SPARSKIT: a basic tool kit for sparse matrix computations

VERSION 2

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Abstract. This paper presents the main features of a tool package for manipulating and working with sparse matrices. One of the goals of the package is to provide basic tools to facilitate exchange of software and data between researchers in sparse matrix computations. Our starting point is the Harwell/Boeing collection of matrices for which we provide a number of tools. Among other things the package provides programs for converting data structures, printing simple statistics on a matrix, plotting a matrix profile, performing basic linear algebra operations with sparse matrices and so on.

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1 Introduction

Research on sparse matrix techniques has become increasingly complex, and this trend is likely to accentuate if only because of the growing need to design efficient sparse matrix algorithms for modern supercomputers. While there are a number of packages and 'user friendly' tools, for performing computations with small dense matrices there is a lack of any similar tool or in fact of any general-purpose libraries for working with sparse matrices. Yet a collection of a few basic programs to perform some elementary and common tasks may be very useful in reducing the typical time to implement and test sparse matrix algorithms. That a common set of routines shared among researchers does not yet exist for sparse matrix computation is rather surprising. Consider the contrasting situation in dense matrix computations. The Linpack and Eispack packages developed in the 70's have been of tremendous help in various areas of scientific computing. One might speculate on the number of hours of programming efforts saved worldwide thanks to the widespread availability of these packages. In contrast, it is often the case that researchers in sparse matrix computation code their own subroutine for such things as converting the storage mode of a matrix or for reordering a matrix according to a certain permutation. One of the reasons for this situation might be the absence of any standard for sparse matrix computations. For instance, the number of different data structures used to store sparse matrices in various applications is staggering. For the same basic data structure there often exist a large number of variations in use. As sparse matrix computation technology is maturing there is a desperate need for some standard for the basic storage schemes and possibly, although this is more controversial, for the basic linear algebra operations.

An important example where a package such as SPARSKIT can be helpful is for exchanging matrices for research or other purposes. In this situation, one must often translate the matrix from some initial data structure in which it is generated, into a different desired data structure. One way around this difficulty is to restrict the number of schemes that can be used and set some standards. However, this is not enough because often the data structures are chosen for their efficiency and convenience, and it is not reasonable to ask practitioners to abandon their favorite storage schemes. What is needed is a large set of programs to translate one data structure into another. In the same vein, subroutines that generate test matrices would be extremely valuable since they would allow users to have access to a large number of matrices without the burden of actually passing large sets of data.

A useful collection of sparse matrices known as the Harwell/Boeing collection, which is publically available [4], has been widely used in recent years for testing and comparison purposes. Because of the importance of this collection many of the tools in SPARSKIT can be considered as companion tools to it. For example, SPARSKIT supplies simple routines to create a Harwell/Boeing (H/B) file from a matrix in any format, tools for creating pic files in order to plot a H/B matrix, a few routines that will deliver statistics for any H/B matrix, etc.. However, SPARSKIT is not limited to being a set of tools to work with H/B matrices. Since one of our main motivations is research on iterative methods, we provide numerous subroutines that may help researchers in this specific area. SPARSKIT will hopefully be an evolving package that will benefit from contributions from other researchers. This report is a succinct description of the package in this release.

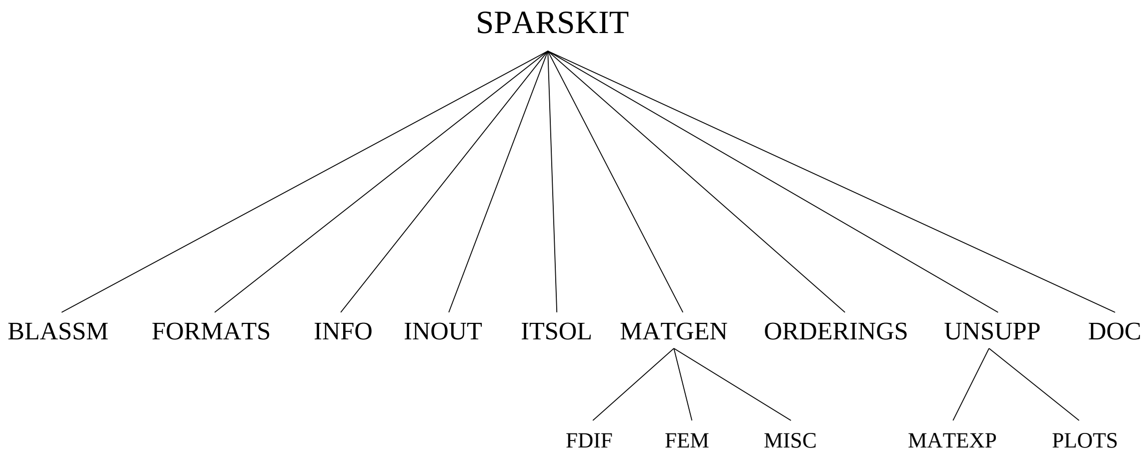


Figure 1: General organization of SPARSKIT.

2 Data structures for sparse matrices and the conversion routines

One of the difficulties in sparse matrix computations is the variety of types of matrices that are encountered in practical applications. The purpose of each of these schemes is to gain efficiency both in terms of memory utilization and arithmetic operations. As a result many different ways of storing sparse matrices have been devised to take advantage of the structure of the matrices or the specificity of the problem from which they arise. For example if it is known that a matrix consists of a few diagonals one may simply store these diagonals as vectors and the offsets of each diagonal with respect to the main diagonal. If the matrix is not regularly structured, then one of the most common storage schemes in use today is what we refer to in SPARSKIT as the Compressed Sparse Row (CSR) scheme. In this scheme all the nonzero entries are stored row by row in a one-dimensional real array A together with an array JA containing their column indices and a pointer array which contains the addresses in A and JA of the beginning of each row. The order of the elements within each row does not matter. Also of importance because of its simplicity is the coordinate storage scheme in which the nonzero entries of A are stored in any order together with their row and column indices. Many of the other existing schemes are specialized to some extent. The reader is referred to the book by Duff et al. [3] for more details.

2.1 Storage Formats

Currently, the conversion routines of SPARSKIT can handle thirteen different storage formats. These include some of the most commonly used schemes but they are by no means exhaustive. We found it particularly useful to have all these storage modes when trying to extract a matrix from someone else's application code in order, for example, to analyze it with the tools described in the next sections or, more commonly, to try a given solution method which requires a different data structure than the one originally used in the application. Often the matrix is stored in one of these modes or a variant that is very close to it. We hope to add many more conversion routines as SPARSKIT evolves.

In this section we describe in detail the storage schemes that are handled in the FORMATS module. For convenience we have decided to label by a three character name each format used. We start by listing the formats and then describe them in detail in separate subsections (except for the dense format which needs no detailed description).

DNS Dense format

BND Linpack Banded format

CSR Compressed Sparse Row format

CSC Compressed Sparse Column format

COO Coordinate format

ELL Ellpack-Itpack generalized diagonal format

DIA Diagonal format

BSR Block Sparse Row format

MSR Modified Compressed Sparse Row format

SSK Symmetric Skyline format

NSK Nonsymmetric Skyline format

LNK Linked list storage format

JAD The Jagged Diagonal format

SSS The Symmetric Sparse Skyline format

USS The Unsymmetric Sparse Skyline format

VBR Variable Block Row format

In the following sections we denote by A the matrix under consideration and by N its row dimension and NNZ the number of its nonzero elements.

2.1.1 Compressed Sparse Row and related formats (CSR, CSC and MSR)

The Compressed Sparse Row format is the basic format used in SPARSKIT. Its data structure consists of three arrays.

- A real array A containing the real values a_{ij} stored row by row, from row 1 to N. The length of A is NNZ.
- An integer array JA containing the column indices of the elements a_{ij} as stored in the array A. The length of JA is NNZ.
- An integer array IA containing the pointers to the beginning of each row in the arrays A and JA. Thus the content of $IA(i)$ is the position in arrays A and JA where the i-th row starts. The length of IA is $N+1$ with $IA(N+1)$ containing the number $IA(1)+NNZ$, i.e., the address in A and JA of the beginning of a fictitious row $N+1$.

The order of the nonzero elements within the same row are not important. A variation to this scheme is to sort the elements in each row in such a way that their column positions are in increasing order. When this sorting in enforced, it is often possible to make substantial savings in the number of operations of some well-known algorithms. The Compressed Sparse Column format is identical with the Compressed Sparse Row format except that the columns of A are stored instead of the rows. In other words the Compressed Sparse Column format is simply the Compressed Sparse Row format for the matrix A^T.

