 1273  
 memory leaks 953, 956, 1327  
 memory management 938, 953ff.  
 merge() intrinsic function 945, 950, 1010,  
   1094f., 1099f.  
 Metcalf and Reid (M&R) 935  
 minloc() intrinsic function 949, 961, 992f.  
 minval() intrinsic function 948, 961  
 missing language features 983ff., 987ff.  
 modularization 956f.  
 MODULE facility 2/xiii, 936f., 939f.,  
   953f., 957, 1067, 1298, 1320, 1322,  
   1324, 1330, 1346  
 MODULE subprograms 940  
 modulo() intrinsic function 946, 1156  
 named constant 940, 1012, 1361  
 named control structure 959, 1219, 1305  
 nearest() intrinsic function 952, 1146  
 nested where construct forbidden 943  
 not() intrinsic function 951  
 nullify statement 953f., 1070, 1302  
 numerical representation functions 951  
 ONLY option 941, 957, 1067  
 operator overloading 2/xiif.  
 operator, user-defined 2/xii  
 optional argument 2/xiv, 947f., 1092,  
   1228, 1230, 1256, 1272, 1275, 1340  
 outer product 969f.  
 overloading 940, 1083, 1102  
 pack() intrinsic function 945, 950, 964,  
   969, 991, 1170, 1176, 1178  
 pack, for selective evaluation 1087  
 parallel extensions 2/xv, 959ff., 964, 981,  
   984, 987, 1002, 1032  
 parallel programming 963ff.  
 PARAMETER attribute 1012  
 pointer 2/xiiif., 938f., 941, 944f., 952ff.,  
   1067, 1070, 1197, 1210, 1212, 1266,  
   1302, 1327, 1336  
 pointer to function (missing) 1067  
 portability 963  
 present() intrinsic function 952  
 PRIVATE attribute 957, 1067  
 product() intrinsic function 948  
 programming conventions 937  
 PUBLIC attribute 957, 1067  
 quick start 936  
 radix() intrinsic function 1231  
 random\_number() intrinsic function 1141,  
   1143  
 random\_seed() intrinsic function 1141  
 real() intrinsic function 947, 1125  
 RECURSIVE keyword 958, 1065, 1067  
 recursive procedure 2/xiv, 958, 1065,  
   1067, 1166  
 reduction functions 948  
 reshape() intrinsic function 950, 969, 1247  
 RESULT keyword 958, 1073  
 SAVE attribute 953f., 958f., 1052, 1070,  
   1266, 1293  
 scale() intrinsic function 1107  
 scatter-with-combine (missing function)  
   984  
 scope 956ff.  
 scoping units 939  
 select case statement 2/xiv, 1010, 1036  
 shape() intrinsic function 938, 949  
 size() intrinsic function 938, 942, 945,  
   948  
 skew sections 985  
 sparse matrix representation 1030  
 specification statement 2/xiv  
 spread() intrinsic function 945, 950, 966ff.,  
   969, 1000, 1094, 1290f.  
 statement functions deprecated 1057  
 stride (of an array) 944  
 structure constructor 2/xii  
 subscript triplet 944  
 sum() intrinsic function 945, 948, 966  
 tiny() intrinsic function 952  
 transformational functions 948  
 transpose() intrinsic function 950, 960,  
   969, 981, 1247  
 tricks 1009, 1072, 1146, 1274, 1278, 1280  
 truncation elemental functions 946  
 type checking 1140  
 ubound() intrinsic function 949  
 undefined pointer 953  
 unpack() intrinsic function 950, 964, 969  
 USE statement 936, 939f., 954, 957, 1067,  
   1384  
 utility functions 987ff.  
 vector subscripts 2/xiif., 969, 981, 984,  
   1002, 1032, 1034, 1250  
 visibility 956ff., 1209, 1293, 1296  
 WG5 technical committee 2/xi, 2/xiii,  
   2/xvf.  
 where construct 943, 985, 1060, 1291  
 X3J3 Committee 2/viii, 2/xf., 2/xv, 947,  
   959, 964, 968, 990  
 zero-length array 944

- see also* Intrinsic procedures  
*see also* Fortran
- Fortran 95 947, 959ff.  
 allocatable variables 961  
 blocks 960  
`cpu_time()` intrinsic function 961  
 elemental functions 2/xiii, 2/xv, 940, 961, 986, 1015, 1083f., 1097f.  
 forall statement 2/xii, 2/xv, 960, 964, 968, 986, 1007  
 initialization of derived data type 2/xv  
 initialization of pointer 2/xv, 961  
 minor changes from Fortran 90 961  
 modified intrinsic functions 961  
 nested where construct 2/xv, 960, 1100  
 pointer association status 961  
 pointers 961  
 PURE attribute 2/xv, 960f., 964, 986  
 SAVE attribute 961  
 side effects 960  
 and skew array section 945, 985  
*see also* Fortran
- Fortran 2000 2/xvi  
 Forward deflation 363  
 Forward difference operator 161  
 Forward Euler differencing 826f.  
 Forward Time Centered Space *see* FTCS  
 Four-step framework, for FFT 983, 1239  
 Fourier analysis and cyclic reduction (FACR) 848f., 854  
 Fourier integrals  
   attenuation factors 583, 1261  
   endpoint corrections 578f., 1261  
   tail integration by parts 583  
   use of fast Fourier transform (FFT) 577ff., 1261ff.  
 Fourier transform 99, 490ff., 1235ff.  
   aliasing 495, 569  
   approximation of Dawson's integral 253  
   autocorrelation 492  
   basis functions compared 508f.  
   contrasted with wavelet transform 584, 594  
   convolution 492, 503f., 531ff., 909, 1253, 1354  
   correlation 492, 538f., 1254  
   cosine transform 190, 511ff., 851, 1245f.  
   cosine transform, second form 513, 852, 1246  
   critical sampling 494, 543, 545  
   definition 490  
   discrete Fourier transform (DFT) 184, 495ff.  
   Gaussian function 600  
   image processing 803, 805  
   infinite range 583  
   inverse of discrete Fourier transform 497  
   method for partial differential equations 848ff.  
   missing data 569  
   missing data, fast algorithm 574f., 1259  
   Nyquist frequency 494ff., 520, 543, 545, 569, 571  
   optimal (Wiener) filtering 539ff., 558  
   Parseval's theorem 492, 498, 544  
   power spectral density (PSD) 492f.  
   power spectrum estimation by FFT 542ff., 1254ff.  
   power spectrum estimation by maximum entropy method 565ff., 1258  
   properties of 491f.  
   sampling theorem 495, 543, 545, 600  
   scalings of 491  
   significance of a peak in 570  
   sine transform 508ff., 850, 1245  
   symmetries of 491  
   uneven sampling, fast algorithm 574f., 1259  
   unevenly sampled data 569ff., 574, 1258  
   and wavelets 592f.  
   Wiener-Khinchin theorem 492, 558, 566f.  
   *see also* Fast Fourier transform (FFT); Spectral density
- Fractal region 360f.  
 Fractional step methods 847f.  
 Fredholm alternative 780  
 Fredholm equations 779f.  
   eigenvalue problems 780, 785  
   error estimate in solution 784  
   first kind 779  
   Fredholm alternative 780  
   homogeneous, second kind 785, 1325  
   homogeneous vs. inhomogeneous 779f.  
   ill-conditioned 780  
   infinite range 789  
   inverse problems 780, 795ff.  
   kernel 779f.  
   nonlinear 781  
   Nystrom method 782ff., 789, 1325  
   product Nystrom method 789, 1328ff.  
   second kind 779f., 782ff., 1325, 1331  
   with singularities 788, 1328ff.  
   with singularities, worked example 792, 1328ff.  
   subtraction of singularity 789  
   symmetric kernel 785  
   *see also* Inverse problems
- Frequency domain 490  
 Frequency spectrum *see* Fast Fourier transform (FFT)
- Frequentist, contrasted with Bayesian 810  
 Fresnel integrals 248ff.  
   asymptotic form 249  
   continued fraction 248f.  
   routine for 249f., 1123  
   series 248
- Friday the Thirteenth 14f., 1011f.  
 FTCS (forward time centered space) 827ff., 839ff., 843  
   stability of 827ff., 839ff., 855
- Full approximation storage (FAS) algorithm 874, 1339ff.  
 Full moon 14f., 936, 1011f.  
 Full multigrid method (FMG) 863, 868, 1334ff.  
 Full Newton methods, nonlinear least squares 683  
 Full pivoting 29, 1014  
 Full weighting 867
- Function  
   Airy 204, 243f., 1121

- approximation 99ff., 184ff., 1043, 1076ff.  
 associated Legendre polynomial 246ff.,  
     764, 1122f., 1319  
 autocorrelation of 492  
 bandwidth limited 495  
 Bessel 172, 204, 223ff., 234, 1101ff.,  
     1115ff.  
 beta 209, 1089  
 binomial coefficients 208f., 1087f.  
 branch cuts of 202f.  
 chi-square probability 215, 798  
 complex 202  
 confluent hypergeometric 204, 239  
 convolution of 492  
 correlation of 492  
 cosine integral 250f., 1123f.  
 Coulomb wave 204, 234  
 cumulative binomial probability 222f.  
 cumulative Poisson 209ff.  
 Dawson's integral 252ff., 600, 1127f.  
 digamma 216  
 elliptic integrals 254ff., 906, 1128ff.  
 error 213f., 248, 252, 601, 631, 635,  
     1094f., 1127, 1276f.  
 evaluation 159ff., 1070ff.  
 evaluation by path integration 201ff., 263,  
     1138  
 exponential integral 172, 215ff., 250,  
     1096f.  
 F-distribution probability 222  
 Fresnel integral 248ff., 1123  
 gamma 206, 1085  
 hypergeometric 202f., 263ff., 1138ff.  
 incomplete beta 219ff., 610, 1098ff., 1269  
 incomplete gamma 209ff., 615, 654, 657f.,  
     1089ff., 1272, 1285  
 inverse hyperbolic 178, 255  
 inverse trigonometric 255  
 Jacobian elliptic 261, 1137f.  
 Kolmogorov-Smirnov probability 618f.,  
     640, 1274, 1281  
 Legendre polynomial 172, 246, 674, 1122,  
     1291  
 logarithm 255  
 modified Bessel 229ff., 1109ff.  
 modified Bessel, fractional order 239ff.,  
     1118ff.  
 overloading 1083  
 parallel evaluation 986, 1009, 1084, 1087,  
     1090, 1102, 1128, 1134  
 path integration to evaluate 201ff.  
 pathological 99f., 343  
 Poisson cumulant 214  
 representations of 490  
 routine for plotting a 342, 1182  
 sine and cosine integrals 248, 250ff.,  
     1125f.  
 sn, dn, cn 261, 1137f.  
 spherical harmonics 246ff., 1122  
 spheroidal harmonic 764ff., 770ff., 1319ff.,  
     1323ff.  
 Student's probability 221f.  
 variable number of arguments 1022  
 Weber 204
- Functional iteration, for implicit equations  
     740f.  
 FWHM (full width at half maximum) 548f.
- G**amma deviate 282f., 1153f.  
 Gamma function 206ff., 1085  
     incomplete *see* Incomplete gamma func-  
         tion  
 Garbage collection 956  
 Gather-scatter operations 2/xiif., 984, 1002,  
     1032, 1034  
     communication bottleneck 969, 981, 1250  
     many-to-one 984, 1002, 1032, 1034  
 Gauss-Chebyshev integration 141, 144, 512f.  
 Gauss-Hermite integration 144, 789  
     abscissas and weights 147, 1062  
     normalization 147  
 Gauss-Jacobi integration 144  
     abscissas and weights 148, 1063  
 Gauss-Jordan elimination 27ff., 33, 64, 1014f.  
     operation count 34, 39  
     solution of normal equations 667, 1288  
     storage requirements 30  
 Gauss-Kronrod quadrature 154  
 Gauss-Laguerre integration 144, 789, 1060  
 Gauss-Legendre integration 145f., 1059  
     *see also* Gaussian integration  
 Gauss-Lobatto quadrature 154, 190, 512  
 Gauss-Radau quadrature 154  
 Gauss-Seidel method (relaxation) 855, 857,  
     864ff., 1338  
     nonlinear 876, 1341  
 Gauss transformation 256  
 Gaussian (normal) distribution 267, 652, 798  
     central limit theorem 652f.  
     deviates from 279f., 571, 1152  
     kurtosis of 606  
     multivariate 690  
     semi-invariants of 608  
     tails compared to Poisson 653  
     two-dimensional (binormal) 631  
     variance of skewness of 606  
 Gaussian elimination 33f., 51, 55, 1014f.  
     fill-in 45, 64  
     integral equations 786, 1326  
     operation count 34  
     outer product variant 1017  
     in reduction to Hessenberg form 478,  
         1231  
     relaxation solution of boundary value prob-  
         lems 753ff., 777, 1316  
 Gaussian function  
     Hardy's theorem on Fourier transforms  
         600  
     *see also* Gaussian (normal) distribution  
 Gaussian integration 127, 140ff., 789, 1059ff.  
     calculation of abscissas and weights 142ff.,  
         1009, 1059ff.  
     error estimate in solution 784  
     extensions of 153f.  
     Golub-Welsch algorithm for weights and  
         abscissas 150, 1064  
     for integral equations 781, 783, 1325  
     from known recurrence relation 150, 1064