The Modified Sparse Row (MSR) format is a rather common variation of the Compressed Sparse Row format which consists of keeping the main diagonal of A separately. The corresponding data structure consists of a real array A and an integer array JA. The first N positions in A contain the diagonal elements of the matrix, in order. The position $N+1$ of the array A is not used. Starting from position $N+2$, the nonzero elements of A, excluding its diagonal elements, are stored row-wise. Corresponding to each element $A(k)$ the integer $JA(k)$ is the column index of the element $A(k)$ in the matrix A. The $N+1$ first positions of JA contain the pointer to the beginning of each row in A and JA. The advantage of this storage mode is that many matrices have a full main diagonal, i.e., $a_{ii} \neq 0, i = 1, \ldots, N$, and this diagonal is best represented by an array of length N. This storage mode is particularly useful for triangular matrices with non-unit diagonals. Often the diagonal is then stored in inverted form (i.e. $1/a_{ii}$ is stored in place of a_{ii}) because triangular systems are often solved repeatedly with the same matrix many times, as is the case for example in preconditioned Conjugate Gradient methods. The column oriented analogue of the MSR format, called MSC format, is also used in some of the other modules, but no transformation to/from it to the CSC format is necessary: for example to pass from CSC to MSC one can use the routine to pass from the CSR to the MSR formats, since the data structures are identical. The above three storage modes are used in many well-known packages.

2.1.2 The banded Linpack format (BND)

Banded matrices represent the simplest form of sparse matrices and they often convey the easiest way of exploiting sparsity. There are many ways of storing a banded matrix. The one we adopted here follows the data structure used in the Linpack banded solution routines. Our motivation is that one can easily take advantage of this widely available package if the matrices are banded. For fairly small matrices (say, $N < 2000$ on supercomputers, $N < 200$ on fast workstations, and with a bandwidth of $O(N^{\frac{1}{2}})$), this may represent a viable and simple way of solving linear systems. One must first transform the initial data structure into the banded Linpack format and then call the appropriate band solver. For large problems it is clear that a better alternative would be to use a sparse solver such as MA28, which requires the input matrix to be in the coordinate format.

In the BND format the nonzero elements of A are stored in a rectangular array ABD with the nonzero elements of the j-th column being stored in the $j - th$ column of ABD. We also need to know the number ML of diagonals below the main diagonals and the number MU of diagonals above the main diagonals. Thus the bandwidth of A is $ML + MU + 1$ which is the minimum number of rows required in the array ABD. An additional integer parameter is needed to indicate which row of ABD contains the lowest diagonal.

2.1.3 The coordinate format (COO)

The coordinate format is certainly the simplest storage scheme for sparse matrices. It consists of three arrays: a real array of size NNZ containing the real values of nonzero elements of A in any order, an integer array containing their row indices and a second integer array containing their column indices. Note that this scheme is as general as the CSR format, but from the point of view of memory requirement it is not as efficient. On the other hand it is attractive because of its simplicity and the fact that it is very commonly used. Incidentally, we should mention a variation to this mode which is perhaps the most economical in terms of memory usage. The modified version requires only a real array A containing the real values a_{ij} along with only one integer array that contains the integer values $(i-1)N+j$ for each corresponding nonzero element a_{ij}. It is clear that this is an unambiguous representation of all the nonzero elements of A. There are two drawbacks to this scheme. First, it requires some integer arithmetic to extract the column and row indices of each element when they are needed. Second, for large matrices it may lead to integer overflow because of the need to deal with integers which may be very large (of the order of N^2). Because of these two drawbacks this scheme has seldom been used in practice.

2.1.4 The diagonal format (DIA)

The matrices that arise in many applications often consist of a few diagonals. This structure has probably been the first one to be exploited for the purpose of improving performance of matrix by vector products on supercomputers, see references in [9]. To store these matrices we may store the diagonals in a rectangular array $DIAG(1:N, 1:NDIAG)$ where $NDIAG$ is the number of diagonals. We also need to know the offsets of each of the diagonals with respect to the main diagonal. These will be stored in an array $IOFF(1:NDIAG)$. Thus, in position (i,k) of the array $DIAG$ is located the element $a_{i,i+ioff(k)}$ of the original matrix. The order in which the diagonals are stored in the columns of $DIAG$ is unimportant. Note also that all the diagonals except the main diagonal have fewer than N elements, so there are positions in $DIAG$ that will not be used.

In many applications there is a small number of non-empty diagonals and this scheme is enough. In general however, it may be desirable to supplement this data structure, e.g., by a compressed sparse row format. A general matrix is therefore represented as the sum of a diagonal-structured matrix and a general sparse matrix. The conversion routine CSRDIA which converts from the compressed sparse row format to the diagonal format has an option to this effect. If the user wants to convert a general sparse matrix to one with, say, 5 diagonals, and if the input matrix has more than 5 diagonals, the rest of the matrix (after extraction of the 5 desired diagonals) will be put, if desired, into a matrix in the CSR format. In addition, the code may also compute the most important 5 diagonals if wanted, or it can get those indicated by the user through the array $IOFF$.

2.1.5 The Ellpack-Itpack format (ELL)

The Ellpack-Itpack format [6, 11, 5] is a generalization of the diagonal storage scheme which is intended for general sparse matrices with a limited maximum number of nonzeros per row. Two rectangular arrays of the same size are required, one real and one integer. The first, $COEF$, is similar to $DIAG$ and contains the nonzero elements of A. Assuming that there are at most $NDIAG$ nonzero elements in each row of A, we can store the nonzero elements of each row of the matrix in a row of the array $COEF(1:N, 1:NDIAG)$ completing the row by zeros if necessary. Together with $COEF$ we need to store an integer array $JCOEF(1:N, 1:NDIAG)$ which contains the column positions of each entry in $COEF$.

2.1.6 The Block Sparse Row format (BSR)

Block matrices are common in all areas of scientific computing. The best way to describe block matrices is by viewing them as sparse matrices whose nonzero entries are square dense blocks. Block matrices arise from the discretization of partial differential equations when there are several degrees of freedom per grid point. There are restrictions to this scheme. Each of the blocks is treated as a dense block. If there are zero elements within each block they must be treated as nonzero elements with the value zero.

There are several variations to the method used for storing sparse matrices with block structure. The one considered here, the Block Sparse Row format, is a simple generalization of the Compressed Sparse Row format.

We denote here by $NBLK$ the dimension of each block, by $NNZR$ the number of nonzero blocks in A (i.e., $NNZR = NNZ/(NBLK^2)$) and by NR the block dimension of A, (i.e., $NR = N/NBLK$), the letter R standing for 'reduced'. Like the Compressed Sparse Row format we need three arrays. A rectangular real array $A(1 : NNZR, 1 : NBLK, 1 : NBLK)$ contains the nonzero blocks listed (block)-row-wise. Associated with this real array is an integer array $JA(1 : NNZR)$ which holds the actual column positions in the original matrix of the $(1,1)$ elements of the nonzero blocks. Finally, the pointer array $IA(1 : NR + 1)$ points to the beginning of each block row in A and JA.

The savings in memory and in the use of indirect addressing with this scheme over Compressed Sparse Row can be substantial for large values of $NBLK$.

2.1.7 The Symmetric Skyline format (SSK)

A skyline matrix is often referred to as a variable band matrix or a profile matrix [3]. The main attraction of skyline matrices is that when pivoting is not necessary then the skyline structure of the matrix is preserved during Gaussian elimination. If the matrix is symmetric we only need to store its lower triangular part. This is a collection of rows whose length varies. A simple method used to store a Symmetric Skyline matrix is to place all the rows in order from 1 to N in a real array A and then keep an integer array which holds the pointers to the beginning of each row, see [2]. The column positions of the nonzero elements stored in A can easily be derived and are therefore not needed. However, there are several variations to this scheme that are commonly used is commercial software packages. For example, we found that in many instances the pointer is to the diagonal element rather than to the first element in the row. In some cases (e.g., IBM's ISSL library) both are supported. Given that these variations are commonly used it is a good idea to provide at least a few of them.

2.1.8 The Non Symmetric Skyline format (NSK)

Conceptually, the data structure of a nonsymmetric skyline matrix consists of two substructures. The first consists of the lower part of A stored in skyline format and the second of its upper triangular part stored in a column oriented skyline format (i.e., the transpose is stored in standard row skyline mode). Several ways of putting these substructures together may be used and there are no compelling reasons for preferring one strategy over another one. One possibility is to use two separate arrays AL and AU for the lower part and upper part respectively, with the diagonal element in the upper part. The data structures for each of two parts is similar to that used for the SSK storage.

2.1.9 The linked list storage format (LNK)

This is one of the oldest data structures used for sparse matrix computations. It consists of four arrays: A, $JCOL$, $LINK$ and $JSTART$. The arrays A and $JCOL$ contain the nonzero elements and their corresponding column indices respectively. The integer array $LINK$ is the usual link pointer array in linked list data structures: $LINK(k)$ points to the position of the nonzero element next to $A(k), JCOL(k)$ in the same row. Note that the order of the elements within each row is unimportant. If $LINK(k) = 0$ then there is no next element, i.e., $A(k), JCOL(k)$ is the last element of the row. Finally, $ISTART$ points to the first element of each row in in the previous arrays. Thus, $k = ISTART(1)$ points to the first element of the first row, in $A, ICOL$, $ISTART(2)$ to the second element, etc.. As a convention $ISTART(i) = 0$, means that the i-th row is empty.

2.1.10 The Jagged Diagonal format (JAD)

This storage mode is very useful for the efficient implementation of iterative methods on parallel and vector processors [9]. Starting from the CSR format, the idea is to first reorder the rows of the matrix decreasingly according to their number of nonzeros entries. Then, a new data structure is built by constructing what we call "jagged diagonals" (j-diagonals). We store as a dense vector, the vector consisting of all the first elements in A, JA from each row, together with an integer vector containing the column positions of the corresponding elements. This is followed by the second jagged diagonal consisting of the elements in the second positions from the left. As we build more and more of these diagonals, their length decreases. The number of j-diagonals is equal to the number of nonzero elements of the first row, i.e., to the largest number of nonzero elements per row. The data structure to represent a general matrix in this form consists, before anything, of the permutation array which reorders the rows. Then the real array A containing the jagged diagonals in succession and the array JA of the corresponding column positions are stored, together with a pointer array IA which points to the beginning of each jagged diagonal in the arrays A, JA. The advantage of this scheme for matrix multiplications has been illustrated in [9] and in [1] in the context of triangular system solutions.

2.1.11 The Symmetric and Unsymmetric Sparse Skyline format (SSS, USS)

This is an extension of the CSR-type format described above. In the symmetric version, the following arrays are used: $DIAG$ stores the diagonal, AL, JAL, IAL stores the strict lower part in CSR format, and AU stores the values of the strict upper part in CSC format. In the unsymmetric version, instead of AU alone, the strict upper part is stored in AU, JAU, IAU in CSC format.

2.1.12 The Variable Block Row format (VBR)

In many applications, matrices are blocked, but the blocks are not all the same size. These so-called variable block matrices arise from the discretization of systems of partial differential equations where there is a varying number of equations at each grid point. Like in the Block Sparse Row (BSR) format, all entries of nonzero blocks (blocks which contain any nonzeros) are stored, even if their value is zero. Also like the BSR format, there is significant savings in integer pointer overhead in the data structure.

Variable block generalizations can be made to many matrix storage formats. The Variable Block Row (VBR) format is a generalization of the Compressed Sparse Row

(CSR) format, and is similar to the variable block format used at the University of Waterloo, and one currently proposed in the Sparse BLAS toolkit.

In the VBR format, the IA and JA arrays of the CSR format store the sparsity structure of the blocks. The entries in each block are stored in A in column-major order so that each block may be passed as a small dense matrix to a Fortran subprogram. The block row and block column partitionings are stored in the vectors *KVSTR* and *KVSTC*, by storing the first row or column number of each block row or column respectively. In most applications, the block row and column partitionings will be conformal, and the same array may be used in the programs. Finally, integer pointers to the beginning of each block in A are stored in the array KA.

IA contains pointers to the beginning of each block row in JA and KA. Thus IA has length equal to the number of block rows (plus one to mark the end of the matrix), and JA has length equal to the number of nonzero blocks. KA has the same length as JA plus one to mark the end of the matrix. *KVSTR* and *KVSTC* have length equal to the number of block rows and columns respectively, and A has length equal to the number of nonzeros in the matrix. The following figure shows the VBR format applied to a small matrix.

This version of Sparskit has a number of routines to support the variable block matrix format. CSRVBR and VBRCSR convert between the VBR and CSR formats; VBRINFO prints some elementary information about the block structure of a matrix in VBR format; AMUXV performs a matrix-vector product with a matrix in VBR format; CSRKVSTR and CSRKVSTC are used to determine row and column block partitionings of a matrix in CSR format, and KVSTMERGE is used to combine row and column partitionings to achieve a conformal partitioning.

2.2 The FORMATS conversion module

It is important to note that there is no need to have a subroutine for each pair of data structures, since all we need is to be able to convert any format to the standard row-compressed format and then back to any other format. There are currently 32 different conversion routines in this module all of which are devoted to converting from one data structure into another.

The naming mechanism adopted is to use a 6-character name for each of the subroutines, the first 3 for the input format and the last 3 for the output format. Thus COOCSR performs the conversion from the coordinate format to the Compressed Sparse Row format. However it was necessary to break the naming rule in one exception. We needed a version of COOCSR that is in-place, i.e., which can take the input matrix, and convert it directly into a CSR format by using very little additional work space. This routine is called COICSR. Each of the formats has a routine to translate it to the CSR format and a routine to convert back to it from the CSR format. The only exception is that a CSCCSR routine is not necessary since the conversion from Column Sparse format to Sparse Row format can be performed with the same routine CSRCSC. This is essentially a transposition operation.

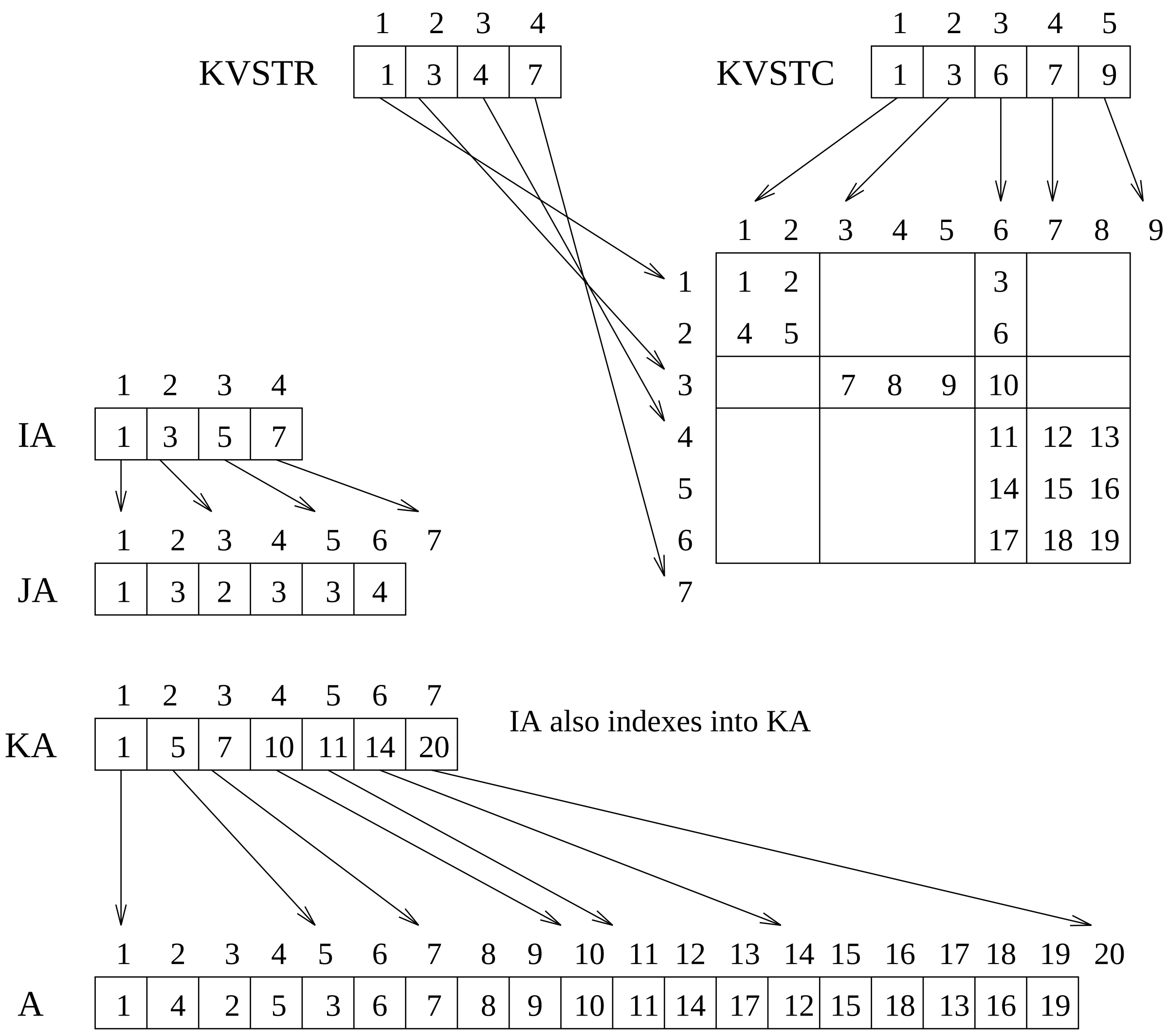


Figure 2: A 6 × 8 sparse matrix and its storage vectors.