- nonclassical weight function 151ff., 788f., 1064f., 1328f.  
 and orthogonal polynomials 142, 1009, 1061  
 parallel calculation of formulas 1009, 1061  
 preassigned nodes 153f.  
 weight function  $\log x$  153  
 weight functions 140ff., 788f., 1059ff., 1328f.
- Gear's method (stiff ODEs) 730  
 Geiger counter 266  
 Generalized eigenvalue problems 455  
 Generalized minimum residual method (GMRES) 78  
 Generic interface *see* Interface, generic  
 Generic procedures 939, 1083, 1094, 1096, 1364  
   elemental 940, 942, 946f., 1015, 1083  
 Geometric progression 972, 996f., 1365, 1372ff.  
`geop()` utility function 972, 974, 989, 996, 1127  
 Geophysics, use of Backus-Gilbert method 809  
 Gerchberg-Saxton algorithm 805  
`get_diag()` utility function 985, 989, 1005, 1226  
 Gilbert and Sullivan 714  
 Givens reduction 462f., 473  
   fast 463  
   operation count 463  
 Glassman, A.J. 180  
 Global optimization 387f., 436ff., 650, 1219ff.  
   continuous variables 443f., 1222  
 Global variables 940, 953f., 1210  
   allocatable array method 954, 1197, 1212, 1266, 1287, 1298  
   communicated via internal subprogram 954, 957f., 1067, 1226  
   danger of 957, 1209, 1293, 1296  
   pointer method 954, 1197, 1212, 1266, 1287, 1302  
 Globally convergent  
   minimization 418ff., 1215  
   root finding 373, 376ff., 382, 749f., 752, 1196, 1314f.
- GMRES (generalized minimum residual method) 78  
 GNU Emacs 1/xvi  
 Godunov's method 837  
 Golden mean (golden ratio) 21, 349, 392f., 399  
 Golden section search 341, 389ff., 395, 1202ff.  
 Golub-Welsch algorithm, for Gaussian quadrature 150, 1064  
 Goodness-of-fit 650, 654, 657f., 662, 690, 1285  
 GOTO statements, danger of 9, 959  
 Gram-Schmidt  
   biorthogonalization 415f.  
   orthogonalization 94, 450f., 1039  
   SVD as alternative to 58  
 Graphics, function plotting 342, 1182f.  
 Gravitational potential 519  
 Gray code 300, 881, 886ff., 1344  
 Greenbaum, A. 79  
 Gregorian calendar 13, 16, 1011, 1013  
 Grid square 116f.  
 Group, dihedral 894, 1345  
 Guard digits 882, 1343
- H**alf weighting 867, 1337  
 Halton's quasi-random sequence 300  
 Hamming window 547  
 Hamming's motto 341  
 Hann window 547  
 Harmonic analysis *see* Fourier transform  
 Hashing 293, 1144, 1148, 1156  
   for random number seeds 1147f.  
 HDLC checksum 890  
 Heap (data structure) 327f., 336, 897, 1179  
 Heapsort 320, 327f., 336, 1171f., 1179  
 Helmholtz equation 852  
 Hermite polynomials 144, 147  
   approximation of roots 1062  
 Hermitian matrix 450ff., 475  
 Hertz (unit of frequency) 490  
 Hessenberg matrix 94, 453, 470, 476ff., 488, 1231  
   *see also* Matrix  
 Hessian matrix 382, 408, 415f., 419f., 676ff., 803, 815  
   is inverse of covariance matrix 667, 679  
   second derivatives in 676  
 Hexadecimal constants 17f., 276, 293  
   initialization 959  
 Hierarchically band diagonal matrix 598  
 Hierarchy of program structure 6ff.  
 High-order not same as high-accuracy 100f., 124, 389, 399, 705, 709, 741  
 High-pass filter 551  
 High-Performance Fortran (HPF) 2/xvf., 964, 981, 984  
   scatter-with-add 1032  
 Hilbert matrix 83  
 Home page, Numerical Recipes 1/xx, 2/xviii  
 Homogeneous linear equations 53  
 Hook step methods 386  
 Hotelling's method for matrix inverse 49, 598  
 Householder transformation 52, 453, 462ff., 469, 473, 475, 478, 481ff., 1227f.  
   operation count 467  
   in QR decomposition 92, 1039  
 HPF *see* High-Performance Fortran  
 Huffman coding 564, 881, 896f., 902, 1346ff.  
`huge()` intrinsic function 951  
 Hyperbolic functions, explicit formulas for  
   inverse 178  
 Hyperbolic partial differential equations 818  
   advective equation 826  
   flux-conservative initial value problems 825ff.  
 Hypergeometric function 202f., 263ff.  
   routine for 264f., 1138  
 Hypothesis, null 603
- I**2B, defined 937

- I4B, defined 937  
 iand() intrinsic function 951  
 ibclr() intrinsic function 951  
 ibits() intrinsic function 951  
 IBM 1/xxiii, 2/xix  
   bad random number generator 268  
   Fortran 90 compiler 2/viii  
   PC 4, 276, 293, 886  
   PC-RT 4  
   radix base for floating point arithmetic 476  
   RS6000 2/viii, 4  
 IBM checksum 894  
 ibset() intrinsic function 951  
 ICCG (incomplete Cholesky conjugate gradient method) 824  
 ICF (intrinsic correlation function) model 817  
 Identity (unit) matrix 25  
 IEEE floating point format 276, 882f., 1343  
 ieor() intrinsic function 951  
 if statement, arithmetic 2/xi  
 if structure 12f.  
 ifirstloc() utility function 989, 993, 1041, 1346  
 IIR (infinite impulse response) filter 552ff., 566  
 Ill-conditioned integral equations 780  
 Image processing 519, 803  
   cosine transform 513  
   fast Fourier transform (FFT) 519, 523, 803  
   as an inverse problem 803  
   maximum entropy method (MEM) 809ff.  
   from modulus of Fourier transform 805  
   wavelet transform 596f., 1267f.  
 imaxloc() utility function 989, 993, 1017  
 iminloc() utility function 989, 993, 1046, 1076  
 Implicit  
   function theorem 340  
   pivoting 30, 1014  
   shifts in QL method 472ff.  
 Implicit differencing 827  
   for diffusion equation 840  
   for stiff equations 729, 740, 1308  
 IMPLICIT NONE statement 2/xiv, 936  
 Implied do-list 968, 971, 1127  
 Importance sampling, in Monte Carlo 306f.  
 Improper integrals 135ff., 1055  
 Impulse response function 531, 540, 552  
 IMSL 1/xxiii, 2/xx, 26, 64, 205, 364, 369, 454  
 In-place selection 335, 1178f.  
 Included file, superseded by module 940  
 Incomplete beta function 219ff., 1098ff.  
   for F-test 613, 1271  
   routine for 220f., 1097  
   for Student's t 610, 613, 1269  
 Incomplete Cholesky conjugate gradient method (ICCG) 824  
 Incomplete gamma function 209ff., 1089ff.  
   for chi-square 615, 654, 657f., 1272, 1285  
   deviates from 282f., 1153  
   in mode estimation 610  
   routine for 211f., 1089  
 Increment of linear congruential generator 268  
 Indentation of blocks 9  
 Index 934ff., 1446ff.  
   this entry 1464  
 Index loss 967f., 1038  
 Index table 320, 329f., 1173ff., 1176  
 Inequality constraints 423  
 Inheritance 8  
 Initial value problems 702, 818f.  
   *see also* Differential equations;  
   Partial differential equations  
 Initialization of derived data type 2/xv  
 Initialization expression 943, 959, 1012, 1127  
 Injection operator 864, 1337  
 Instability *see* Stability  
 Integer model, in Fortran 90 1144, 1149, 1156  
 Integer programming 436  
 Integral equations 779ff.  
   adaptive stepsize control 788  
   block-by-block method 788  
   correspondence with linear algebraic equations 779ff.  
   degenerate kernel 785  
   eigenvalue problems 780, 785  
   error estimate in solution 784  
   Fredholm 779f., 782ff., 1325, 1331  
   Fredholm alternative 780  
   homogeneous, second kind 785, 1325  
   ill-conditioned 780  
   infinite range 789  
   inverse problems 780, 795ff.  
   kernel 779  
   nonlinear 781, 787  
   Nystrom method 782ff., 789, 1325  
   product Nystrom method 789, 1328ff.  
   with singularities 788ff., 1328ff.  
   with singularities, worked example 792, 1328ff.  
   subtraction of singularity 789  
   symmetric kernel 785  
   unstable quadrature 787f.  
   Volterra 780f., 786f., 1326f.  
   wavelets 782  
   *see also* Inverse problems  
 Integral operator, wavelet approximation of 597, 782  
 Integration of functions 123ff., 1052ff.  
   cosine integrals 250, 1125  
   Fourier integrals 577ff., 1261  
   Fourier integrals, infinite range 583  
   Fresnel integrals 248, 1123  
   Gauss-Hermite 147f., 1062  
   Gauss-Jacobi 148, 1063  
   Gauss-Laguerre 146, 1060  
   Gauss-Legendre 145, 1059  
   integrals that are elliptic integrals 254  
   path integration 201ff.  
   sine integrals 250, 1125  
   *see also* Quadrature  
 Integro-differential equations 782  
 INTENT attribute 1072, 1092  
 Interface (Fortran 90) 939, 942, 1067

- for communication between program parts
  - 957, 1209, 1293, 1296
- explicit 939, 942, 1067, 1384
- generic 2/xiii, 940, 1015, 1083, 1094, 1096
- implicit 939
  - for Numerical Recipes 1384ff.
- Interface block 939, 1084, 1384
- Interface, in programs 2, 8
- Intermediate value theorem 343
- Internal subprogram (Fortran 90) 2/xiv, 954, 957, 1067, 1202f., 1226
  - nesting of 2/xii
  - resembles C macro 1302
  - supersedes statement function 1057, 1256
- International Standards Organization (ISO) 2/xf., 2/xiii
- Internet, availability of code over 1/xx, 2/xvii
- Interpolation 99ff.
  - Aitken's algorithm 102
  - avoid 2-stage method 100
  - avoid in Fourier analysis 569
  - bicubic 118f., 1049f.
  - bilinear 117
  - caution on high-order 100
  - coefficients of polynomial 100, 113ff., 191, 575, 1047f., 1078
  - for computing Fourier integrals 578
  - error estimates for 100
  - of functions with poles 104ff., 1043f.
  - inverse quadratic 353, 395ff., 1204
  - multidimensional 101f., 116ff., 1049ff.
  - in multigrid method 866, 1337
  - Neville's algorithm 102f., 182, 1043
  - Nystrom 783, 1326
  - offset arrays 104, 113
  - operation count for 100
  - operator 864, 1337
  - order of 100
  - and ordinary differential equations 101
  - oscillations of polynomial 100, 116, 389, 399
  - parabolic, for minimum finding 395, 1204
  - polynomial 99, 102ff., 182, 1043
  - rational Chebyshev approximation 197ff., 1081
  - rational function 99, 104ff., 194ff., 225, 718ff., 726, 1043f., 1080, 1306
  - reverse (extrapolation) 574, 1261
  - spline 100, 107ff., 120f., 1044f., 1050f.
  - trigonometric 99
    - see also* Fitting
- Interprocessor communication 969, 981
- Interval variable (statistics) 623
- Intrinsic correlation function (ICF) model 817
- Intrinsic data types 937
- Intrinsic procedures
  - array inquiry 938, 942, 948ff.
  - array manipulation 950
  - array reduction 948
  - array unary and binary functions 949
  - backwards-compatibility 946
  - bit manipulation 2/xiii, 951
  - character 952
  - cmplx 1254
  - conversion elemental 946
  - elemental 940, 942, 946f., 951, 1083, 1364
  - generic 939, 1083f., 1364
  - lexical comparison 952
  - numeric inquiry 2/xiv, 1107, 1231, 1343
  - numerical 946, 951f.
  - numerical representation 951
  - pack used for sorting 1171
  - random number 1143
  - real 1254
  - top 10 945
  - truncation 946f.
    - see also* Fortran 90
- Inverse hyperbolic function 178, 255
- Inverse iteration *see* Eigensystems
- Inverse problems 779, 795ff.
  - Backus-Gilbert method 806ff.
  - Bayesian approach 799, 810f., 816f.
  - central idea 799
  - constrained linear inversion method 799ff.
  - data inversion 807
  - deterministic constraints 804ff.
  - in geophysics 809
  - Gerchberg-Saxton algorithm 805
  - incomplete Fourier coefficients 813
  - and integral equations 780
  - linear regularization 799ff.
  - maximum entropy method (MEM) 810, 815f.
  - MEM demystified 814
  - Phillips-Twomey method 799ff.
  - principal solution 797
  - regularization 796ff.
  - regularizing operator 798
  - stabilizing functional 798
  - Tikhonov-Miller regularization 799ff.
  - trade-off curve 795
  - trade-off curve, Backus-Gilbert method 809
  - two-dimensional regularization 803
  - use of conjugate gradient minimization 804, 815
  - use of convex sets 804
  - use of Fourier transform 803, 805
  - Van Cittert's method 804
- Inverse quadratic interpolation 353, 395ff., 1204
- Inverse response kernel, in Backus-Gilbert method 807
- Inverse trigonometric function 255
- ior() intrinsic function 951
- ISBN (International Standard Book Number)
  - checksum 894
- ishft() intrinsic function 951
- ishftc() intrinsic function 951
- ISO (International Standards Organization) 2/xf., 2/xiii
- Iterated integrals 155
- Iteration 9f.
  - functional 740f.
  - to improve solution of linear algebraic equations 47ff., 195, 1022
  - for linear algebraic equations 26

- required for two-point boundary value problems 745  
 in root finding 340f.  
 Iteration matrix 856  
 ITPACK 71  
 Iverson, John 2/xi
- J**acobi matrix, for Gaussian quadrature 150, 1064  
 Jacobi polynomials, approximation of roots 1064  
 Jacobi transformation (or rotation) 94, 453, 456ff., 462, 475, 489, 1041, 1225  
 Jacobian determinant 279, 774  
 Jacobian elliptic functions 261, 1137f.  
 Jacobian matrix 374, 376, 379, 382, 731, 1197f., 1309  
   singular in Newton's rule 386  
 Jacobi's method (relaxation) 855ff., 864  
 Jenkins-Traub method 369  
 Julian Day 1, 13, 16, 936, 1010ff.  
 Jump transposition errors 895
- K-S** test *see* Kolmogorov-Smirnov test  
 Kalman filter 700  
 Kanji 2/xii  
 Kaps-Rentrop method 730, 1308  
 Kendall's tau 634, 637ff., 1279  
 Kennedy, Ken 2/xv  
 Kepler's equation 1061  
 Kermit checksum 889  
 Kernel 779  
   averaging, in Backus-Gilbert method 807  
   degenerate 785  
   finite rank 785  
   inverse response 807  
   separable 785  
   singular 788f., 1328  
   symmetric 785  
 Keys used in sorting 329, 889  
 Keyword argument 2/xiv, 947f., 1341  
 kind() intrinsic function 951  
 KIND parameter 946, 1261, 1284  
   and `cmplx()` intrinsic function 1125, 1192, 1254  
   default 937  
   for Numerical Recipes 1361  
   for random numbers 1144  
   and `real()` intrinsic function 1125  
 Kolmogorov-Smirnov test 614, 617ff., 694, 1273f.  
   two-dimensional 640, 1281ff.  
   variants 620ff., 640, 1281  
 Kuiper's statistic 621  
 Kurtosis 606, 608, 1269
- L**-estimate 694  
 Labels, statement 9  
 Lag 492, 538, 553  
 Lagged Fibonacci generator 1142, 1148ff.  
 Lagrange multiplier 795  
 Lagrange's formula for polynomial interpolation 84, 102f., 575, 578  
 Laguerre polynomials, approximation of roots 1061  
 Laguerre's method 341, 365f., 1191f.  
 Lanczos lemma 498f.  
 Lanczos method for gamma function 206, 1085  
 Landen transformation 256  
 LAPACK 26, 1230  
 Laplace's equation 246, 818  
   *see also* Poisson equation  
 Las Vegas 625  
 Latin square or hypercube 305f.  
 Laurent series 566  
 Lax method 828ff., 836, 845f.  
   multidimensional 845f.  
 Lax-Wendroff method 835ff.  
`lbound()` intrinsic function 949  
 Leakage in power spectrum estimation 544, 548  
 Leakage width 548f.  
 Leapfrog method 833f.  
 Least squares filters *see* Savitzky-Golay filters  
 Least squares fitting 645, 651ff., 655ff., 660ff., 665ff., 1285f., 1288f.  
   contrasted to general minimization problems 684ff.  
   degeneracies in 671f., 674  
   Fourier components 570  
   as M-estimate for normal errors 696  
   as maximum likelihood estimator 652  
   as method for smoothing data 645, 1283  
   Fourier components 1258  
   freezing parameters in 668, 700  
   general linear case 665ff., 1288, 1290f.  
   Levenberg-Marquardt method 678ff., 816, 1292f.  
   Lomb periodogram 570, 1258  
   multidimensional 675  
   nonlinear 386, 675ff., 816, 1292  
   nonlinear, advanced methods 683  
   normal equations 645, 666f., 800, 1288  
   normal equations often singular 670, 674  
   optimal (Wiener) filtering 540f.  
   QR method in 94, 668  
   for rational Chebyshev approximation 199f., 1081f.  
   relation to linear correlation 630, 658  
   Savitzky-Golay filter as 645, 1283  
   singular value decomposition (SVD) 25f., 51ff., 199f., 670ff., 1081, 1290  
   skewed by outliers 653  
   for spectral analysis 570, 1258  
   standard (probable) errors on fitted parameters 667, 671  
   weighted 652  
   *see also* Fitting  
 L'Ecuyer's long period random generator 271, 273  
 Least squares fitting  
   standard (probable) errors on fitted parameters 1288, 1290  
   weighted 1285  
 Left eigenvalues or eigenvectors 451  
 Legal matters 1/xx, 2/xvii  
 Legendre elliptic integral *see* Elliptic integrals



- Legendre polynomials 246, 1122  
 fitting data to 674, 1291f.  
 recurrence relation 172  
 shifted monic 151  
*see also* Associated Legendre polynomials;  
 Spherical harmonics
- Lehmer-Schur algorithm 369
- Lemarie's wavelet 593
- Lentz's method for continued fraction 165, 212
- Lepage, P. 309
- Leptokurtic distribution 606
- Levenberg-Marquardt algorithm 386, 678ff., 816, 1292  
 advanced implementation 683
- Levinson's method 86, 1038
- Lewis, H.W. 275
- Lexical comparison functions 952
- LGT, defined 937
- License information 1/xx, 2/xviii.
- Limbo 356
- Limit cycle, in Laguerre's method 365
- Line minimization *see* Minimization, along a ray
- Line search *see* Minimization, along a ray
- Linear algebra, intrinsic functions for parallelization 969f., 1026, 1040, 1200, 1326
- Linear algebraic equations 22ff., 1014  
 band diagonal 43ff., 1019  
 biconjugate gradient method 77, 1034ff.  
 Cholesky decomposition 89f., 423, 455, 668, 1038f.  
 complex 41  
 computing  $\mathbf{A}^{-1} \cdot \mathbf{B}$  40  
 conjugate gradient method 77ff., 599, 1034  
 cyclic tridiagonal 67, 1030  
 direct methods 26, 64, 1014, 1030  
 Fortran 90 vs. library routines 1016  
 Gauss-Jordan elimination 27ff., 1014  
 Gaussian elimination 33f., 1014f.  
 Hilbert matrix 83  
 Hotelling's method 49, 598  
 and integral equations 779ff., 783, 1325  
 iterative improvement 47ff., 195, 1022  
 iterative methods 26, 77ff., 1034  
 large sets of 23  
 least squares solution 53ff., 57f., 199f., 671, 1081, 1290  
 LU decomposition 34ff., 195, 386, 732, 783, 786, 801, 1016, 1022, 1325f.  
 nonsingular 23  
 overdetermined 25f., 199, 670, 797  
 partitioned 70  
 QR decomposition 91f., 382, 386, 668, 1039f., 1199  
 row vs. column elimination 31f.  
 Schultz's method 49, 598  
 Sherman-Morrison formula 65ff., 83  
 singular 22, 53, 58, 199, 670  
 singular value decomposition (SVD) 51ff., 199f., 670ff., 797, 1022, 1081, 1290  
 sparse 23, 43, 63ff., 732, 804, 1020f., 1030  
 summary of tasks 25f.  
 Toeplitz 82, 85ff., 195, 1038  
 tridiagonal 26, 42f., 64, 109, 150, 453f., 462ff., 469ff., 488, 839f., 853, 861f., 1018f., 1227ff.  
 Vandermonde 82ff., 114, 1037, 1047  
 wavelet solution 597ff., 782  
 Woodbury formula 68ff., 83  
*see also* Eigensystems
- Linear congruential random number generator 267ff., 1142  
 choice of constants for 274ff.
- Linear constraints 423
- Linear convergence 346, 393
- Linear correlation (statistics) 630ff., 1276
- Linear dependency  
 constructing orthonormal basis 58, 94  
 of directions in  $N$ -dimensional space 409  
 in linear algebraic equations 22f.
- Linear equations *see* Differential equations;  
 Integral equations; Linear algebraic equations
- Linear inversion method, constrained 799ff.
- Linear prediction 557ff.  
 characteristic polynomial 559  
 coefficients 557ff., 1256  
 compared to maximum entropy method 558  
 compared with regularization 801  
 contrasted to polynomial extrapolation 560  
 related to optimal filtering 558  
 removal of bias in 563  
 stability 559f., 1257
- Linear predictive coding (LPC) 563ff.
- Linear programming 387, 423ff., 1216ff.  
 artificial variables 429  
 auxiliary objective function 430  
 basic variables 426  
 composite simplex algorithm 435  
 constraints 423  
 convergence criteria 432  
 degenerate feasible vector 429  
 dual problem 435  
 equality constraints 423  
 feasible basis vector 426  
 feasible vector 424  
 fundamental theorem 426  
 inequality constraints 423  
 left-hand variables 426  
 nonbasic variables 426  
 normal form 426  
 objective function 424  
 optimal feasible vector 424  
 pivot element 428f.  
 primal-dual algorithm 435  
 primal problem 435  
 reduction to normal form 429ff.  
 restricted normal form 426ff.  
 revised simplex method 435  
 right-hand variables 426  
 simplex method 402, 423ff., 431ff., 1216ff.  
 slack variables 429  
 tableau 427  
 vertex of simplex 426

- Linear recurrence *see* Recurrence relation  
 Linear regression 655ff., 660ff., 1285ff.  
     *see also* Fitting  
 Linear regularization 799ff.  
 LINPACK 26  
 Literal constant 937, 1361  
 Little-endian 293  
 Local extrapolation 709  
 Local extremum 387f., 437  
 Localization of roots *see* Bracketing  
 Logarithmic function 255  
 Lomb periodogram method of spectral analysis  
     569f., 1258f.  
     fast algorithm 574f., 1259  
 Loops 9f.  
 Lorentzian probability distribution 282, 696f.  
 Low-pass filter 551, 644f., 1283f.  
 Lower subscript 944  
 lower\_triangle() utility function 989, 1007,  
     1200  
 LP coefficients *see* Linear prediction  
 LPC (linear predictive coding) 563ff.  
 LU decomposition 34ff., 47f., 51, 55, 64, 97,  
     374, 667, 732, 1016, 1022  
     for  $\mathbf{A}^{-1} \cdot \mathbf{B}$  40  
     backsubstitution 39, 1017  
     band diagonal matrix 43ff., 1020  
     complex equations 41f.  
     Crout's algorithm 36ff., 45, 1017  
     for integral equations 783, 786, 1325f.  
     for inverse iteration of eigenvectors 488  
     for inverse problems 801  
     for matrix determinant 41  
     for matrix inverse 40, 1016  
     for nonlinear sets of equations 374, 386,  
         1196  
     operation count 36, 39  
     outer product Gaussian elimination 1017  
     for Padé approximant 195, 1080  
     pivoting 37f., 1017  
     repeated backsubstitution 40, 46  
     solution of linear algebraic equations 40,  
         1017  
     solution of normal equations 667  
     for Toeplitz matrix 87  
 Lucifer 290
- M**&R (Metcalf and Reid) 935  
 M-estimates 694ff.  
     how to compute 697f.  
     local 695ff.  
     *see also* Maximum likelihood estimate  
 Machine accuracy 19f., 881f., 1189, 1343  
 Macintosh, *see* Apple Macintosh  
 Maehly's procedure 364, 371  
 Magic  
     in MEM image restoration 814  
     in Padé approximation 195  
 Mantissa in floating point format 19, 882,  
     909, 1343  
 Marginals 624  
 Marquardt method (least squares fitting) 678ff.,  
     816, 1292f.  
 Marsaglia shift register 1142, 1148ff.  
 Marsaglia, G. 1142, 1149
- mask 1006f., 1102, 1200, 1226, 1305, 1333f.,  
     1368, 1378, 1382  
     optional argument 948  
     optional argument, facilitates parallelism  
         967f., 1038  
 Mass, center of 295ff.  
 MasterCard checksum 894  
 Mathematical Center (Amsterdam) 353  
 Mathematical intrinsic functions 946, 951f.  
 matmul() intrinsic function 945, 949, 969,  
     1026, 1040, 1050, 1076, 1200, 1216,  
     1290, 1326  
 Matrix 23ff.  
     add vector to diagonal 1004, 1234, 1366,  
         1381  
     approximation of 58f., 598f.  
     band diagonal 42ff., 64, 1019  
     band triangular 64  
     banded 26, 454  
     bidiagonal 52  
     block diagonal 64, 754  
     block triangular 64  
     block tridiagonal 64  
     bordered 64  
     characteristic polynomial 449, 469  
     Cholesky decomposition 89f., 423, 455,  
         668, 1038f.  
     column augmented 28, 1014  
     complex 41  
     condition number 53, 78  
     create unit matrix 1006, 1382  
     curvature 677  
     cyclic banded 64  
     cyclic tridiagonal 67, 1030  
     defective 450, 476, 489  
     of derivatives *see* Hessian matrix; Jacobian  
         determinant  
     design (fitting) 645, 665, 801, 1082  
     determinant of 25, 41  
     diagonal of sparse matrix 1033ff.  
     diagonalization 452ff., 1225ff.  
     elementary row and column operations  
         28f.  
     finite differencing of partial differential  
         equations 821ff.  
     get diagonal 985, 1005, 1226f., 1366,  
         1381f.  
     Hermitian 450, 454, 475  
     Hermitian conjugate 450  
     Hessenberg 94, 453, 470, 476ff., 488,  
         1231ff.  
     Hessian *see* Hessian matrix  
     hierarchically band diagonal 598  
     Hilbert 83  
     identity 25  
     ill-conditioned 53, 56, 114  
     indexed storage of 71f., 1030  
     and integral equations 779, 783, 1325  
     inverse 25, 27, 34, 40, 65ff., 70, 95ff.,  
         1014, 1016f.  
     inverse, approximate 49  
     inverse by Hotelling's method 49, 598  
     inverse by Schultz's method 49, 598  
     inverse multiplied by a matrix 40  
     iteration for inverse 49, 598

- Jacobi transformation 453, 456ff., 462, 1225f.
- Jacobian 731, 1309
- logical dimension 24
- lower triangular 34f., 89, 781, 1016
- lower triangular mask 1007, 1200, 1382
- multiplication denoted by dot 23
- multiplication, intrinsic function 949, 969, 1026, 1040, 1050, 1200, 1326
- norm 50
- normal 450ff.
- nullity 53
- nullspace 25, 53f., 449, 795
- orthogonal 91, 450, 463ff., 587
- orthogonal transformation 452, 463ff., 469, 1227
- orthonormal basis 58, 94
- outer product denoted by cross 66, 420
- partitioning for determinant 70
- partitioning for inverse 70
- pattern multiply of sparse 74
- physical dimension 24
- positive definite 26, 89f., 668, 1038
- QR decomposition 91f., 382, 386, 668, 1039, 1199
- range 53
- rank 53
- residual 49
- row and column indices 23
- row vs. column operations 31f.
- self-adjoint 450
- set diagonal elements 1005, 1200, 1366, 1382
- similarity transform 452ff., 456, 476, 478, 482
- singular 53f., 58, 449
- singular value decomposition 26, 51ff., 797
- sparse 23, 63ff., 71, 598, 732, 754, 804, 1030ff.
- special forms 26
- splitting in relaxation method 856f.
- spread 808
- square root of 423, 455
- symmetric 26, 89, 450, 454, 462ff., 668, 785, 1038, 1225, 1227
- threshold multiply of sparse 74, 1031
- Toeplitz 82, 85ff., 195, 1038
- transpose() intrinsic function 950
- transpose of sparse 73f., 1033
- triangular 453
- tridiagonal 26, 42f., 64, 109, 150, 453f., 462ff., 469ff., 488, 839f., 853, 861f., 1018f., 1227ff.
- tridiagonal with fringes 822
- unitary 450
- updating 94, 382, 386, 1041, 1199
- upper triangular 34f., 91, 1016
- upper triangular mask 1006, 1226, 1305, 1382
- Vandermonde 82ff., 114, 1037, 1047  
*see also* Eigensystems
- Matrix equations *see* Linear algebraic equations
- Matterhorn 606
- maxexponent() intrinsic function 1107
- Maximization *see* Minimization
- Maximum entropy method (MEM) 565ff., 1258
- algorithms for image restoration 815f.
- Bayesian 816f.
- Cornwell-Evans algorithm 816
- demystified 814
- historic vs. Bayesian 816f.
- image restoration 809ff.
- intrinsic correlation function (ICF) model 817
- for inverse problems 809ff.
- operation count 567
- see also* Linear prediction
- Maximum likelihood estimate (M-estimates) 690, 694ff.
- and Bayes' Theorem 811
- chi-square test 690
- defined 652
- how to compute 697f.
- mean absolute deviation 696, 698, 1294
- relation to least squares 652
- maxloc() intrinsic function 949, 992f., 1015
- modified in Fortran 95 961
- maxval() intrinsic function 945, 948, 961, 1016, 1273
- Maxwell's equations 825f.
- Mean(s)
- of distribution 604f., 608f., 1269
- statistical differences between two 609ff., 1269f.
- Mean absolute deviation of distribution 605, 696, 1294
- related to median 698
- Measurement errors 650
- Median 320
- calculating 333
- of distribution 605, 608f.
- as L-estimate 694
- role in robust straight line fitting 698
- by selection 698, 1294
- Median-of-three, in Quicksort 324
- MEM *see* Maximum entropy method (MEM)
- Memory leak 953, 956, 1071, 1327
- Memory management 938, 941f., 953ff., 1327, 1336
- merge construct 945, 950, 1099f.
- for conditional scalar expression 1010, 1094f.
- contrasted with where 1023
- parallelization 1011
- Merge-with-dummy-values idiom 1090
- Merit function 650
- in general linear least squares 665
- for inverse problems 797
- nonlinear models 675
- for straight line fitting 656, 698
- for straight line fitting, errors in both coordinates 660, 1286
- Mesh-drift instability 834f.
- Mesokurtic distribution 606
- Metcalf, Michael 2/viii  
*see also* M&R
- Method of regularization 799ff.