Considerable effort has been put at attempting to make the conversion routines in-place, i.e., in allowing some or all of the output arrays to be the same as the input arrays. The purpose is to save storage whenever possible without sacrificing performance. The added flexibility can be very convenient in some situations. When the additional coding complexity to permit the routine to be in-place was not too high this was always done. If the subroutine is in-place this is clearly indicated in the documentation. As mentioned above, we found it necessary in one instance to provide both the in-place version as well as the regular version: COICSR is an in-place version of the COOCSR routine. We would also like to add that other routines that avoid the CSR format for some of the more important data structures may eventually be included. For now, there is only one such routine [1] namely, COOELL.

[1]Contributed by E. Rothman from Cornell University.

2.3 Internal format used in SPARSKIT

Most of the routines in SPARSKIT use internally the Compressed Sparse Row format. The selection of the CSR mode has been motivated by several factors. Simplicity, generality, and widespread use are certainly the most important ones. However, it has often been argued that the column scheme may have been a better choice. One argument in this favor is that vector machines usually give a better performance for such operations as matrix vector by multiplications for matrices stored in CSC format. In fact for parallel machines which have a low overhead in loop synchronization (e.g., the Alliants), the situation is reversed, see [9] for details. For almost any argument in favor of one scheme there seems to be an argument in favor of the other. Fortunately, the difference provided in functionality is rather minor. For example the subroutine APLB to add two matrices in CSR format, described in Section 5.1, can actually be also used to add two matrices in CSC format, since the data structures are identical. Several such subroutines can be used for both schemes, by pretending that the input matrices are stored in CSR mode whereas in fact they are stored in CSC mode.

3 Manipulation routines

The module UNARY of SPARSKIT consists of a number of utilities to manipulate and perform basic operations with sparse matrices. The following sections give an overview of this part of the package.

3.1 Miscellaneous operations with sparse matrices

There are a large number of non-algebraic operations that are commonly used when working with sparse matrices. A typical example is to transform A into $B = PAQ$ where P and Q are two permutation matrices. Another example is to extract the lower triangular part of A or a given diagonal from A. Several other such 'extraction' operations are supplied in SPARSKIT. Also provided is the transposition function. This may seem as an unnecessary addition since the routine CSRCSC already does perform this function economically. However, the new transposition provided is in-place, in that it may transpose the matrix and overwrite the result on the original matrix, thus saving memory usage. Since many of these manipulation routines involve one matrix (as opposed to two in the basic linear algebra routines) we created a module called UNARY to include these subroutines.

Another set of subroutines that are sometimes useful are those involving a 'mask'. A mask defines a given nonzero pattern and for all practical purposes a mask matrix is a sparse matrix whose nonzero entries are all ones (therefore there is no need to store its real values). Sometimes it is useful to extract from a given matrix A the 'masked' matrix according to a mask M, i.e., to compute the matrix $A \odot M$, where $\odot$ denotes the element-wise matrix product, and M is some mask matrix.

3.2 The module UNARY

This module of SPARSKIT consists of a number of routines to perform some basic non-algebraic operations on a matrix. The following is a list of the routines currently supported with a brief explanation.

SUBMAT	Extracts a square or rectangular submatrix from a sparse matrix. Both the input and output matrices are in CSR format. The routine is in-place.
FILTER	Filters out elements from a matrix according to their magnitude. Both the input and the output matrices are in CSR format. The output matrix, is obtained from the input matrix by removing all the elements that are smaller than a certain threshold. The threshold is computed for each row according to one of three provided options. The algorithm is in-place.
FILTERM	Same as above, but for the MSR format.
CSORT	Sorts the elements of a matrix stored in CSR format in increasing order of the column numbers.
TRANSP	This is an in-place transposition routine, i.e., it can be viewed as an in-place version of the CSRCSC routine in FORMATS. One notable disadvantage of TRANSP is that unlike CSRCSC it does not sort the nonzero elements in increasing number of the column positions.
COPMAT	Copy of a matrix into another matrix (both stored CSR).
MSRCOP	Copies a matrix in MSR format into a matrix in MSR format.
GETELM	Function returning the value of a_{ij} for any pair (i, j). Also returns address of the element in arrays A, JA.
GETDIA	Extracts a specified diagonal from a matrix. An option is provided to transform the input matrix so that the extracted diagonal is zeroed out in input matrix. Otherwise the diagonal is extracted and the input matrix remains untouched.
GETL	This subroutine extracts the lower triangular part of a matrix, including the main diagonal. The algorithm is in-place.
GETU	Extracts the upper triangular part of a matrix. Similar to GETL.

LEVELS	Computes the level scheduling data structure for lower triangular matrices, see [1].
AMASK	Extracts $C = A \odot M$, i.e., performs the mask operation. This routine computes a sparse matrix from an input matrix A by extracting only the elements in A, where the corresponding elements of M are nonzero. The mask matrix M, is a sparse matrix in CSR format without the real values, i.e., only the integer arrays of the CSR format are passed.
CPERM	Permutes the columns of a matrix, i.e., computes the matrix $B = AQ$ where Q is a permutation matrix.
RPERM	Permutes the rows of a matrix, i.e., computes the matrix $B = PA$ where P is a permutation matrix.
DPERM	Permutes the rows and columns of a matrix, i.e., computes $B = PAQ$ given two permutation matrices P and Q. This routine gives a special treatment to the common case where $Q = P^T$.
DPERM2	General submatrix permutation/extraction routine.
DMPERM	Symmetric permutation of row and column (B=PAP') in MSR format
DVPERM	Performs an in-place permutation of a real vector, i.e., performs $x := Px$, where P is a permutation matrix.
IVPERM	Performs an in-place permutation of an integer vector.
RETMX	Returns the maximum absolute value in each row of an input matrix.
DIAPOS	Returns the positions in the arrays A and JA of the diagonal elements, for a matrix stored in CSR format.
EXTBDG	Extracts the main diagonal blocks of a matrix. The output is a rectangular matrix of dimension $N \times NBLK$, containing the $N/NBLK$ blocks, in which $NBLK$ is the block-size (input).
GETBWD	Returns bandwidth information on a matrix. This subroutine returns the bandwidth of the lower part and the upper part of a given matrix. May be used to determine these two parameters for converting a matrix into the BND format.

BLKFND	Attempts to find the block-size of a matrix stored in CSR format. One restriction is that the zero elements in each block if there are any are assumed to be represented as nonzero elements in the data structure for the A matrix, with zero values.
BLKCHK	Checks whether a given integer is the block size of A. This routine is called by BLKFND. Same restriction as above.
INFDIA	Computes the number of nonzero elements of each of the $2n-1$ diagonals of a matrix. Note that the first diagonal is the diagonal with offset $-n$ which consists of the entry $a_{n,1}$ and the last one is the diagonal with offset n which consists of the element $a_{1,n}$.
AMUBDG	Computes the number of nonzero elements in each row of the product of two sparse matrices A and B. Also returns the total number of nonzero elements.
APLBDG	Computes the number of nonzero elements in each row of the sum of two sparse matrices A and B. Also returns the total number of nonzero elements.
RNRMS	Computes the norms of the rows of a matrix. The usual three norms $\|.\|_1$, $\|.\|_2$, and $\|.\|_\infty$ are supported.
CNRMS	Computes the norms of the columns of a matrix. Similar to RNRMS.
ROSCAL	Scales the rows of a matrix by their norms. The same three norms as in RNRMS are available.
COSCAL	Scales the columns of a matrix by their norms. The same three norms as in RNRMS are available.
ADDBLK	Adds a matrix B into a block of A.
GET1UP	Collects the first elements of each row of the upper triangular portion of the matrix.
XTROWS	Extracts given rows from a matrix in CSR format.
CSRKVSTR	Finds block partitioning of matrix in CSR format.
CSRKVSTC	Finds block column partitioning of matrix in CSR format.
KVSTMERGE	Merges block partitionings for conformal row/column pattern.

4 Input/Output routines

The INOUT module of SPARSKIT comprises a few routines for reading, writing, and for plotting and visualizing the structure of sparse matrices. Many of these routines are essentially geared towards the utilization of the Harwell/Boeing collection of matrices. There are currently eleven subroutines in this module.

READMT	Reads a matrix in the Harwell/Boeing format.
PRTMT	Creates a Harwell Boeing file from an arbitrary matrix in CSR or CSC format.
DUMP	DUMP prints the rows of a matrix in a file, in a nice readable format. The best format is internally calculated depending on the number of nonzero elements. This is a simple routine which might be helpful for debugging purposes.
PSPLTM	Generates a post-script plot of the non-zero pattern of A.
PLTMT	Creates a pic file for plotting the pattern of a matrix.
SMMS	Write the matrx in a format used in SMMS package.
READSM	Reads matrices in coordinate format (as in SMMS package).
READSK	Reads matrices in CSR format (simplified H/B format).
SKIT	Writes matrices to a file, format same as above.
PRTUNF	Writes matrices (in CSR format) in unformatted files.
READUNF	Reads unformatted file containing matrices in CSR format.

The routines readmt and prtmt allow to read and create files containing matrices stored in the H/B format. For details concerning this format the reader is referred to [4] or the summary given in the documentation of the subroutine READMT. While the purpose of readmt is clear, it is not obvious that one single subroutine can write a matrix in H/B format and still satisfy the needs of all users. For example for some matrices all nonzero entries are actually integers and a format using say a 10 digit mantissa may entail an enormous waste of storage if the matrix is large. The solution provided is to compute internally the best formats for the integer arrays IA and JA. A little help is required from the user for the real values in the arrays A and RHS. Specifically, the desired format is obtained from a parameter of the subroutine by using a simple notation, which is explained in detail in the documentation of the routine.

Besides the pair of routines that can read/write matrices in H/B format, there are three other pairs which can be used to input and output matrices in different formats. The SMMS and READSM pair write and read matrices in the format used in the package SMMS. Specifically, READSM reads a matrix in SMMS format from a file and outputs it in CSR format. SMMS accepts a matrix in CSR format and writes it to a file in SMMS format. The SMMS format is essentially a COO format. The size of the matrix appears in the first line of the file. Each other line of the file contains triplets in the form of (i, j, a_{ij}) which denote the non-zero elements of the matrix. Similarly, READSK and SKIT read and write matrices in CSR format. This pair is very similar to READMT and PRTMT, only that the files read/written by READSK and SKIT do not have headers. The pair READUNF and PRTUNF reads and writes the matrices (stored as ia, ja and a) in binary form, i.e. the number in the file written by PRTUNF will be in machine representations. The primary motivation for this is that handling the arrays in binary form takes less space than in the usual ASCII form, and is usually faster. If the matrices are large and they are only used on compatible computers, it might be desirable to use unformatted files.

We found it extremely useful to be able to visualize a sparse matrix, notably for debugging purposes. A simple look at the plot can sometimes reveal whether the matrix obtained from some reordering technique does indeed have the expected structure. For now two simple plotting mechanisms are provided. First, a preprocessor called PLTMT to the Unix utility 'Pic' allows one to generate a pic file from a matrix that is in the Harwell/Boeing format or any other format. For example for a Harwell/Boeing matrix file, the command is of the form

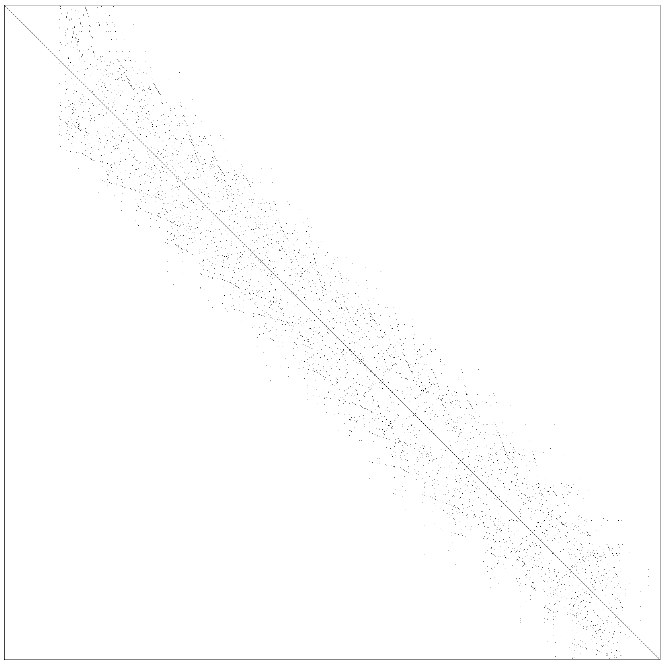
```
hb2pic.ex < HB_file.
```

The output file is then printed by the usual troff or TeX commands. A translation of this routine into one that generates a post-script file is also available (called PSPLTM). We should point out that the plotting routines are very simple in nature and should not be used to plot large matrices. For example the pltmt routine outputs one pic command line for every nonzero element. This constitutes a convenient tool for document preparation for example. Matrices of size just up to a few thousands can be printed this way. Several options concerning the size of the plot and caption generation are available.

There is also a simple utility program called "hb2ps" which takes a matrix file with HB format and translates it into a post-script file. The usage of this program is as follows:

```
hb2ps.ex < HB_file > Postscript_file.
```

The file can be previewed with ghostscript. The following graph shows a pattern of an unsymmetric matrix.



AN UNSYMMETRIC MATRIX FROM PHILIPS LTD, J.P.WHELAN,1978.

5 Basic algebraic operations

The usual algebraic operations involving two matrices, such as $C = A + B$, $C = A + \beta B$, $C = AB$, etc.., are fairly common in sparse matrix computations. These basic matrix operations are included in the module called BLASSM. In addition there is a large number of basic operations, involving a sparse matrix and a vector, such as matrix-vector products and triangular system solutions that are very commonly used. Some of these are included in the module MATVEC. Sometimes it is desirable to compute the patterns of the matrices $A + B$ and AB, or in fact of any result of the basic algebraic operations. This can be implemented by way of job options which will determine whether to fill-in the real values or not during the computation. We now briefly describe the contents of each of the two modules BLASSM and MATVEC.

5.1 The BLASSM module

Currently, the module BLASSM (Basic Linear Algebra Subroutines for Sparse Matrices) contains the following nine subroutines:

AMUB	Performs the product of two matrices, i.e., computes $C = AB$, where A and B are both in CSR format.

APLB	Performs the addition of two matrices, i.e., computes $C = A + B$, where A and B are both in CSR format.
APLSB	Performs the operation $C = A + \sigma B$, where σ is a scalar, and A, B are two matrices in CSR format.
APMBT	Performs either the addition $C = A + B^T$ or the subtraction $C = A - B^T$.
APLSBT	Performs the operation $C = A + sB^T$.
DIAMUA	Computes the product of diagonal matrix (from the left) by a sparse matrix, i.e., computes $C = DA$, where D is a diagonal matrix and A is a general sparse matrix stored in CSR format.
AMUDIA	Computes the product of a sparse matrix by a diagonal matrix from the right, i.e., computes $C = AD$, where D is a diagonal matrix and A is a general sparse matrix stored in CSR format.
APLDIA	Computes the sum of a sparse matrix and a diagonal matrix, $C = A + D$.
APLSCA	Performs an in-place addition of a scalar to the diagonal entries of a sparse matrix, i.e., performs the operation $A := A + \sigma I$.

Missing from this list are the routines **AMUBT** which multiplies A by the transpose of B, $C = AB^T$, and **ATMUB** which multiplies the transpose of A by B, $C = A^T B$.

These are very difficult to implement and we found it better to perform it with two passes. Operations of the form $tA + sB$ have been avoided as their occurrence does not warrant additional subroutines. Several other operations similar to those defined for vectors have not been included. For example the scaling of a matrix in sparse format is simply a scaling of its real array A, which can be done with the usual BLAS1 scaling routine, on the array A.

5.2 The MATVEC module

In its current status, this module contains matrix by vector products and various sparse triangular solution methods. The contents are as follows.

AMUX	Performs the product of a matrix by a vector. Matrix stored in Compressed Sparse Row (CSR) format.

ATMUX	Performs the product of the transpose of a matrix by a vector. Matrix A stored in Compressed Sparse Row format. Can also be viewed as the product of a matrix in the Compressed Sparse Column format by a vector.
AMUXE	Performs the product of a matrix by a vector. Matrix stored in Ellpack/Itpack (ELL) format.
AMUXD	Performs the product of a matrix by a vector. Matrix stored in Diagonal (DIA) format.
AMUXJ	Performs the product of a matrix by a vector. Matrix stored in Jagged Diagonal (JAD) format.
VBRMV	Sparse matrix - full vector product in VBR format.
LSOL	Unit lower triangular system solution. Matrix stored in Compressed Sparse Row (CSR) format.
LDSOL	Lower triangular system solution. Matrix stored in Modified Sparse Row (MSR) format. Diagonal elements inverted.
LSOLC	Unit lower triangular system solution. Matrix stored in Compressed Sparse Column (CSC) format.
LDSOLC	Lower triangular system solution. Matrix stored in Modified Sparse Column (MSC) format with diagonal elements inverted.
LDSOLL	Unit lower triangular system solution with the level scheduling approach. Matrix stored in Modified Sparse Row format, with diagonal elements inverted.
USOL	Unit upper triangular system solution. Matrix stored in Compressed Sparse Row (CSR) format.
UDSOL	Upper triangular system solution. Matrix stored in Modified Sparse Row (MSR) format. Diagonal elements inverted.
USOLC	Unit upper triangular system solution. Matrix stored in Compressed Sparse Column (CSC) format.
UDSOLC	Upper triangular system solution. Matrix stored in Modified Sparse Column (MSC) format with diagonal elements inverted.