- Metropolis algorithm 437f., 1219
- Microsoft 1/xxii, 2/xix
- Microsoft Fortran PowerStation 2/viii
- Midpoint method *see* Modified midpoint method;  
Semi-implicit midpoint rule
- Mikado, or Town of Titipu 714
- Miller's algorithm 175, 228, 1106
- MIMD machines (Multiple Instruction Multiple  
Data) 964, 985, 1071, 1084
- Minimal solution of recurrence relation 174
- Minimax polynomial 186, 198, 1076
- Minimax rational function 198
- Minimization 387ff.  
along a ray 77, 376f., 389, 406ff., 412f.,  
415f., 418, 1195f., 1211, 1213  
annealing, method of simulated 387f.,  
436ff., 1219ff.  
bracketing of minimum 390ff., 402, 1201f.  
Brent's method 389, 395ff., 399, 660f.,  
1204ff., 1286  
Broyden-Fletcher-Goldfarb-Shanno algo-  
rithm 390, 418ff., 1215  
chi-square 653ff., 675ff., 1285, 1292  
choice of methods 388f.  
combinatorial 436f., 1219  
conjugate gradient method 390, 413ff.,  
804, 815, 1210, 1214  
convergence rate 393, 409  
Davidon-Fletcher-Powell algorithm 390,  
418ff., 1215  
degenerate 795  
direction-set methods 389, 406ff., 1210ff.  
downhill simplex method 389, 402ff.,  
444, 697f., 1208, 1222ff.  
finding best-fit parameters 650  
Fletcher-Reeves algorithm 390, 414ff.,  
1214  
functional 795  
global 387f., 443f., 650, 1219, 1222  
globally convergent multidimensional 418,  
1215  
golden section search 390ff., 395, 1202ff.  
multidimensional 388f., 402ff., 1208ff.,  
1214  
in nonlinear model fitting 675f., 1292  
Polak-Ribiere algorithm 389, 414ff., 1214  
Powell's method 389, 402, 406ff., 1210ff.  
quasi-Newton methods 376, 390, 418ff.,  
1215  
and root finding 375  
scaling of variables 420  
by searching smaller subspaces 815  
steepest descent method 414, 804  
termination criterion 392, 404  
use in finding double roots 341  
use for sparse linear systems 77ff.  
using derivatives 389f., 399ff., 1205ff.  
variable metric methods 390, 418ff., 1215  
*see also* Linear programming
- Minimum residual method, for sparse system  
78
- minloc() intrinsic function 949, 992f.  
modified in Fortran 95 961
- MINPACK 683
- minval() intrinsic function 948, 961
- MIPS 886
- Missing data problem 569
- Mississippi River 438f., 447
- MMP (massively multiprocessor) machines  
965ff., 974, 981, 984, 1016ff., 1021,  
1045, 1226ff., 1250
- Mode of distribution 605, 609
- Modeling of data *see* Fitting
- Model-trust region 386, 683
- Modes, homogeneous, of recursive filters 554
- Modified Bessel functions *see* Bessel func-  
tions
- Modified Lentz's method, for continued frac-  
tions 165
- Modified midpoint method 716ff., 720, 1302f.
- Modified moments 152
- Modula-2 7
- Modular arithmetic, without overflow 269,  
271, 275
- Modular programming 2/xiii, 7f., 956ff.,  
1209, 1293, 1296, 1346
- MODULE facility 2/xiii, 936f., 939f., 957,  
1067, 1298, 1320, 1322, 1324, 1330,  
1346  
initializing random number generator 1144ff.  
in nr.f90 936, 941f., 1362, 1384ff.  
in nrtype.f90 936f., 1361f.  
in nrutil.f90 936, 1070, 1362, 1364ff.  
sparse matrix 1031  
undefined variables on exit 953, 1266
- Module subprogram 940
- modulo() intrinsic function 946, 1156
- Modulus of linear congruential generator 268
- Moments  
of distribution 604ff., 1269  
filter that preserves 645  
modified problem of 151f.  
problem of 83  
and quadrature formulas 791, 1328  
semi-invariants 608
- Monic polynomial 142f.
- Monotonicity constraint, in upwind differenc-  
ing 837
- Monte Carlo 155ff., 267  
adaptive 306ff., 1161ff.  
bootstrap method 686f.  
comparison of sampling methods 309  
exploration of binary tree 290  
importance sampling 306f.  
integration 124, 155ff., 295ff., 306ff.,  
1161  
integration, recursive 314ff., 1164ff.  
integration, using Sobol' sequence 304  
integration, VEGAS algorithm 309ff.,  
1161  
and Kolmogorov-Smirnov statistic 622,  
640  
partial differential equations 824  
quasi-random sequences in 299ff.  
quick and dirty 686f.  
recursive 306ff., 314ff., 1161, 1164ff.  
significance of Lomb periodogram 570  
simulation of data 654, 684ff., 690  
stratified sampling 308f., 314, 1164

- Moon, calculate phases of 1f., 14f., 936, 1010f.
- Mother functions 584
- Mother Nature 684, 686
- Moving average (MA) model 566
- Moving window averaging 644
- Mozart 9
- MS 1/xxii, 2/xix
- Muller's method 364, 372
- Multidimensional
- confidence levels of fitting 688f.
  - data, use of binning 623
  - Fourier transform 515ff., 1241, 1246, 1251
  - Fourier transform, real data 519ff., 1248f.
  - initial value problems 844ff.
  - integrals 124, 155ff., 295ff., 306ff., 1065ff., 1161ff.
  - interpolation 116ff., 1049ff.
  - Kolmogorov-Smirnov test 640, 1281
  - least squares fitting 675
  - minimization 402ff., 406ff., 413ff., 1208ff., 1214f., 1222ff.
  - Monte Carlo integration 295ff., 306ff., 1161ff.
  - normal (Gaussian) distribution 690
  - optimization 388f.
  - partial differential equations 844ff.
  - root finding 340ff., 358, 370, 372ff., 746, 749f., 752, 754, 1194ff., 1314ff.
  - search using quasi-random sequence 300
  - secant method 373, 382f., 1199f.
  - wavelet transform 595, 1267f.
- Multigrid method 824, 862ff., 1334ff.
- avoid SOR 866
  - boundary conditions 868f.
  - choice of operators 868
  - coarse-to-fine operator 864, 1337
  - coarse-grid correction 864f.
  - cycle 865
  - dual viewpoint 875
  - fine-to-coarse operator 864, 1337
  - full approximation storage (FAS) algorithm 874, 1339ff.
  - full multigrid method (FMG) 863, 868, 1334ff.
  - full weighting 867
  - Gauss-Seidel relaxation 865f., 1338
  - half weighting 867, 1337
  - importance of adjoint operator 867
  - injection operator 864, 1337
  - interpolation operator 864, 1337
  - line relaxation 866
  - local truncation error 875
  - Newton's rule 874, 876, 1339, 1341
  - nonlinear equations 874ff., 1339ff.
  - nonlinear Gauss-Seidel relaxation 876, 1341
  - odd-even ordering 866, 869, 1338
  - operation count 862
  - prolongation operator 864, 1337
  - recursive nature 865, 1009, 1336
  - relative truncation error 875
  - relaxation as smoothing operator 865
  - restriction operator 864, 1337
  - speeding up FMG algorithm 873
  - stopping criterion 875f.
  - straight injection 867
  - symbol of operator 866f.
  - use of Richardson extrapolation 869
  - V-cycle 865, 1336
  - W-cycle 865, 1336
  - zebra relaxation 866
- Multiple precision arithmetic 906ff., 1352ff.
- Multiple roots 341, 362
- Multiplication, complex 171
- Multiplication, multiple precision 907, 909, 1353f.
- Multiplier of linear congruential generator 268
- Multistep and multivalued methods (ODEs) 740ff.
- see also* Differential Equations; Predictor-corrector methods
- Multivariate normal distribution 690
- Murphy's Law 407
- Musical scores 5f.
- N**AG 1/xxiii, 2/xx, 26, 64, 205, 454
- Fortran 90 compiler 2/viii, 2/xiv
- Named constant 940
- initialization 1012
  - for Numerical Recipes 1361
- Named control structure 959, 1219, 1305
- National Science Foundation (U.S.) 1/xvii, 1/xix, 2/ix
- Natural cubic spline 109, 1044f.
- Navier-Stokes equation 830f.
- nearest() intrinsic function 952, 1146
- Needle, eye of (minimization) 403
- Negation, multiple precision 907, 1353f.
- Negentropy 811, 896
- Nelder-Mead minimization method 389, 402, 1208
- Nested iteration 868
- Neumann boundary conditions 820, 840, 851, 858
- Neutrino 640
- Neville's algorithm 102f., 105, 134, 182, 1043
- Newton-Cotes formulas 125ff., 140
- Newton-Raphson method *see* Newton's rule
- Newton's rule 143f., 180, 341, 355ff., 362, 364, 469, 1059, 1189
- with backtracking 376, 1196
  - caution on use of numerical derivatives 356ff.
  - fractal domain of convergence 360f.
  - globally convergent multidimensional 373, 376ff., 382, 749f., 752, 1196, 1199, 1314f.
  - for matrix inverse 49, 598
  - in multidimensions 370, 372ff., 749f., 752, 754, 1194ff., 1314ff.
  - in nonlinear multigrid 874, 876, 1339, 1341
  - nonlinear Volterra equations 787
  - for reciprocal of number 911, 1355
  - safe 359, 1190
  - scaling of variables 381

- singular Jacobian 386  
 solving stiff ODEs 740  
 for square root of number 912, 1356  
 Niederreiter sequence 300  
 NL2SOL 683  
 Noise  
   bursty 889  
   effect on maximum entropy method 567  
   equivalent bandwidth 548  
   fitting data which contains 647f., 650  
   model, for optimal filtering 541  
 Nominal variable (statistics) 623  
 Nonexpansive projection operator 805  
 Non-interfering directions *see* Conjugate directions  
 Nonlinear eigenvalue problems 455  
 Nonlinear elliptic equations, multigrid method 874ff., 1339ff.  
 Nonlinear equations, in MEM inverse problems 813  
 Nonlinear equations, roots of 340ff.  
 Nonlinear instability 831  
 Nonlinear integral equations 781, 787  
 Nonlinear programming 436  
 Nonnegativity constraints 423  
 Nonparametric statistics 633ff., 1277ff.  
 Nonpolynomial complete (NP-complete) 438  
 Norm, of matrix 50  
 Normal (Gaussian) distribution 267, 652, 682, 798, 1294  
   central limit theorem 652f.  
   deviates from 279f., 571, 1152  
   kurtosis of 607  
   multivariate 690  
   semi-invariants of 608  
   tails compared to Poisson 653  
   two-dimensional (binormal) 631  
   variance of skewness of 606  
 Normal equations (fitting) 26, 645, 666ff., 795, 800, 1288  
   often are singular 670  
 Normalization  
   of Bessel functions 175  
   of floating-point representation 19, 882, 1343  
   of functions 142, 765  
   of modified Bessel functions 232  
 not() intrinsic function 951  
 Notch filter 551, 555f.  
 NP-complete problem 438  
 nr.f90 (module file) 936, 1362, 1384ff.  
 nrerror() utility function 989, 995  
 nrtype.f90 (module file) 936f.  
   named constants 1361  
 nrutil.f90 (module file) 936, 1070, 1362, 1364ff.  
   table of contents 1364  
 Null hypothesis 603  
 nullify statement 953f., 1070, 1302  
 Nullity 53  
 Nullspace 25, 53f., 449, 795  
 Number-theoretic transforms 503f.  
 Numeric inquiry functions 2/xiv, 1107, 1231, 1343  
 Numerical derivatives 180ff., 645, 1075  
 Numerical integration *see* Quadrature  
 Numerical intrinsic functions 946, 951f.  
 Numerical Recipes  
   compatibility with First Edition 4  
   Example Book 3  
   Fortran 90 types 936f., 1361  
   how to get programs 1/xx, 2/xvii  
   how to report bugs 1/iv, 2/iv  
   interface blocks (Fortran 90) 937, 941f., 1084, 1384ff.  
   no warranty on 1/xx, 2/xvii  
   plan of two-volume edition 1/xiii  
   table of dependencies 921ff., 1434ff.  
   as trademark 1/xxiii, 2/xx  
   utility functions (Fortran 90) 936f., 945, 968, 970, 972ff., 977, 984, 987ff., 1015, 1071f., 1361ff.  
 Numerical Recipes Software 1/xv, 1/xxiiff., 2/xviii.  
   address and fax number 1/iv, 1/xxii, 2/iv, 2/xix  
   Web home page 1/xx, 2/xvii  
 Nyquist frequency 494ff., 520, 543, 545, 569ff.  
 Nystrom method 782f., 789, 1325  
   product version 789, 1331
- O**bject extensibility 8  
 Objective function 424  
 Object-oriented programming 2/xvi, 2, 8  
 Oblateness parameter 764  
 Obsolete features *see* Fortran, Obsolescent features  
 Octal constant, initialization 959  
 Odd-even ordering  
   allows parallelization 1333  
   in Gauss-Seidel relaxation 866, 869, 1338  
   in successive over-relaxation (SOR) 859, 1332  
 Odd parity 888  
 OEM information 1/xxii  
 One-sided power spectral density 492  
 ONLY option, for USE statement 941, 957, 1067  
 Operation count  
   balancing 476  
   Bessel function evaluation 228  
   bisection method 346  
   Cholesky decomposition 90  
   coefficients of interpolating polynomial 114f.  
   complex multiplication 97  
   cubic spline interpolation 109  
   evaluating polynomial 168  
   fast Fourier transform (FFT) 498  
   Gauss-Jordan elimination 34, 39  
   Gaussian elimination 34  
   Givens reduction 463  
   Householder reduction 467  
   interpolation 100  
   inverse iteration 488  
   iterative improvement 48  
   Jacobi transformation 460  
   Kendall's tau 637

- linear congruential generator 268
  - LU decomposition 36, 39
  - matrix inversion 97
  - matrix multiplication 96
  - maximum entropy method 567
  - multidimensional minimization 413f.
  - multigrid method 862
  - multiplication 909
  - polynomial evaluation 97f., 168
  - QL method 470, 473
  - QR decomposition 92
  - QR method for Hessenberg matrices 484
  - reduction to Hessenberg form 479
  - selection by partitioning 333
  - sorting 320ff.
  - Spearman rank-order coefficient 638
  - Toeplitz matrix 83
  - Vandermonde matrix 83
  - Operator overloading 2/xiif., 7
  - Operator splitting 823, 847f., 861
  - Operator, user-defined 2/xii
  - Optimal feasible vector 424
  - Optimal (Wiener) filtering 535, 539ff., 558, 644
    - compared with regularization 801
  - Optimization *see* Minimization
  - Optimization of code 2/xiii
  - Optional argument 2/xiv, 947f., 1092, 1228, 1230, 1256, 1272, 1275, 1340
    - dim 948
    - mask 948, 968, 1038
    - testing for 952
  - Ordering Numerical Recipes 1/xxf., 2/xviif.
  - Ordinal variable (statistics) 623
  - Ordinary differential equations *see* Differential equations
  - Orthogonal *see* Orthonormal functions; Orthonormal polynomials
  - Orthogonal transformation 452, 463ff., 469, 584, 1227
  - Orthonormal basis, constructing 58, 94, 1039
  - Orthonormal functions 142, 246
  - Orthonormal polynomials
    - Chebyshev 144, 184ff., 1076ff.
    - construct for arbitrary weight 151ff., 1064
    - in Gauss-Hermite integration 147, 1062
    - and Gaussian quadrature 142, 1009, 1061
    - Gaussian weights from recurrence 150, 1064
    - Hermite 144, 1062
    - Jacobi 144, 1063
    - Laguerre 144, 1060
    - Legendre 144, 1059
    - weight function  $\log x$  153
  - Orthonormality 51, 142, 463
  - Outer product Gaussian elimination 1017
  - Outer product of matrices (denoted by cross) 66, 420, 949, 969f., 989, 1000ff., 1017, 1026, 1040, 1076, 1200, 1216, 1275
  - outerand() utility function 989, 1002, 1015
  - outerdiff() utility function 989, 1001
  - outerdiv() utility function 989, 1001
  - outerprod() utility function 970, 989, 1000, 1017, 1026, 1040, 1076, 1200, 1216, 1275
  - outersum() utility function 989, 1001
  - Outgoing wave boundary conditions 820
  - Outlier 605, 653, 656, 694, 697
    - see also* Robust estimation
  - Overcorrection 857
  - Overflow 882, 1343
    - how to avoid in modulo multiplication 269
    - in complex arithmetic 171
  - Overlap-add and overlap-save methods 536f.
  - Overloading
    - operator 2/xiif.
    - procedures 940, 1015, 1083, 1094, 1096
  - Overrelaxation parameter 857, 1332
    - choice of 858
- P**ack() intrinsic function 945, 950, 964, 991, 1031
  - communication bottleneck 969
  - for index table 1176
  - for partition-exchange 1170
  - for selection 1178
  - for selective evaluation 1087
- Pack-unpack idiom 1087, 1134, 1153
- Padé approximant 194ff., 1080f.
- Padé approximation 105
- Parabolic interpolation 395, 1204
- Parabolic partial differential equations 818, 838ff.
- Parallel axis theorem 308
- Parallel programming 2/xv, 941, 958ff., 962ff., 965f., 968f., 987
  - array operations 964f.
  - array ranking 1278f.
  - band diagonal linear equations 1021
  - Bessel functions 1107ff.
  - broadcasts 965ff.
  - C and C++ 2/viii
  - communication costs 969, 981, 1250
  - counting do-loops 1015
  - cyclic reduction 974
  - deflation 977ff.
  - design matrix 1082
  - dimensional expansion 965ff.
  - eigensystems 1226, 1229f.
  - fast Fourier transform (FFT) 981, 1235ff., 1250
  - in Fortran 90 963ff.
  - Fortran 90 tricks 1009, 1274, 1278, 1280
  - function evaluation 986, 1009, 1084f., 1087, 1090, 1102, 1128, 1134
  - Gaussian quadrature 1009, 1061
  - geometric progressions 972
  - index loss 967f., 1038
  - index table 1176f.
  - interprocessor communication 981
  - Kendall's tau 1280
  - linear algebra 969f., 1000ff., 1018f., 1026, 1040, 1200, 1326
  - linear recurrence 973f., 1073ff.
  - logo 2/viii, 1009
  - masks 967f., 1006f., 1038, 1102, 1200, 1226, 1305, 1333f., 1368, 1378, 1382
  - merge statement 1010

- MIMD (multiple instruction, multiple data) 964, 985f., 1084  
 MMP (massively multiprocessor) machines 965ff., 974, 984, 1016ff., 1226ff., 1250  
 nrutil.f90 (module file) 1364ff.  
 odd-even ordering 1333  
 one-dimensional FFT 982f.  
 parallel note icon 1009  
 partial differential equations 1333  
   in-place selection 1178f.  
   polynomial coefficients from roots 980  
   polynomial evaluation 972f., 977, 998  
   random numbers 1009, 1141ff.  
   recursive doubling 973f., 976f., 979, 988, 999, 1071f.  
   scatter-with-combine 984, 1002f., 1032f.  
   second order recurrence 974f., 1074  
 SIMD (Single Instruction Multiple Data) 964, 985f., 1009, 1084f.  
 singular value decomposition (SVD) 1026  
 sorting 1167ff., 1171, 1176f.  
 special functions 1009  
 SSP (small-scale parallel) machines 965ff., 984, 1010ff., 1016ff., 1059f., 1226ff., 1250  
 subvector scaling 972, 974, 996, 1000  
 successive over-relaxation (SOR) 1333  
 supercomputers 2/viii, 962  
 SVD algorithm 1026  
 synthetic division 977ff., 999, 1048, 1071f., 1079, 1192  
 tridiagonal systems 975f., 1018, 1229f.  
 utilities 1364ff.  
 vector reduction 972f., 977, 998  
   vs. serial programming 965, 987  
 PARAMETER attribute 1012  
 Parameters in fitting function 651, 684ff.  
 Parity bit 888  
 Park and Miller minimal standard random generator 269, 1142  
 Parkinson's Law 328  
 Parseval's Theorem 492, 544  
   discrete form 498  
 Partial differential equations 818ff., 1332ff.  
   advective equation 826  
   alternating-direction implicit method (ADI) 847, 861f.  
   amplification factor 828, 834  
   analyze/factorize/operate package 824  
   artificial viscosity 831, 837  
   biconjugate gradient method 824  
   boundary conditions 819ff.  
   boundary value problems 819, 848  
   Cauchy problem 818f.  
   caution on high-order methods 844f.  
   Cayley's form 844  
   characteristics 818  
   Chebyshev acceleration 859f., 1332  
   classification of 818f.  
   comparison of rapid methods 854  
   conjugate gradient method 824  
   Courant condition 829, 832ff., 836  
   Courant condition (multidimensional) 846  
   Crank-Nicholson method 840, 842, 844, 846  
   cyclic reduction (CR) method 848f., 852ff.  
   diffusion equation 818, 838ff., 846, 855  
   Dirichlet boundary conditions 508, 820, 840, 850, 856, 858  
   elliptic, defined 818  
   error, varieties of 831ff.  
   explicit vs. implicit differencing 827  
   FACR method 854  
   finite difference method 821ff.  
   finite element methods 824  
   flux-conservative initial value problems 825ff.  
   forward Euler differencing 826f.  
   Forward Time Centered Space (FTCS) 827ff., 839ff., 843, 855  
   Fourier analysis and cyclic reduction (FACR) 848ff., 854  
   Gauss-Seidel method (relaxation) 855, 864ff., 876, 1338, 1341  
   Godunov's method 837  
   Helmholtz equation 852  
   hyperbolic 818, 825f.  
   implicit differencing 840  
   incomplete Cholesky conjugate gradient method (ICCG) 824  
   inhomogeneous boundary conditions 850f.  
   initial value problems 818f.  
   initial value problems, recommendations on 838ff.  
   Jacobi's method (relaxation) 855ff., 864  
   Laplace's equation 818  
   Lax method 828ff., 836, 845f.  
   Lax method (multidimensional) 845f.  
   matrix methods 824  
   mesh-drift instability 834f.  
   Monte Carlo methods 824  
   multidimensional initial value problems 844ff.  
   multigrid method 824, 862ff., 1009, 1334ff.  
   Neumann boundary conditions 508, 820, 840, 851, 858  
   nonlinear diffusion equation 842  
   nonlinear instability 831  
   numerical dissipation or viscosity 830  
   operator splitting 823, 847f., 861  
   outgoing wave boundary conditions 820  
   parabolic 818, 838ff.  
   parallel computing 1333  
   periodic boundary conditions 850, 858  
   piecewise parabolic method (PPM) 837  
   Poisson equation 818, 852  
   rapid (Fourier) methods 508ff., 824, 848ff.  
   relaxation methods 823, 854ff., 1332f.  
   Schrödinger equation 842ff.  
   second-order accuracy 833ff., 840  
   shock 831, 837  
   sparse matrices from 64  
   spectral methods 825  
   spectral radius 856ff., 862  
   stability vs. accuracy 830  
   stability vs. efficiency 821  
   staggered grids 513, 852  
   staggered leapfrog method 833f.  
   strongly implicit procedure 824



- successive over-relaxation (SOR) 857ff., 862, 866, 1332f.  
 time splitting 847f., 861  
 two-step Lax-Wendroff method 835ff.  
 upwind differencing 832f., 837  
 variational methods 824  
 varieties of error 831ff.  
 von Neumann stability analysis 827f., 830, 833f., 840  
 wave equation 818, 825f.  
*see also* Elliptic partial differential equations; Finite difference equations (FDEs)
- Partial pivoting 29  
 Partition-exchange 323, 333  
   and pack() intrinsic function 1170  
 Partitioned matrix, inverse of 70  
 Party tricks 95ff., 168  
 Parzen window 547  
 Pascal, Numerical Recipes in 2/x, 2/xvii, 1  
 Pass-the-buck idiom 1102, 1128  
 Path integration, for function evaluation 201ff., 263, 1138  
 Pattern multiply of sparse matrices 74  
 PBCG (preconditioned biconjugate gradient method) 78f., 824  
 PC methods *see* Predictor-corrector methods  
 PCGPACK 71  
 PDEs *see* Partial differential equations  
 Pearson's r 630ff., 1276  
 PECE method 741  
 Pentagon, symmetries of 895  
 Percentile 320  
 Period of linear congruential generator 268  
 Periodic boundary conditions 850, 858  
 Periodogram 543ff., 566, 1258ff.  
   Lomb's normalized 569f., 574f., 1258ff.  
   variance of 544f.  
 Perl (programming language) 1/xvi  
 Perron's theorems, for convergence of recurrence relations 174f.  
 Perturbation methods for matrix inversion 65ff.  
 Phase error 831  
 Phase-locked loop 700  
 Phi statistic 625  
 Phillips-Twomey method 799ff.  
 Pi, computation of 906ff., 1352ff., 1357f.  
 Piecewise parabolic method (PPM) 837  
 Pincherle's theorem 175  
 Pivot element 29, 33, 757  
   in linear programming 428f.  
 Pivoting 27, 29ff., 46, 66, 90, 1014  
   full 29, 1014  
   implicit 30, 38, 1014, 1017  
   in LU decomposition 37f., 1017  
   partial 29, 33, 37f., 1017  
   and QR decomposition 92  
   in reduction to Hessenberg form 478  
   in relaxation method 757  
   as row and column operations 32  
   for tridiagonal systems 43  
 Pixel 519, 596, 803, 811  
 PL/1 2/x  
 Planck's constant 842  
 Plane rotation *see* Givens reduction; Jacobi transformation (or rotation)  
 Platykurtic distribution 606  
 Plotting of functions 342, 1182f.  
 POCS (projection onto convex sets) 805  
 Poetry 5f.  
 Pointer (Fortran 90) 2/xiiiif., 938f., 944f., 953ff., 1197, 1212, 1266  
   as alias 939, 944f., 1286, 1333  
   allocating an array 941  
   allocating storage for derived type 955  
   for array of arrays 956, 1336  
   array of, forbidden 956, 1337  
   associated with target 938f., 944f., 952f., 1197  
   in Fortran 95 961  
   to function, forbidden 1067, 1210  
   initialization to null 2/xv, 961  
   returning array of unknown size 955f., 1184, 1259, 1261, 1327  
   undefined status 952f., 961, 1070, 1266, 1302  
 Poisson equation 519, 818, 852  
 Poisson probability function  
   cumulative 214  
   deviates from 281, 283ff., 571, 1154  
   semi-invariants of 608  
   tails compared to Gaussian 653  
 Poisson process 278, 282ff., 1153  
 Polak-Ribiere algorithm 390, 414ff., 1214  
 Poles *see* Complex plane, poles in  
 Polishing of roots 356, 363ff., 370f., 1193  
 poly() utility function 973, 977, 989, 998, 1072, 1096, 1192, 1258, 1284  
 Polymorphism 8  
 Polynomial interpolation 99, 102ff., 1043  
   Aitken's algorithm 102  
   in Bulirsch-Stoer method 724, 726, 1305  
   coefficients for 113ff., 1047f.  
   Lagrange's formula 84, 102f.  
   multidimensional 116ff., 1049ff.  
   Neville's algorithm 102f., 105, 134, 182, 1043  
   pathology in determining coefficients for 116  
   in predictor-corrector method 740  
   smoothing filters 645  
   *see also* Interpolation  
 Polynomials 167ff.  
   algebraic manipulations 169, 1072  
   approximate roots of Hermite polynomials 1062  
   approximate roots of Jacobi polynomials 1064  
   approximate roots of Laguerre polynomials 1061  
   approximating modified Bessel functions 230  
   approximation from Chebyshev coefficients 191, 1078f.  
 AUTODIN-II 890  
 CCITT 889f.  
 characteristic 368, 1193  
 characteristic, for digital filters 554, 559, 1257

- characteristic, for eigenvalues of matrix 449, 469
- Chebyshev 184ff., 1076ff.
- coefficients from roots 980
- CRC-16 890
- cumulants of 977, 999, 1071f., 1192, 1365, 1378f.
- deflation 362ff., 370f., 977
- derivatives of 167, 978, 1071
- division 84, 169, 362, 370, 977, 1072
- evaluation of 167, 972, 977, 998f., 1071, 1258, 1365, 1376ff.
- evaluation of derivatives 167, 978, 1071
- extrapolation in Bulirsch-Stoer method 724, 726, 1305f.
- extrapolation in Romberg integration 134
- fitting 83, 114, 191, 645, 665, 674, 1078f., 1291
- generator for CRC 889
- ill-conditioned 362
- masked evaluation of 1378
- matrix method for roots 368, 1193
- minimax 186, 198, 1076
- monic 142f.
- multiplication 169
- operation count for 168
- orthonormal 142, 184, 1009, 1061
- parallel operations on 977ff., 998f., 1071f., 1192
- primitive modulo 2 287ff., 301f., 889
- roots of 178ff., 362ff., 368, 1191ff.
- shifting of 192f., 978, 1079
- stopping criterion in root finding 366
- poly<sub>term</sub>() utility function 974, 977, 989, 999, 1071f., 1192
- Port, serial data 892
- Portability 3, 963
- Portable random number generator *see* Random number generator
- Positive definite matrix, testing for 90
- Positivity constraints 423
- Postal Service (U.S.), barcode 894
- PostScript 1/xvi, 1/xxiii, 2/xx
- Powell's method 389, 402, 406ff., 1210ff.
- Power (in a signal) 492f.
- Power series 159ff., 167, 195
- economization of 192f., 1061, 1080
- Padé approximant of 194ff., 1080f.
- Power spectral density *see* Fourier transform; Spectral density
- Power spectrum estimation *see* Fourier transform; Spectral density
- PowerStation, Microsoft Fortran 2/xix
- PPM (piecewise parabolic method) 837
- Precision
- converting to double 1362
- floating point 882, 937, 1343, 1361ff.
- multiple 906ff., 1352ff., 1362
- Preconditioned biconjugate gradient method (PBCG) 78f.
- Preconditioning, in conjugate gradient methods 824
- Predictor-corrector methods 702, 730, 740ff.
- Adams-Bashforth-Moulton schemes 741
- adaptive order methods 744
- compared to other methods 740
- fallacy of multiple correction 741
- with fixed number of iterations 741
- functional iteration vs. Newton's rule 742
- multivalued compared with multistep 742ff.
- starting and stopping 742, 744
- stepsize control 742f.
- present() intrinsic function 952
- Prime numbers 915
- Primitive polynomials modulo 2 287ff., 301f., 889
- Principal directions 408f., 1210
- Principal solution, of inverse problem 797
- PRIVATE attribute 957, 1067
- Prize, \$1000 offered 272, 1141, 1150f.
- Probability *see* Random number generator; Statistical tests
- Probability density, change of variables in 278f.
- Procedure *see* Program(s); Subprogram
- Process loss 548
- product() intrinsic function 948
- Product Nystrom method 789, 1331
- Program(s)
- as black boxes 1/xviii, 6, 26, 52, 205, 341, 406
- dependencies 921ff., 1434ff.
- encapsulation 7
- interfaces 2, 8
- modularization 7f.
- organization 5ff.
- type declarations 2
- typography of 2f., 12, 937
- validation 3f.
- Programming, serial vs. parallel 965, 987
- Projection onto convex sets (POCS) 805
- Projection operator, nonexpansive 805
- Prolongation operator 864, 1337
- Protocol, for communications 888
- PSD (power spectral density) *see* Fourier transform; Spectral density
- Pseudo-random numbers 266ff., 1141ff.
- PUBLIC attribute 957, 1067
- Puns, particularly bad 167, 744, 747
- PURE attribute 2/xv, 960f., 964, 986
- put<sub>diag</sub>() utility function 985, 990, 1005, 1200
- Pyramidal algorithm 586, 1264
- Pythagoreans 392
- QL** *see* Eigensystems
- QR *see* Eigensystems
- QR decomposition 91f., 382, 386, 1039f., 1199
- backsubstitution 92, 1040
- and least squares 668
- operation count 92
- pivoting 92
- updating 94, 382, 386, 1041, 1199
- use for orthonormal basis 58, 94
- Quadratic
- convergence 49, 256, 351, 356, 409f., 419, 906
- equations 20, 178, 391, 457