Most of the above routines are short and rather straightforward. A long test program is provided to run all of the subroutines on a large number of matrices that are dynamically generated using the MATGEN module.

6 The basic statistics and information routines

It is sometimes very informative when analyzing solution methods, to be able in a short amount of time to obtain some statistical information about a sparse matrix. The purpose of the subroutine info1, is to print out such information. The first question we had to address was to determine the type of information that is inexpensive to obtain and yet practical and useful. The simplest and most common statistics are: total number of nonzero elements, average number of nonzero elements per row (with standard deviation), band size. Our preliminary package Info1 contains the above and a number of other features. For example it answers the following questions: Is the matrix lower triangular, upper triangular? does it have a symmetric structure? If not how close is it from having this property? Is it weakly row-diagonally dominant? What percentage of the rows are weakly diagonally dominant? Same questions for column diagonal dominance. A sample output from info1 is listed in Figure3. This print-out was generated by typing

```
info1.ex < pores_2
```

where `pores_2` is a file containing a matrix in H/B format.

If the Harwell-Boeing matrix is symmetric then Info1 takes this information into account to obtain the correct information instead of the information on the lower triangular part only. Moreover, in cases where only the pattern is provided (no real values), then info1 will print a message to this effect and will then give information related only to the structure of the matrix. The output for an example of this type is shown in Figure 4. We should point out that the runs for these two tests were basically instantaneous on a Sun-4 workstation.

Currently, this module contains the following subroutines:

N_IMP_DIAG	Computes the most important diagonals.
DIAG_DOMI	Computes the percentage of weakly diagonally dominant rows/columns.
BANDWIDTH	Computes the lower, upper, maximum, and average bandwidths.
NONZ	Computes maximum numbers of nonzero elements per column/row, min numbers of nonzero elements per column/row, and numbers of zero columns/rows.
FROBNORM	Computes the Frobenius norm of A.

ANSYM	Computes the Frobenius norm of the symmetric and non-symmetric parts of A, computes the number of matching elements in symmetry and the relative symmetry match. The routine ANSYM provides some information on the degree of symmetry of A.
DISTAIJ	Computes the average distance of a(i,j) from diag and standard deviation for this average.
SKYLINE	Computes the number of nonzeros in the skyline storage.
DISTDIAG	Computes the numbers of elements in each diagonal.
BANDPART	Computes the bandwidth of the banded matrix, which contains 'nper' percent of the original matrix.
NONZ_LUD	Computes the number of nonzero elements in strict lower part, strict upper part, and main diagonal.
AVNZ_COL	Computes average number of nonzero elements/column and standard deviation for the average.
VBRINFO	Prints information about matrices in variable block row format.

7 Matrix generation routines

One of the difficulties encountered when testing and comparing numerical methods, is that it is sometimes difficult to guarantee that the matrices compared are indeed identical. Even though a paper may give full details on the test problems considered, programming errors or differences in coding may lead to the incorrect matrices and the incorrect conclusions. This has often happened in the past and is likely to be avoided if the matrices were generated with exactly the same code. The module MATGEN of SPARSKIT includes several matrix generation routines.

7.1 Finite Difference Matrices

1. Scalar 5-point and 7-point matrices arising from discretization of the elliptic type equation:

$$Lu = \frac{\partial}{\partial x}(a\frac{\partial}{\partial x}u) + \frac{\partial}{\partial y}(b\frac{\partial}{\partial y}u) + \frac{\partial}{\partial z}(c\frac{\partial}{\partial z}u) + \frac{\partial}{\partial x}(du) + \frac{\partial}{\partial y}(eu) + \frac{\partial}{\partial z}(fu) + gu = hu \tag{1}$$

```
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
* UNSYMMETRIC MATRIX FROM PORES                                               *
*                   Key = PORES 2  , Type = RUA                               *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
    *  Dimension N                                      =       1224  *
    *  Number of nonzero elements                       =       9613  *
    *  Average number of nonzero elements/Column        =     7.8538  *
    *  Standard deviation for above average             =     5.4337  *
    *  Nonzero elements in strict lower part            =       4384  *
    *  Nonzero elements in strict upper part            =       4005  *
    *  Nonzero elements in main diagonal                =       1224  *
    *  Weight of longest column                         =         30  *
    *  Weight of shortest column                        =          2  *
    *  Weight of longest row                            =         16  *
    *  Weight of shortest row                           =          5  *
    *  Matching elements in symmetry                    =       6358  *
    *  Relative Symmetry Match (symmetry=1)             =     0.6614  *
    *  Average distance of a(i,j)  from diag.           =  0.615E+02  *
    *  Standard deviation for above average             =  0.103E+03  *
    *-----------------------------------------------------------------*
    *  Frobenius norm of A                              =  0.150E+09  *
    *  Frobenius norm of symmetric part                 =  0.103E+09  *
    *  Frobenius norm of nonsymmetric part              =  0.980E+08  *
    *  Maximum element in A                             =  0.378E+08  *
    *  Percentage of weakly diagonally dominant rows    =  0.490E-02  *
    *  Percentage of weakly diagonally dominant columns =  0.481E+00  *
    *-----------------------------------------------------------------*
    *  Lower bandwidth  (max: i-j, a(i,j) .ne. 0)       =        470  *
    *  Upper bandwidth  (max: j-i, a(i,j) .ne. 0)       =        471  *
    *  Maximum Bandwidth                                =        736  *
    *  Average Bandwidth                                =  0.190E+03  *
    *  Number of nonzeros in skyline storage            =     342833  *
    *  90% of matrix is in the band of width            =        527  *
    *  80% of matrix is in the band of width            =        145  *
    *  The total number of nonvoid diagonals is         =        367  *
    *  The 10 most important diagonals are (offsets)    :             *
    *     0    -1     1     2    -2     3    32   264  -264   -32     *
    *  The accumulated percentages they represent are   :             *
    *  12.7  24.6  31.7  37.9  43.6  49.0  52.4  55.7  58.6  61.4     *
    *-----------------------------------------------------------------*
    *  The matrix does not have a block structure                     *
    *-----------------------------------------------------------------*
```

Figure 3: Sample output from Info1.ex

```
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
* SYMMETRIC PATTERN FROM CANNES,LUCIEN MARRO,JUNE 1981.                       *
*                   Key = CAN 1072 , Type = PSA                               *
* No values provided - Information on pattern only                            *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
    *  Dimension N                                      =       1072  *
    *  Number of nonzero elements                       =       6758  *
    *  Average number of nonzero elements/Column        =     6.3041  *
    *  Standard deviation for above average             =     6.2777  *
    *  Nonzero elements in strict lower part            =       5686  *
    *  Nonzero elements in strict upper part            =       5686  *
    *  Nonzero elements in main diagonal                =       1072  *
    *  Weight of longest column                         =         39  *
    *  Weight of shortest column                        =          4  *
    *  Matching elements in symmetry                    =       6758  *
    *  Relative Symmetry Match (symmetry=1)             =     1.0000  *
    *  Average distance of a(i,j)  from diag.           =  0.110E+03  *
    *  Standard deviation for above average             =  0.174E+03  *
    *-----------------------------------------------------------------*
    *  Lower bandwidth  (max: i-j, a(i,j) .ne. 0)       =          0  *
    *  Upper bandwidth  (max: j-i, a(i,j) .ne. 0)       =       1048  *
    *  Maximum Bandwidth                                =       1049  *
    *  Average Bandwidth                                =  0.117E+03  *
    *  Number of nonzeros in skyline storage            =     278320  *
    *  90% of matrix is in the band of width            =        639  *
    *  80% of matrix is in the band of width            =        343  *
    *  The total number of nonvoid diagonals is         =        627  *
    *  The  5 most important diagonals are (offsets)    :             *
    *     0     1     2     3     4                                   *
    *  The accumulated percentages they represent are   :             *
    *  15.9  24.7  29.7  33.9  36.3                                   *
    *-----------------------------------------------------------------*
    *  The matrix does not have a block structure                     *
    *-----------------------------------------------------------------*
```

Figure 4: Sample output from Info1.ex for matrix with pattern only

on rectangular regions with general mixed type boundary conditions of the following form

$$\alpha \frac{\partial u}{\partial n} + \beta u = \gamma$$

The user provides the functions $a, b, c, ..., h, \beta, \gamma$ and α is a constant on each boundary surface. The resulting matrix is in general sparse format, possibly printed in a file in the H/B format.

There is a switch in the subroutine which makes it possible to choose between a strict centered difference type of discretization, or an upwind scheme for the first order derivatives.

2. Block 5-point and 7-point matrices arising from discretization of the elliptic type equation (1) in which u is now a vector of $nfree$ components, and $a, b, c, ..., g$ are $nfree \times nfree$ matrices provided by the user.