- interpolation 353, 364
  - programming 436
  - Quadrature 123ff., 1052ff.
    - adaptive 123, 190, 788
    - alternative extended Simpson's rule 128
    - arbitrary weight function 151ff., 789, 1064, 1328
    - automatic 154
    - Bode's rule 126
    - change of variable in 137ff., 788, 1056ff.
    - by Chebyshev fitting 124, 189, 1078
    - classical formulas for 124ff.
    - Clenshaw-Curtis 124, 190, 512f.
    - closed formulas 125, 127f.
    - and computer science 881
    - by cubic splines 124
    - error estimate in solution 784
    - extended midpoint rule 129f., 135, 1054f.
    - extended rules 127ff., 134f., 786, 788ff., 1326, 1328
    - extended Simpson's rule 128
    - Fourier integrals 577ff., 1261ff.
    - Fourier integrals, infinite range 583
    - Gauss-Chebyshev 144, 512f.
    - Gauss-Hermite 144, 789, 1062
    - Gauss-Jacobi 144, 1063
    - Gauss-Kronrod 154
    - Gauss-Laguerre 144, 789, 1060
    - Gauss-Legendre 144, 783, 789, 1059, 1325
    - Gauss-Lobatto 154, 190, 512
    - Gauss-Radau 154
    - Gaussian integration 127, 140ff., 781, 783, 788f., 1009, 1059ff., 1325, 1328f.
    - Gaussian integration, nonclassical weight function 151ff., 788f., 1064f., 1328f.
    - for improper integrals 135ff., 789, 1055, 1328
    - for integral equations 781f., 786, 1325ff.
    - Monte Carlo 124, 155ff., 295ff., 306ff., 1161ff.
    - multidimensional 124, 155ff., 1052, 1065ff.
    - multidimensional, by recursion 1052, 1065
    - Newton-Cotes formulas 125ff., 140
    - open formulas 125ff., 129f., 135
    - related to differential equations 123
    - related to predictor-corrector methods 740
    - Romberg integration 124, 134f., 137, 182, 717, 788, 1054f., 1065, 1067
    - semi-open formulas 130
    - Simpson's rule 126, 133, 136f., 583, 782, 788ff., 1053
    - Simpson's three-eighths rule 126, 789f.
    - singularity removal 137ff., 788, 1057ff., 1328ff.
    - singularity removal, worked example 792, 1328ff.
    - trapezoidal rule 125, 127, 130ff., 134f., 579, 583, 782, 786, 1052ff., 1326f.
    - using FFTs 124
    - weight function  $\log x$  153
    - see also* Integration of functions
  - Quadrature mirror filter 585, 593
  - Quantum mechanics, Uncertainty Principle 600
  - Quartile value 320
  - Quasi-Newton methods for minimization 390, 418ff., 1215
  - Quasi-random sequence 299ff., 318, 881, 888
    - Halton's 300
    - for Monte Carlo integration 304, 309, 318
    - Sobol's 300ff., 1160
    - see also* Random number generator
  - Quicksort 320, 323ff., 330, 333, 1169f.
  - Quotient-difference algorithm 164
- R**-estimates 694
- Radioactive decay 278
  - Radix base for floating point arithmetic 476, 882, 907, 913, 1231, 1343, 1357
  - Radix conversion 902, 906, 913, 1357
  - radix() intrinsic function 1231
  - Radix sort 1172
  - Ramanujan's identity for  $\pi$  915
  - Random bits, generation of 287ff., 1159f.
  - Random deviates 266ff., 1141ff.
    - binomial 285f., 1155
    - exponential 278, 1151f.
    - gamma distribution 282f., 1153
    - Gaussian 267, 279f., 571, 798, 1152f.
    - normal 267, 279f., 571, 1152f.
    - Poisson 283ff., 571, 1154f.
    - quasi-random sequences 299ff., 881, 888, 1160f.
    - uniform 267ff., 1158f., 1166
    - uniform integer 270, 274ff.
  - Random number generator 266ff., 1141ff.
    - bitwise operations 287
    - Box-Muller algorithm 279, 1152
    - Data Encryption Standard 290ff., 1144, 1156ff.
    - good choices for modulus, multiplier and increment 274ff.
    - initializing 1144ff.
    - for integer-valued probability distribution 283f., 1154
    - integer vs. real implementation 273
    - L'Ecuyer's long period 271f.
    - lagged Fibonacci generator 1142, 1148ff.
    - linear congruential generator 267ff., 1142
    - machine language 269
    - Marsaglia shift register 1142, 1148ff.
    - Minimal Standard, Park and Miller's 269, 1142
    - nonrandomness of low-order bits 268f.
    - parallel 1009
    - perfect 272, 1141, 1150f.
    - planes, numbers lie on 268
    - portable 269ff., 1142
    - primitive polynomials modulo 2 287ff.
    - pseudo-DES 291, 1144, 1156ff.
    - quasi-random sequences 299ff., 881, 888, 1160f.
    - quick and dirty 274
    - quicker and dirtier 275
    - in Quicksort 324
    - random access to  $n$ th number 293

- random bits 287ff., 1159f.
- recommendations 276f.
- rejection method 281ff.
- serial 1141f.
- shuffling procedure 270, 272
- in simulated annealing method 438
- spectral test 274
- state space 1143f.
- state space exhaustion 1141
- subtractive method 273, 1143
- system-supplied 267f.
- timings 276f., 1151
- transformation method 277ff.
- trick for trigonometric functions 280
- Random numbers *see* Monte Carlo; Random deviates
- Random walk 20
- random\_number() intrinsic function 1141, 1143
- random\_seed() intrinsic function 1141
- RANDU, infamous routine 268
- Range 53f.
- Rank (matrix) 53
  - kernel of finite 785
- Rank (sorting) 320, 332, 1176
- Rank (statistics) 633ff., 694f., 1277
  - Kendall's tau 637ff., 1279
  - Spearman correlation coefficient 634f., 1277ff.
  - sum squared differences of 634, 1277
- Ratio variable (statistics) 623
- Rational Chebyshev approximation 197ff., 1081f.
- Rational function 99, 167ff., 194ff., 1080f.
  - approximation for Bessel functions 225
  - approximation for continued fraction 164, 211, 219f.
  - Chebyshev approximation 197ff., 1081f.
  - evaluation of 170, 1072f.
  - extrapolation in Bulirsch-Stoer method 718ff., 726, 1306f.
  - interpolation and extrapolation using 99, 104ff., 194ff., 718ff., 726
  - as power spectrum estimate 566
  - interpolation and extrapolation using 1043f., 1080ff., 1306
  - minimax 198
- Re-entrant procedure 1052
- real() intrinsic function, ambiguity of 947
- Realizable (causal) 552, 554f.
- reallocate() utility function 955, 990, 992, 1070, 1302
- Rearranging *see* Sorting
- Reciprocal, multiple precision 910f., 1355f.
- Record, in data file 329
- Recurrence relation 172ff., 971ff.
  - arithmetic progression 971f., 996
  - associated Legendre polynomials 247
  - Bessel function 172, 224, 227f., 234
  - binomial coefficients 209
  - Bulirsch-Stoer 105f.
  - characteristic polynomial of tridiagonal matrix 469
  - Clenshaw's recurrence formula 176f.
  - and continued fraction 175
  - continued fraction evaluation 164f.
  - convergence 175
  - cosine function 172, 500
  - cyclic reduction 974
  - dominant solution 174
  - exponential integrals 172
  - gamma function 206
  - generation of random bits 287f.
  - geometric progression 972, 996
  - Golden Mean 21
  - Legendre polynomials 172
  - minimal vs. dominant solution 174
  - modified Bessel function 232
  - Neville's 103, 182
  - orthonormal polynomials 142
  - Perron's theorems 174f.
  - Pincherle's theorem 175
  - for polynomial cumulants 977, 999, 1071f.
  - polynomial interpolation 103, 183
  - primitive polynomials modulo 2 287f.
  - random number generator 268
  - rational function interpolation 105f., 1043
  - recursive doubling 973, 977, 988, 999, 1071f., 1073
  - second order 974f., 1074
  - sequence of trig functions 173
  - sine function 172, 500
  - spherical harmonics 247
  - stability of 21, 173ff., 177, 224f., 227f., 232, 247, 975
  - trig functions 572
  - weight of Gaussian quadrature 144f.
- Recursion
  - in Fortran 90 958
  - in multigrid method 865, 1009, 1336
- Recursive doubling 973f., 979
  - cumulants of polynomial 977, 999, 1071f.
  - linear recurrences 973, 988, 1073
  - tridiagonal systems 976
- RECURSIVE keyword 958, 1065, 1067
- Recursive Monte Carlo integration 306ff., 1161
- Recursive procedure 2/xiv, 958, 1065, 1067, 1166
  - as parallelization tool 958
  - base case 958
  - for multigrid method 1009, 1336
  - re-entrant 1052
- Recursive stratified sampling 314ff., 1164ff.
- Red-black *see* Odd-even ordering
- Reduction functions 948ff.
- Reduction of variance in Monte Carlo integration 299, 306ff.
- References (explanation) 4f.
- References (general bibliography) 916ff., 1359f.
- Reflection formula for gamma function 206
- Regula falsi (false position) 347ff., 1185f.
- Regularity condition 775
- Regularization
  - compared with optimal filtering 801
  - constrained linear inversion method 799ff.
  - of inverse problems 796ff.
  - linear 799ff.
  - nonlinear 813

- objective criterion 802  
 Phillips-Twomey method 799ff.  
 Tikhonov-Miller 799ff.  
 trade-off curve 799  
 two-dimensional 803  
 zeroth order 797  
*see also* Inverse problems
- Regularizing operator 798
- Reid, John 2/xiv, 2/xvi
- Rejection method for random number generator 281ff.
- Relaxation method
  - for algebraically difficult sets 763
  - automated allocation of mesh points 774f., 777
  - computation of spheroidal harmonics 764ff., 1319ff.
  - for differential equations 746f., 753ff., 1316ff.
  - elliptic partial differential equations 823, 854ff., 1332f.
  - example 764ff., 1319ff.
  - Gauss-Seidel method 855, 864ff., 876, 1338, 1341
  - internal boundary conditions 775ff.
  - internal singular points 775ff.
  - Jacobi's method 855f., 864
  - successive over-relaxation (SOR) 857ff., 862, 866, 1332f.
  - see also* Multigrid method
- Remes algorithms
  - exchange algorithm 553
  - for minimax rational function 199
- reshape() intrinsic function 950
  - communication bottleneck 969
  - order keyword 1050, 1246
- Residual 49, 54, 78
  - in multigrid method 863, 1338
- Resolution function, in Backus-Gilbert method 807
- Response function 531
- Restriction operator 864, 1337
- RESULT keyword 958, 1073
- Reward, \$1000 offered 272, 1141, 1150f.
- Richardson's deferred approach to the limit 134, 137, 182, 702, 718ff., 726, 788, 869
  - see also* Bulirsch-Stoer method
- Richtmyer artificial viscosity 837
- Ridders' method, for numerical derivatives 182, 1075
- Ridders' method, root finding 341, 349, 351, 1187
- Riemann shock problem 837
- Right eigenvalues and eigenvectors 451
- Rise/fall time 548f.
- Robust estimation 653, 694ff., 700, 1294
  - Andrew's sine 697
  - average deviation 605
  - double exponential errors 696
  - Kalman filtering 700
  - Lorentzian errors 696f.
  - mean absolute deviation 605
  - nonparametric correlation 633ff., 1277
  - Tukey's biweight 697
  - use of a priori covariances 700
  - see also* Statistical tests
- Romberg integration 124, 134f., 137, 182, 717, 788, 1054f., 1065
- Root finding 143, 340ff., 1009, 1059
  - advanced implementations of Newton's rule 386
  - Bairstow's method 364, 370, 1193
  - bisection 343, 346f., 352f., 359, 390, 469, 698, 1184f.
  - bracketing of roots 341, 343ff., 353f., 362, 364, 369, 1183f.
  - Brent's method 341, 349, 660f., 1188f., 1286
  - Broyden's method 373, 382f., 386, 1199
  - compared with multidimensional minimization 375
  - complex analytic functions 364
  - in complex plane 204
  - convergence criteria 347, 374
  - deflation of polynomials 362ff., 370f., 1192
  - without derivatives 354
  - double root 341
  - eigenvalue methods 368, 1193
  - false position 347ff., 1185f.
  - Jenkins-Traub method 369
  - Laguerre's method 341, 366f., 1191f.
  - Lehmer-Schur algorithm 369
  - Maehly's procedure 364, 371
  - matrix method 368, 1193
  - Muller's method 364, 372
  - multiple roots 341
  - Newton's rule 143f., 180, 341, 355ff., 362, 364, 370, 372ff., 376, 469, 740, 749f., 754, 787, 874, 876, 911f., 1059, 1189, 1194, 1196, 1314ff., 1339, 1341, 1355f.
  - pathological cases 343, 356, 362, 372
  - polynomials 341, 362ff., 449, 1191f.
  - in relaxation method 754, 1316
  - Ridders' method 341, 349, 351, 1187
  - root-polishing 356, 363ff., 369ff., 1193
  - safe Newton's rule 359, 1190
  - secant method 347ff., 358, 364, 399, 1186f.
  - in shooting method 746, 749f., 1314f.
  - singular Jacobian in Newton's rule 386
  - stopping criterion for polynomials 366
  - use of minimum finding 341
  - using derivatives 355ff., 1189
  - zero suppression 372
  - see also* Roots
- Root polishing 356, 363ff., 369ff., 1193
- Roots
  - Chebyshev polynomials 184
  - complex  $n$ th root of unity 999f., 1379
  - cubic equations 179f.
  - Hermite polynomials, approximate 1062
  - Jacobi polynomials, approximate 1064
  - Laguerre polynomials, approximate 1061
  - multiple 341, 364ff., 1192
  - nonlinear equations 340ff.
  - polynomials 341, 362ff., 449, 1191f.
  - quadratic equations 178