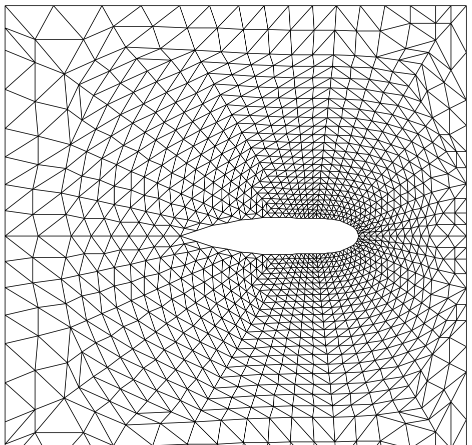
7.2 Finite Element Matrices

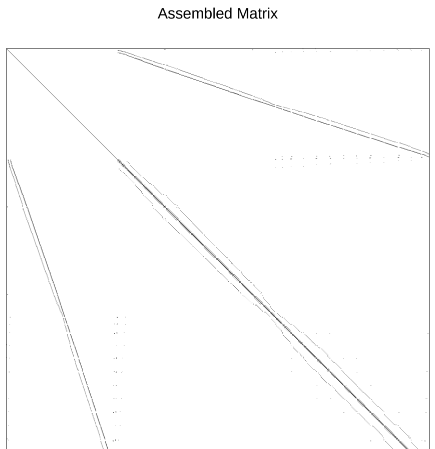
Finite element matrices created from the convection-diffusion type problem

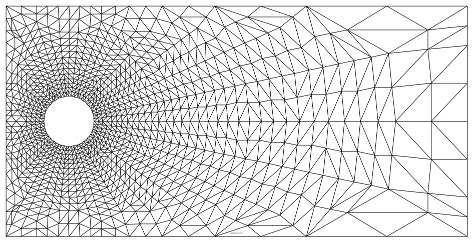
$$-\nabla.(K\nabla u) + C\nabla u = f \tag{2}$$

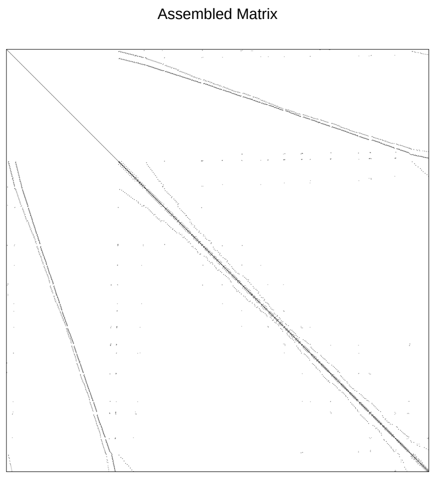
on a domain D with Dirichlet boundary conditions. A coarse initial domain is described by the user and the code does an arbitrary user-specified number of refinements of the grid and assembles the matrix, in CSR format. Linear triangular elements are used. If only the matrix is desired the heat source f can be zero. Arbitrary grids can be input, but the user may also take advantage of nine initial grids supplied by the package for simple test problems.

Two examples of meshes and the corresponding assemble matrices are shown in the following two pairs of figures: the first pair of figures are the mesh and assembled matrix with mesh number 8 and refinement 1; the second pair of figures are the mesh and assembled matrix with mesh number 9 and refinement 1.









7.3 Markov Chains

Markov chain matrices arising from a random walk on a triangular grid. This is mainly useful for testing nonsymmetric eigenvalue codes. It has been suggested by G.W. Stewart in one of his papers [10] and was used by Y. Saad in a few subsequent papers as a test problem for nonsymmetric eigenvalue methods, see, e.g., [8].

7.4 Other Matrices

Currently we have only one additional set of matrices. These are the test matrices [2] from Zlatev et. al. [12] and Osterby and Zlatev [7]. The first two matrix generators described in the above references are referred to as $D(n, c)$ and $E(n, c)$ respectively. A more elaborate class where more than two parameters can be varied, is referred to as the class $F(m, n, c, r, \alpha)$ in [7, 12]. The three subroutines to generate these matrices are called MATRF2 (for the class $F(m, n, c, r, \alpha)$), DCN (for the class $D(c, n)$) and ECN (for the class $E(c, n)$). These codes can generate rectangular as well as square matrices and allow a good flexibility in making the matrices more or less dense and more or less well conditioned.

8 The ORDERING Routines

The following subroutines are available in the directory ORDERINGS.

levset.f	Reordering based on level sets, including Cuthill-McKee implemented with breadth first search.

[2]These subroutines have been contributed to the author by E. Rothman from Cornell University.

color.f	Reordering based on coloring, including a greedy algorithm for multicolor ordering.
ccn.f	Reordering routines based on strongly connected components. Contributed by Laura C. Dutto from the University of Montreal.

9 The ITSOL directory

In ITSOL, the following is available.

ILUT	Preconditioned GMRES algorithm with four preconditioners:
pgmres	Preconditioned GMRES solver. This solver may be used with all four of the precondioners below. Supports right preconditioning only.
ilut	A robust preconditioner called ILUT which uses a dual thresholding strategy for dropping elements. Arbitrary accuracy is allowed in ILUT.
ilutp	ILUT with partial pivoting
ilu0	simple ILU(0) preconditioning
milu0	MILU(0) preconditioning
ITERS	This file currently has several basic iterative linear system solvers which use reverse communication. They are:
cg	Conjugate Gradient Method
cgnr	Conjugate Gradient Method- for Normal Residual equation
bcg	BiConjugate Gradient Method
bcgstab	BCG stablized
tfqmr	TransposeFree QuasiMinimum Residual method
gmres	Generalized Minimum Residual method
fgmres	Flexible version of Generalized Minimum Residual method
dqgmres	Direct versions of Quasi Generalized Minimum Residual method

dbcg	BCG with partial pivoting

10 The UNSUPP directory

In addition to the basic tools described in the previous sections, SPARSKIT includes a directory called UNSUPP includes software that is not necessarily portable or that does not fit in all previous modules. For example software for viewing matrix patterns on some particular workstation may be found here. Another example is routines related to matrix exponentials. Many of these are available from NETLIB but others may be contributed by researchers for comparison purposes.

10.1 Plots

The following items are available in PLOTS.

PSGRD	contains subroutine "psgrid" which plots a symmetric graph.
TEXPLT1	contains subroutine "texplt" allows several matrices in the same picture by calling texplt several times and exploiting job and different shifts.
TEXGRID1	contains subroutine "texgrd" which generates tex commands for plotting a symmetric graph associated with a mesh. Allows several grids in the same picture by calling texgrd several times and exploiting job and different shifts.

10.2 Matrix Exponentials

Two subroutines are available in this directory.

EXPPRO	A subroutine for computing the product of a matrix exponential times a vector, i.e. $w = exp(t\ A)\ v$.
PHIPRO	computes $w = \phi(A\ t)\ v$, where $\phi(x) = (1 - exp(x))/x$; Also allows to solve the system of ODE's $y' = Ay + b$.

11 Distribution

The SPARSKIT package follows the Linpack-Eispack approach in that it aims at providing efficient and well tested subroutines written in portable FORTRAN. Similarly to the Linpack and Eispack packages, the goal is to make available a common base of useful codes for a specific area of computation, in this case sparse linear algebra. The package is in the public domain and will be made accessible through the internet.

See Figure 1 for an illustration of the organization of SPARSKIT. Read the README file in the main directory for more information.

For information concerning distribution contact the author at saad@cs.umn.edu.

12 Conclusion and Future Plans

It is hoped that SPARSKIT will be useful in many ways to researchers in different areas of scientific computing. In this version of SPARSKIT, there are few sparse problem solvers, such as direct solution methods, or eigenvalue solvers. Some of these are available from different sources and we felt that it was not appropriate to provide additional ones. The original motivation for SPARSKIT is that there is a gap to fill in the manipulation and basic computations with sparse matrices. Once this gap is filled with some satisfaction, then additional functionality may be added.

We briefly mentioned in the introduction the possibility of using SPARSKIT to develop an interactive package. Large matrices of dimension tens of of thousands can easily be manipulated with the current supercomputers, in real time. One of the difficulties with such an interactive package is that we do not yet have reliable routines for computing eigenvalues/eigenvectors of large sparse matrices. The state of the art in solving linear systems is in a much better situation. However, one must not contemplate performing the same type of computations as with small dense matrices. As an example, getting all the eigenvalues of a sparse matrix is not likely to be too useful when the matrix is very large.

Beyond interactive software for sparse linear algebra, one can envision the integration of SPARSKIT in a larger package devoted to solving certain types of Partial Differential Equations, possibly interactively.

Acknowledgements. The idea of creating a tool package for sparse matrices germinated while the author was at the Center for Supercomputing Research and Development of the University of Illinois (1986-1987) and part of this work was performed there. Initially the author has benefited from helpful comments from Iain Duff (then visiting CSRD) and a number of colleagues at CSRD. Billy Stewart and his students at NCSU used a preliminary version of SPARSKIT in a class project and made some valuable comments. Ernie Rothman (Cornell) and Laura Dutto (Montreal) contributed some software. The author has also benefited from helpful discussions from a number of other colleagues, including Mike Heroux, Giuseppe Radicatti, Ahmed Sameh, Horst Simon, Phuong Vu, and Harry Wijshoff. Students who contributed to version 2 of SPARSKIT include Kesheng Wu, Edmond Chow, and Dongli Su.

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APPENDIX: QUICK REFERENCE

For convenience we list in this appendix the most important subroutines in the various modules of SPARSKIT. More detailed information can be found either in the body of the paper or in the documentation of the package.

FORMATS Module

- CSRDNS : converts a row-stored sparse matrix into the dense format.
- DNSCSR : converts a dense matrix to a sparse storage format.
- COOCSR : converts coordinate to to csr format
- COICSR : in-place conversion of coordinate to csr format
- CSRCOO : converts compressed sparse row to coordinate format.
- CSRSSR : converts compressed sparse row to symmetric sparse row format.
- SSRCSR : converts symmetric sparse row to compressed sparse row format.
- CSRELL : converts compressed sparse row to Ellpack format
- ELLCSR : converts Ellpack format to compressed sparse row format.
- CSRMSR : converts compressed sparse row format to modified sparse row format.
- MSRCSR : converts modified sparse row format to compressed sparse row format.
- CSRCSC : converts compressed sparse row format to compressed sparse column format (transposition).
- CSRLNK : converts compressed sparse row to linked list format.
- LNKCSR : converts linked list format to compressed sparse row fmt.
- CSRDIA : converts the compressed sparse row format into the diagonal format.
- DIACSR : converts the diagonal format into the compressed sparse row format.
- BSRCSR : converts the block-row sparse format into the compressed sparse row format.
- CSRBSR : converts the compressed sparse row format into the block-row sparse format.
- CSRBND : converts the compressed sparse row format into the banded format (Linpack style).

- BNDCSR : converts the banded format (Linpack style) into the compressed sparse row storage.
- CSRSSK : converts the compressed sparse row format to the symmetric skyline format
- SSKSSR : converts symmetric skyline format to symmetric sparse row format.
- CSRJAD : converts the csr format into the jagged diagonal format.
- JADCSR : converts the jagged-diagonal format into the csr format.
- CSRUSS : converts the csr format to unsymmetric sparse skyline format.
- USSCSR : converts unsymmetric sparse skyline format to the csr format.
- CSRSSS : converts the csr format to symmetric sparse skyline format.
- SSSCSR : converts symmetric sparse skyline format to the csr format.
- CSRVBR : converts compressed sparse row into variable block row format.
- VBRCSR : converts the variable block row format into the
- COOELL : converts the coordinate format into the Ellpack/Itpack format. compressed sparse row format.

UNARY Module

- SUBMAT : extracts a submatrix from a sparse matrix.
- FILTER : filters elements from a matrix according to their magnitude.
- FILTERM: Same as above, but for the MSR format.
- TRANSP : in-place transposition routine (see also CSRCSC in formats)
- GETELM : returns $a(i,j)$ for any (i,j) from a CSR-stored matrix.
- COPMAT : copies a matrix into another matrix (both stored csr).
- MSRCOP : copies a matrix in MSR format into a matrix in MSR format.
- GETELM : returns a(i,j) for any (i,j) from a CSR-stored matrix.
- GETDIA : extracts a specified diagonal from a matrix.
- GETL : extracts lower triangular part.

- GETU : extracts upper triangular part.
- LEVELS : gets the level scheduling structure for lower triangular matrices.
- AMASK : extracts $C = A \odot M$
- RPERM : permutes the rows of a matrix ($B = PA$)
- CPERM : permutes the columns of a matrix ($B = AQ$)
- DPERM : permutes a matrix ($B = PAQ$) given two permutations P, Q
- DPERM2 : general submatrix permutation/extraction routine.
- DMPERM : symmetric permutation of row and column (B=PAP') in MSR fmt.
- DVPERM : permutes a vector (in-place).
- IVPERM : permutes an integer vector (in-place).
- RETMX : returns the max absolute value in each row of the matrix.
- DIAPOS : returns the positions of the diagonal elements in A.
- EXTBDG : extracts the main diagonal blocks of a matrix.
- GETBWD : returns the bandwidth information on a matrix.
- BLKFND : finds the block-size of a matrix.
- BLKCHK : checks whether a given integer is the block size of A.
- INFDIA : obtains information on the diagonals of A.
- AMUBDG : computes the number of nonzero elements in each row of $A * B$.
- APLBDG : computes the number of nonzero elements in each row of $A + B$.
- RNRMS : computes the norms of the rows of A.
- CNRMS : computes the norms of the columns of A.
- ROSCAL : scales the rows of a matrix by their norms.
- COSCAL : scales the columns of a matrix by their norms.
- ADDBLK : adds a matrix B into a block of A.
- GET1UP : collects the first elements of each row of the upper triangular portion of the matrix.
- XTROWS : extracts given rows from a matrix in CSR format.

INOUT Module

- READMT : reads matrices in the boeing/Harwell format.
- PRTMT : prints matrices in the boeing/Harwell format.
- DUMP : prints rows of a matrix, in a readable format.
- PLTMT : produces a 'pic' file for plotting a sparse matrix.
- PSPLTM : Generates a post-script plot of the non-zero pattern of A.
- SMMS : Write the matrix in a format used in SMMS package.
- READSM : Reads matrices in coordinate format (as in SMMS package).
- READSK : Reads matrices in CSR format (simplified H/B formate).
- SKIT : Writes matrices to a file, format same as above.
- PRTUNF : Writes matrices (in CSR format) unformatted.
- READUNF : Reads unformatted data of matrices (in CSR format).

INFO Module

- INFOFUN : routines for statistics on a sparse matrix.

MATGEN Module

- GEN57PT : generates 5-point and 7-point matrices.
- GEN57BL : generates block 5-point and 7-point matrices.
- GENFEA : generates finite element matrices in assembled form.
- GENFEU : generates finite element matrices in unassembled form.
- ASSMB1 : assembles an unassembled matrix (as produced by genfeu).
- MATRF2 : Routines for generating sparse matrices by Zlatev et al.
- DCN: Routines for generating sparse matrices by Zlatev et al.
- ECN: Routines for generating sparse matrices by Zlatev et al.
- MARKGEN: subroutine to produce a Markov chain matrix for a random walk.

BLASSM Module

- AMUB : computes $C = A * B$.
- APLB : computes $C = A + B$.
- APLSB : computes $C = A + sB$.
- APMBT : Computes $C = A \pm B^T$.
- APLSBT : Computes $C = A + s * B^T$.
- DIAMUA : Computes $C = Diag * A$.
- AMUDIA : Computes $C = A * Diag$.
- APLDIA : Computes $C = A + Diag$.
- APLSCA : Computes $A := A + sI$ (s = scalar).

MATVEC Module

- AMUX : A times a vector. Compressed Sparse Row (CSR) format.
- ATMUX : A^T times a vector. CSR format.
- AMUXE : A times a vector. Ellpack/Itpack (ELL) format.
- AMUXD : A times a vector. Diagonal (DIA) format.
- AMUXJ : A times a vector. Jagged Diagonal (JAD) format.
- VBRMV : A times a vector. Variable Block Row (VBR) format.
- LSOL : Unit lower triangular system solution. Compressed Sparse Row (CSR) format.
- LDSOL : Lower triangular system solution. Modified Sparse Row (MSR) format.
- LSOL : Unit lower triangular system solution. Compressed Sparse Column (CSC) format.
- LDSOLC: Lower triangular system solution. Modified Sparse Column (MSC) format.
- LDSOLL: Lower triangular system solution with level scheduling. MSR format.
- USOL : Unit upper triangular system solution. Compressed Sparse Row (CSR) format.

- UDSOL : Upper triangular system solution. Modified Sparse Row (MSR) format.
- USOLC : Unit upper triangular system solution. Compressed Sparse Column (CSC) format.
- UDSOLC: Upper triangular system solution. Modified Sparse Column (MSC) format.

ORDERINGS Module

- levset.f : level set based reordering, including RCM
- color.f : coloring based reordering
- ccn.f : reordering based on strongly connected components

ITSOL Module

- ILUT: ILUT(k) preconditioned GMRES mini package.
- ITERS: nine basic iterative linear system solvers.

PLOTS Module

- PSGRD: plots a symmetric graph.
- TEXPLT1: allows several matrices in the same picture.
- TEXGRID1: allows several grids in the same picture.

MATEXP Module

- EXPPRO: computes $w = exp(t\ A)\ v$.
- PHIPRO: computes $w = \phi(A\ t)\ v$, where $\phi(x) = (1 - exp(x))/x$. Also solves the P.D.E. system $y' = Ay + b$.