- reflection in unit circle 560, 1257
  - square, multiple precision 912, 1356
  - see also* Root finding
  - Rosenbrock method 730, 1308
    - compared with semi-implicit extrapolation 739
    - stepsize control 731, 1308f.
  - Roundoff error 20, 881, 1362
    - bracketing a minimum 399
    - compile time vs. run time 1012
    - conjugate gradient method 824
    - eigensystems 458, 467, 470, 473, 476, 479, 483
    - extended trapezoidal rule 132
    - general linear least squares 668, 672
    - graceful 883, 1343
    - hardware aspects 882, 1343
    - Householder reduction 466
    - IEEE standard 882f., 1343
    - interpolation 100
    - least squares fitting 658, 668
    - Levenberg-Marquardt method 679
    - linear algebraic equations 23, 27, 29, 47, 56, 84, 1022
    - linear predictive coding (LPC) 564
    - magnification of 20, 47, 1022
    - maximum entropy method (MEM) 567
    - measuring 881f., 1343
    - multidimensional minimization 418, 422
    - multiple roots 362
    - numerical derivatives 180f.
    - recurrence relations 173
    - reduction to Hessenberg form 479
    - series 164f.
    - straight line fitting 658
    - variance 607
  - Row degeneracy 22
  - Row-indexed sparse storage 71f., 1030
    - transpose 73f.
  - Row operations on matrix 28, 31f.
  - Row totals 624
  - RSS algorithm 314ff., 1164
  - RST properties (reflexive, symmetric, transitive) 338
  - Runge-Kutta method 702, 704ff., 731, 740, 1297ff., 1308
    - Cash-Karp parameters 710, 1299f.
    - embedded 709f., 731, 1298, 1308
    - high-order 705
    - quality control 722
    - stepsize control 708ff.
  - Run-length encoding 901
  - Runge-Kutta method
    - high-order 1297
    - stepsize control 1298f.
  - Rybicki, G.B. 84ff., 114, 145, 252, 522, 574, 600
- S**-box for Data Encryption Standard 1148
- Sampling
  - importance 306f.
  - Latin square or hypercube 305f.
  - recursive stratified 314ff., 1164
  - stratified 308f.
  - uneven or irregular 569, 648f., 1258
- Sampling theorem 495, 543
  - for numerical approximation 600ff.
- Sande-Tukey FFT algorithm 503
- SAVE attribute 953f., 958f., 961, 1052, 1070, 1266, 1293
  - redundant use of 958f.
- SAVE statements 3
- Savitzky-Golay filters
  - for data smoothing 644ff., 1283f.
  - for numerical derivatives 183, 645
- scale() intrinsic function 1107
- Scalloped loss 548
- Scatter-with-combine functions 984, 1002f., 1032, 1366, 1380f.
- scatter\_add() utility function 984, 990, 1002, 1032
- scatter\_max() utility function 984, 990, 1003
- Schonfelder, Lawrie 2/xi
- Schrage's algorithm 269
- Schrödinger equation 842ff.
- Schultz's method for matrix inverse 49, 598
- Scope 956ff., 1209, 1293, 1296
- Scoping unit 939
- SDLC checksum 890
- Searching
  - with correlated values 111, 1046f.
  - an ordered table 110f., 1045f.
  - selection 333, 1177f.
- Secant method 341, 347ff., 358, 364, 399, 1186f.
  - Broyden's method 382f., 1199f.
  - multidimensional (Broyden's) 373, 382f., 1199
- Second Euler-Maclaurin summation formula 135f.
- Second order differential equations 726, 1307
- Seed of random number generator 267, 1146f.
- select case statement 2/xiv, 1010, 1036
- Selection 320, 333, 1177f.
  - find  $m$  largest elements 336, 1179f.
  - heap algorithm 336, 1179
  - for median 698, 1294
  - operation count 333
  - by packing 1178
  - parallel algorithms 1178
  - by partition-exchange 333, 1177f.
  - without rearrangement 335, 1178f.
  - timings 336
  - use to find median 609
- Semi-implicit Euler method 730, 735f.
- Semi-implicit extrapolation method 730, 735f., 1310f.
  - compared with Rosenbrock method 739
  - stepsize control 737, 1311f.
- Semi-implicit midpoint rule 735f., 1310f.
- Semi-invariants of a distribution 608
- Sentinel, in Quicksort 324, 333
- Separable kernel 785
- Separation of variables 246
- Serial computing
  - convergence of quadrature 1060
  - random numbers 1141
  - sorting 1167
- Serial data port 892

- Series 159ff.  
 accelerating convergence of 159ff.  
 alternating 160f., 1070  
 asymptotic 161  
 Bessel function  $K_\nu$  241  
 Bessel function  $Y_\nu$  235  
 Bessel functions 160, 223  
 cosine integral 250  
 divergent 161  
 economization 192f., 195, 1080  
 Euler's transformation 160f., 1070  
 exponential integral 216, 218  
 Fresnel integral 248  
 hypergeometric 202, 263, 1138  
 incomplete beta function 219  
 incomplete gamma function 210, 1090f.  
 Laurent 566  
 relation to continued fractions 163f.  
 roundoff error in 164f.  
 sine and cosine integrals 250  
 sine function 160  
 Taylor 355f., 408, 702, 709, 754, 759  
 transformation of 160f., 1070  
 van Wijngaarden's algorithm 161, 1070
- Shaft encoder 886
- Shakespeare 9
- Shampine's Rosenbrock parameters 732, 1308
- shape() intrinsic function 938, 949
- Shell algorithm (Shell's sort) 321ff., 1168
- Sherman-Morrison formula 65ff., 83, 382
- Shifting of eigenvalues 449, 470f., 480
- Shock wave 831, 837
- Shooting method  
 computation of spheroidal harmonics 772, 1321ff.  
 for differential equations 746, 749ff., 770ff., 1314ff., 1321ff.  
 for difficult cases 753, 1315f.  
 example 770ff., 1321ff.  
 interior fitting point 752, 1315f., 1323ff.
- Shuffling to improve random number generator 270, 272
- Side effects  
 prevented by data hiding 957, 1209, 1293, 1296  
 and PURE subprograms 960
- Sidelobe fall-off 548
- Sidelobe level 548
- sign() intrinsic function, modified in Fortran 95 961
- Signal, bandwidth limited 495
- Significance (numerical) 19
- Significance (statistical) 609f.  
 one- vs. two-sided 632  
 peak in Lomb periodogram 570  
 of 2-d K-S test 640, 1281  
 two-tailed 613
- SIMD machines (Single Instruction Multiple Data) 964, 985f., 1009, 1084f.
- Similarity transform 452ff., 456, 476, 478, 482
- Simplex  
 defined 402  
 method in linear programming 389, 402, 423ff., 431ff., 1216ff.  
 method of Nelder and Mead 389, 402ff., 444, 697f., 1208f., 1222ff.  
 use in simulated annealing 444, 1222ff.
- Simpson's rule 124ff., 128, 133, 136f., 583, 782, 788f., 1053f.
- Simpson's three-eighths rule 126, 789f.
- Simulated annealing *see* Annealing, method of simulated
- Simulation *see* Monte Carlo
- Sine function  
 evaluated from  $\tan(\theta/2)$  173  
 recurrence 172  
 series 160
- Sine integral 248, 250ff., 1123, 1125f.  
 continued fraction 250  
 series 250  
*see also* Cosine integral
- Sine transform *see* Fast Fourier transform (FFT); Fourier transform
- Singleton's algorithm for FFT 525
- Singular value decomposition (SVD) 23, 25, 51ff., 1022  
 approximation of matrices 58f.  
 backsubstitution 56, 1022f.  
 and bases for nullspace and range 53  
 confidence levels from 693f.  
 covariance matrix 693f.  
 fewer equations than unknowns 57  
 for inverse problems 797  
 and least squares 54ff., 199f., 668, 670ff., 1081, 1290f.  
 in minimization 410  
 more equations than unknowns 57f.  
 parallel algorithms 1026  
 and rational Chebyshev approximation 199f., 1081f.  
 of square matrix 53ff., 1023  
 use for ill-conditioned matrices 56, 58, 449  
 use for orthonormal basis 58, 94
- Singularities  
 of hypergeometric function 203, 263  
 in integral equations 788ff., 1328  
 in integral equations, worked example 792, 1328ff.  
 in integrands 135ff., 788, 1055, 1328ff.  
 removal in numerical integration 137ff., 788, 1057ff., 1328ff.
- Singularity, subtraction of the 789
- SIPSOL 824
- Six-step framework, for FFT 983, 1240
- size() intrinsic function 938, 942, 945, 948
- Skew array section 2/xii, 945, 960, 985, 1284
- Skewness of distribution 606, 608, 1269
- Smoothering  
 of data 114, 644ff., 1283f.  
 of data in integral equations 781  
 importance in multigrid method 865
- sn function 261, 1137f.
- Snyder, N.L. 1/xvi
- Sobol's quasi-random sequence 300ff., 1160f.
- Sonata 9
- Sonnet 9
- Sorting 320ff., 1167ff.  
 bubble sort 1168

- bubble sort cautioned against 321
- compared to selection 333
- covariance matrix 669, 681, 1289
- eigenvectors 461f., 1227
- Heapsort 320, 327f., 336, 1171f., 1179
- index table 320, 329f., 1170, 1173ff., 1176
- operation count 320ff.
- by packing 1171
- parallel algorithms 1168, 1171f., 1176
- Quicksort 320, 323ff., 330, 333, 1169f.
- radix sort 1172
- rank table 320, 332, 1176
- ranking 329, 1176
- by reshaping array slices 1168
- Shell's method 321f., 1168
- straight insertion 321f., 461f., 1167, 1227
- SP, defined 937
- SPARC or SPARCstation 1/xxii, 2/xix, 4
- Sparse linear equations 23, 63ff., 732, 1030
  - band diagonal 43, 1019ff.
  - biconjugate gradient method 77, 599, 1034
  - data type for 1030
  - indexed storage 71f., 1030
  - in inverse problems 804
  - minimum residual method 78
  - named patterns 64, 822
  - partial differential equations 822ff.
  - relaxation method for boundary value problems 754, 1316
  - row-indexed storage 71f., 1030
  - wavelet transform 584, 598
  - see also* Matrix
- Spearman rank-order coefficient 634f., 694f., 1277
- Special functions *see* Function
- Spectral analysis *see* Fourier transform; Periodogram
- Spectral density 541
  - and data windowing 545ff.
  - figures of merit for data windows 548f.
  - normalization conventions 542f.
  - one-sided PSD 492
  - periodogram 543ff., 566, 1258ff.
  - power spectral density (PSD) 492f.
  - power spectral density per unit time 493
  - power spectrum estimation by FFT 542ff., 1254ff.
  - power spectrum estimation by MEM 565ff., 1258
  - two-sided PSD 493
  - variance reduction in spectral estimation 545
- Spectral lines, how to smooth 644
- Spectral methods for partial differential equations 825
- Spectral radius 856ff., 862
- Spectral test for random number generator 274
- Spectrum *see* Fourier transform
- Spherical Bessel functions 234
  - routine for 245, 1121
- Spherical harmonics 246ff.
  - orthogonality 246
  - routine for 247f., 1122
  - stable recurrence for 247
  - table of 246
  - see also* Associated Legendre polynomials
- Spheroidal harmonics 764ff., 770ff., 1319ff.
  - boundary conditions 765
  - normalization 765
  - routine for 768ff., 1319ff., 1323ff.
- Spline 100
  - cubic 107ff., 1044f.
  - gives tridiagonal system 109
  - natural 109, 1044f.
  - operation count 109
  - two-dimensional (bicubic) 120f., 1050f.
- spread() intrinsic function 945, 950, 969, 1000, 1094, 1290f.
  - and dimensional expansion 966ff.
- Spread matrix 808
- Spread spectrum 290
- Square root, complex 172
- Square root, multiple precision 912, 1356f.
- Square window 546, 1254ff.
- SSP (small-scale parallel) machines 965ff., 972, 974, 984, 1011, 1016ff., 1021, 1059f., 1226ff., 1250
- Stability 20f.
  - of Clenshaw's recurrence 177
  - Courant condition 829, 832ff., 836, 846
  - diffusion equation 840
  - of Gauss-Jordan elimination 27, 29
  - of implicit differencing 729, 840
  - mesh-drift in PDEs 834f.
  - nonlinear 831, 837
  - partial differential equations 820, 827f.
  - of polynomial deflation 363
  - in quadrature solution of Volterra equation 787f.
  - of recurrence relations 173ff., 177, 224f., 227f., 232, 247
  - and stiff differential equations 728f.
  - von Neumann analysis for PDEs 827f., 830, 833f., 840
  - see also* Accuracy
- Stabilized Kolmogorov-Smirnov test 621
- Stabilizing functional 798
- Staggered leapfrog method 833f.
- Standard (probable) errors 1288, 1290
- Standard deviation
  - of a distribution 605, 1269
  - of Fisher's z 632
  - of linear correlation coefficient 630
  - of sum squared difference of ranks 635, 1277
- Standard (probable) errors 610, 656, 661, 667, 671, 684
- Stars, as text separator 1009
- Statement function, superseded by internal subprogram 1057, 1256
- Statement labels 9
- Statistical error 653
- Statistical tests 603ff., 1269ff.
  - Anderson-Darling 621
  - average deviation 605, 1269
  - bootstrap method 686f.
  - chi-square 614f., 623ff., 1272, 1275f.



- contingency coefficient  $C$  625, 1275  
contingency tables 622ff., 638, 1275f.  
correlation 603f.  
Cramer's  $V$  625, 1275  
difference of distributions 614ff., 1272  
difference of means 609ff., 1269f.  
difference of variances 611, 613, 1271  
entropy measures of association 626ff., 1275f.  
F-test 611, 613, 1271  
Fisher's  $z$ -transformation 631f., 1276  
general paradigm 603  
Kendall's tau 634, 637ff., 1279  
Kolmogorov-Smirnov 614, 617ff., 640, 694, 1273f., 1281  
Kuiper's statistic 621  
kurtosis 606, 608, 1269  
L-estimates 694  
linear correlation coefficient 630ff., 1276  
M-estimates 694ff.  
mean 603ff., 608ff., 1269f.  
measures of association 604, 622ff., 1275  
measures of central tendency 604ff., 1269  
median 605, 694  
mode 605  
moments 604ff., 608, 1269  
nonparametric correlation 633ff., 1277  
Pearson's  $r$  630ff., 1276  
for periodic signal 570  
phi statistic 625  
R-estimates 694  
rank correlation 633ff., 1277  
robust 605, 634, 694ff.  
semi-invariants 608  
for shift vs. for spread 620f.  
significance 609f., 1269ff.  
significance, one- vs. two-sided 613, 632  
skewness 606, 608, 1269  
Spearman rank-order coefficient 634f., 694f., 1277  
standard deviation 605, 1269  
strength vs. significance 609f., 622  
Student's  $t$  610, 631, 1269  
Student's  $t$ , for correlation 631  
Student's  $t$ , paired samples 612, 1271  
Student's  $t$ , Spearman rank-order coefficient 634, 1277  
Student's  $t$ , unequal variances 611, 1270  
sum squared difference of ranks 635, 1277  
Tukey's trimean 694  
two-dimensional 640, 1281ff.  
variance 603ff., 607f., 612f., 1269ff.  
Wilcoxon 694  
*see also* Error; Robust estimation
- Steak, without sizzle 809
- Steed's method  
Bessel functions 234, 239  
continued fractions 164f.
- Steepest descent method 414  
in inverse problems 804
- Step  
doubling 130, 708f., 1052  
tripling 136, 1055
- Stieltjes, procedure of 151
- Stiff equations 703, 727ff., 1308ff.  
Kaps-Rentrop method 730, 1308  
methods compared 739  
predictor-corrector method 730  
r.h.s. independent of  $x$  729f.  
Rosenbrock method 730, 1308  
scaling of variables 730  
semi-implicit extrapolation method 730, 1310f.  
semi-implicit midpoint rule 735f., 1310f.
- Stiff functions 100, 399
- Stirling's approximation 206, 812
- Stoermer's rule 726, 1307
- Stopping criterion, in multigrid method 875f.
- Stopping criterion, in polynomial root finding 366
- Storage  
band diagonal matrix 44, 1019  
sparse matrices 71f., 1030
- Storage association 2/xiv
- Straight injection 867
- Straight insertion 321f., 461f., 1167, 1227
- Straight line fitting 655ff., 667f., 1285ff.  
errors in both coordinates 660ff., 1286ff.  
robust estimation 698, 1294ff.
- Strassen's fast matrix algorithms 96f.
- Stratified sampling, Monte Carlo 308f., 314
- Stride (of an array) 944  
communication bottleneck 969
- Strongly implicit procedure (SIPSOL) 824
- Structure constructor 2/xii
- Structured programming 5ff.
- Student's probability distribution 221f.
- Student's  $t$ -test  
for correlation 631  
for difference of means 610, 1269  
for difference of means (paired samples) 612, 1271  
for difference of means (unequal variances) 611, 1270  
for difference of ranks 635, 1277  
Spearman rank-order coefficient 634, 1277
- Sturmian sequence 469
- Sub-random sequences *see* Quasi-random sequence
- Subprogram 938  
for data hiding 957, 1209, 1293, 1296  
internal 954, 957, 1057, 1067, 1226, 1256  
in module 940  
undefined variables on exit 952f., 961, 1070, 1266, 1293, 1302
- Subscript triplet (for array) 944
- Subtraction, multiple precision 907, 1353
- Subtractive method for random number generator 273, 1143
- Subvector scaling 972, 974, 996, 1000
- Successive over-relaxation (SOR) 857ff., 862, 1332f.  
bad in multigrid method 866  
Chebyshev acceleration 859f., 1332f.  
choice of overrelaxation parameter 858  
with logical mask 1333f.  
parallelization 1333
- sum() intrinsic function 945, 948, 966

- Sum squared difference of ranks 634, 1277  
 Sums *see* Series  
 Sun 1/xxii, 2/xix, 886  
   SPARCstation 1/xxii, 2/xix, 4  
 Supernova 1987A 640  
 SVD *see* Singular value decomposition (SVD)  
 swap() utility function 987, 990f., 1015, 1210  
 Symbol, of operator 866f.  
 Synthetic division 84, 167, 362, 370  
   parallel algorithms 977ff., 999, 1048,  
     1071f., 1079, 1192  
   repeated 978f.  
 Systematic errors 653
- T**ableau (interpolation) 103, 183  
 Tangent function, continued fraction 163  
 Target, for pointer 938f., 945, 952f.  
 Taylor series 180, 355f., 408, 702, 709, 742,  
   754, 759  
 Test programs 3  
 Thermodynamics, analogy for simulated an-  
   nealing 437  
 Thinking Machines, Inc. 964  
 Threshold multiply of sparse matrices 74,  
   1031  
 Tides 560f.  
 Tikhonov-Miller regularization 799ff.  
 Time domain 490  
 Time splitting 847f., 861  
 tiny() intrinsic function 952  
 Toeplitz matrix 82, 85ff., 195, 1038  
   LU decomposition 87  
   new, fast algorithms 88f.  
   nonsymmetric 86ff., 1038  
 Tongue twisters 333  
 Torus 297f., 304  
 Trade-off curve 795, 809  
 Trademarks 1/xxii, 2/xixf.  
 Transformation  
   Gauss 256  
   Landen 256  
   method for random number generator 277ff.  
 Transformational functions 948ff.  
 Transforms, number theoretic 503f.  
 Transport error 831ff.  
 transpose() intrinsic function 950, 960, 969,  
   981, 1050, 1246  
 Transpose of sparse matrix 73f.  
 Trapezoidal rule 125, 127, 130ff., 134f., 579,  
   583, 782, 786, 1052, 1326f.  
 Traveling salesman problem 438ff., 1219ff.  
 Tridiagonal matrix 42, 63, 150, 453f., 488,  
   839f., 1018f.  
   in alternating-direction implicit method  
     (ADI) 861f.  
   from cubic spline 109  
   cyclic 67, 1030  
   in cyclic reduction 853  
   eigenvalues 469ff., 1228  
   with fringes 822  
   from operator splitting 861f.  
   parallel algorithm 975, 1018, 1229f.  
   recursive splitting 1229f.  
   reduction of symmetric matrix to 462ff.,  
     470, 1227f.
- serial algorithm 1018f.  
*see also* Matrix
- Trigonometric  
 functions, linear sequences 173  
 functions, recurrence relation 172, 572  
 functions,  $\tan(\theta/2)$  as minimal 173  
 interpolation 99  
 solution of cubic equation 179f.
- Truncation error 20f., 399, 709, 881, 1362  
 in multigrid method 875  
 in numerical derivatives 180
- Tukey's biweight 697  
 Tukey's trimean 694  
 Turbo Pascal (Borland) 8  
 Twin errors 895
- Two-dimensional *see* Multidimensional  
 Two-dimensional K-S test 640, 1281ff.  
 Two-pass algorithm for variance 607, 1269  
 Two-point boundary value problems 702,  
   745ff., 1314ff.  
   automated allocation of mesh points 774f.,  
     777  
   boundary conditions 745ff., 749, 751f.,  
     771, 1314ff.  
   difficult cases 753, 1315f.  
   eigenvalue problem for differential equa-  
     tions 748, 764ff., 770ff., 1319ff.  
   free boundary problem 748, 776  
   grid (mesh) points 746f., 754, 774f., 777  
   internal boundary conditions 775ff.  
   internal singular points 775ff.  
   linear requires no iteration 751  
   multiple shooting 753  
   problems reducible to standard form 748  
   regularity condition 775  
   relaxation method 746f., 753ff., 1316ff.  
   relaxation method, example of 764ff.,  
     1319  
   shooting to a fitting point 751ff., 1315f.,  
     1323ff.  
   shooting method 746, 749ff., 770ff., 1314ff.,  
     1321ff.  
   shooting method, example of 770ff., 1321ff.  
   singular endpoints 751, 764, 771, 1315f.,  
     1319ff.  
   *see also* Elliptic partial differential equa-  
     tions
- Two-sided exponential error distribution 696  
 Two-sided power spectral density 493  
 Two-step Lax-Wendroff method 835ff.  
 Two-volume edition, plan of 1/xiii  
 Two's complement arithmetic 1144  
 Type declarations, explicit vs. implicit 2
- U**bound() intrinsic function 949  
 ULTRIX 1/xxiii, 2/xix  
 Uncertainty coefficient 628  
 Uncertainty principle 600  
 Undefined status, of arrays and pointers 952f.,  
   961, 1070, 1266, 1293, 1302  
 Underflow, in IEEE arithmetic 883, 1343  
 Underrelaxation 857  
 Uniform deviates *see* Random deviates, uni-  
   form

- Unitary (function) 843f.  
 Unitary (matrix) *see* Matrix  
 unit<sub>u</sub>matrix() utility function 985, 990, 1006, 1216, 1226, 1325  
 UNIX 1/xxiii, 2/viii, 2/xix, 4, 17, 276, 293, 886  
 Upper Hessenberg matrix *see* Hessenberg matrix  
 U.S. Postal Service barcode 894  
 unpack() intrinsic function 950, 964  
 communication bottleneck 969  
 Upper subscript 944  
 upper<sub>u</sub>triangle() utility function 990, 1006, 1226, 1305  
 Upwind differencing 832f., 837  
 USE statement 936, 939f., 954, 957, 1067, 1384  
 USES keyword in program listings 2  
 Utility functions 987ff., 1364ff.  
 add vector to matrix diagonal 1004, 1234, 1366, 1381  
 alphabetical listing 988ff.  
 argument checking 994f., 1370f.  
 arithmetic progression 996, 1072, 1127, 1365, 1371f.  
 array reallocation 992, 1070f., 1365, 1368f.  
 assertion of numerical equality 995, 1022, 1365, 1370f.  
 compared to intrinsics 990ff.  
 complex *n*th root of unity 999f., 1379  
 copying arrays 991, 1034, 1327f., 1365f.  
 create unit matrix 1006, 1382  
 cumulative product of an array 997f., 1072, 1086, 1375  
 cumulative sum of an array 997, 1280f., 1365, 1375  
 data types 1361  
 elemental functions 1364  
 error handling 994f., 1036, 1370f.  
 generic functions 1364  
 geometric progression 996f., 1365, 1372ff.  
 get diagonal of matrix 1005, 1226f., 1366, 1381f.  
 length of a vector 1008, 1383  
 linear recurrence 996  
 location in an array 992ff., 1015, 1017ff.  
 location of first logical “true” 993, 1041, 1369  
 location of maximum array value 993, 1015, 1017, 1365, 1369  
 location of minimum array value 993, 1369f.  
 logical assertion 994, 1086, 1090, 1092, 1365, 1370  
 lower triangular mask 1007, 1200, 1382  
 masked polynomial evaluation 1378  
 masked swap of elements in two arrays 1368  
 moving data 990ff., 1015  
 multiply vector into matrix diagonal 1004f., 1366, 1381  
 nrutil.f90 (module file) 1364ff.  
 outer difference of vectors 1001, 1366, 1380  
 outer logical and of vectors 1002  
 outer operations on vectors 1000ff., 1379f.  
 outer product of vectors 1000f., 1076, 1365f., 1379  
 outer quotient of vectors 1001, 1379  
 outer sum of vectors 1001, 1379f.  
 overloading 1364  
 partial cumulants of a polynomial 999, 1071, 1192f., 1365, 1378f.  
 polynomial evaluation 996, 998f., 1258, 1365, 1376ff.  
 scatter-with-add 1002f., 1032f., 1366, 1380f.  
 scatter-with-combine 1002f., 1032f., 1380f.  
 scatter-with-max 1003f., 1366, 1381  
 set diagonal elements of matrix 1005, 1200, 1366, 1382  
 skew operation on matrices 1004ff., 1381ff.  
 swap elements of two arrays 991, 1015, 1365ff.  
 upper triangular mask 1006, 1226, 1305, 1382
- V**-cycle 865, 1336  
 vabs() utility function 990, 1008, 1290  
 Validation of Numerical Recipes procedures 3f.  
 Valley, long or narrow 403, 407, 410  
 Van Cittert’s method 804  
 Van Wijngaarden-Dekker-Brent method *see* Brent’s method  
 Vandermonde matrix 82ff., 114, 1037, 1047  
 Variable length code 896, 1346ff.  
 Variable metric method 390, 418ff., 1215  
 compared to conjugate gradient method 418  
 Variable step-size integration 123, 135, 703, 707ff., 720, 726, 731, 737, 742ff., 1298ff., 1303, 1308f., 1311ff.
- Variance(s)  
 correlation 605  
 of distribution 603ff., 608, 611, 613, 1269  
 pooled 610  
 reduction of (in Monte Carlo) 299, 306ff.  
 statistical differences between two 609, 1271  
 two-pass algorithm for computing 607, 1269  
*see also* Covariance
- Variational methods, partial differential equations 824  
 VAX 275, 293  
 Vector(s)  
 length 1008, 1383  
 norms 1036  
 outer difference 1001, 1366, 1380  
 outer operations 1000ff., 1379f.  
 outer product 1000f., 1076, 1365f., 1379  
 Vector reduction 972, 977, 998  
 Vector subscripts 2/xiif., 984, 1002, 1032, 1034  
 communication bottleneck 969, 981, 1250  
 VEGAS algorithm for Monte Carlo 309ff., 1161  
 Verhoeff’s algorithm for checksums 894f., 1345

- Viète's formulas for cubic roots 179  
 Vienna Fortran 2/xv  
 Virus, computer 889  
 Viscosity  
   artificial 831, 837  
   numerical 830f., 837  
 Visibility 956ff., 1209, 1293, 1296  
 VMS 1/xxii, 2/xix  
 Volterra equations 780f., 1326  
   adaptive stepsize control 788  
   analogy with ODEs 786  
   block-by-block method 788  
   first kind 781, 786  
   nonlinear 781, 787  
   second kind 781, 786ff., 1326f.  
   unstable quadrature 787f.  
 von Neuman, John 963, 965  
 von Neumann-Richtmyer artificial viscosity 837  
 von Neumann stability analysis for PDEs 827f., 830, 833f., 840  
 Vowellish (coding example) 896f., 902
- W**-cycle 865, 1336  
 Warranty, disclaimer of 1/xx, 2/xvii  
 Wave equation 246, 818, 825f.  
 Wavelet transform 584ff., 1264ff.  
   appearance of wavelets 590ff.  
   approximation condition of order  $p$  585  
   coefficient values 586, 589, 1265  
   contrasted with Fourier transform 584, 594  
   Daubechies wavelet filter coefficients 584ff., 588, 590f., 594, 598, 1264ff.  
   detail information 585  
   discrete wavelet transform (DWT) 586f., 1264  
   DWT (discrete wavelet transform) 586f., 1264ff.  
   eliminating wrap-around 587  
   fast solution of linear equations 597ff.  
   filters 592f.  
   and Fourier domain 592f.  
   image processing 596f.  
   for integral equations 782  
   inverse 587  
   Lemarie's wavelet 593  
   of linear operator 597ff.  
   mother-function coefficient 587  
   mother functions 584  
   multidimensional 595, 1267f.  
   nonsmoothness of wavelets 591  
   pyramidal algorithm 586, 1264  
   quadrature mirror filter 585  
   smooth information 585  
   truncation 594f.  
   wavelet filter coefficient 584, 587  
   wavelets 584, 590ff.  
 Wavelets *see* Wavelet transform  
 Weber function 204  
 Weighted Kolmogorov-Smirnov test 621  
 Weighted least-squares fitting *see* Least squares fitting
- Weighting, full vs. half in multigrid 867  
 Weights for Gaussian quadrature 140ff., 788f., 1059ff., 1328f.  
   nonclassical weight function 151ff., 788f., 1064f., 1328f.  
 Welch window 547, 1254ff.  
 WG5 (ISO/IEC JTC1/SC22/WG5 Committee) 2/xiff.  
 where construct 943, 1291  
   contrasted with merge 1023  
   for iteration of a vector 1060  
   nested 2/xv, 943, 960, 1100  
   not MIMD 985  
 While iteration 13  
 Wiener filtering 535, 539ff., 558, 644  
   compared to regularization 801  
 Wiener-Khinchin theorem 492, 558, 566f.  
 Wilcoxon test 694  
 Window function  
   Bartlett 547, 1254ff.  
   flat-topped 549  
   Hamming 547  
   Hann 547  
   Parzen 547  
   square 544, 546, 1254ff.  
   Welch 547, 1254ff.  
 Windowing for spectral estimation 1255f.  
 Windows 95 2/xix  
 Windows NT 2/xix  
 Winograd Fourier transform algorithms 503  
 Woodbury formula 68ff., 83  
 Wordlength 18  
 Workspace, reallocation in Fortran 90 1070f.  
 World Wide Web, Numerical Recipes site 1/xx, 2/xvii  
 Wraparound  
   in integer arithmetic 1146, 1148  
   order for storing spectrum 501  
   problem in convolution 533  
 Wronskian, of Bessel functions 234, 239
- X**.25 protocol 890  
 X3J3 Committee 2/viii, 2/xff., 2/xv, 947, 959, 964, 968, 990  
 XMODEM checksum 889  
 X-ray diffraction pattern, processing of 805
- Y**ale Sparse Matrix Package 64, 71
- Z**-transform 554, 559, 565  
 Z-transformation, Fisher's 631f., 1276  
 Zaman, A. 1149  
 Zealots 814  
 Zebra relaxation 866  
 Zero contours 372  
 Zero-length array 944  
 Zeroth-order regularization 796ff.  
 Zip code, barcode for 894  
 Ziv-Lempel compression 896  
 zroots\_unity() utility function 974, 990, 999