

# Lis User Manual

Version 1.2.103



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Akira Nishida, Research Institute for Information Technology, Kyushu University, 6-10-1, Hakozaki, Higashi-ku, Fukuoka 812-8581 Japan  
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Cover: Ogata Korin, Irises.

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## 0 Changes from Version 1.1

1. Added the support for the eigensolvers.
2. Changed the specifications of the following functions:
  - (a) Changed the names of `lis_output_residual_history()` and `lis_get_residual_history()` to `lis_solver_output_rhistory()` and `lis_solver_get_rhistory()`, respectively.
  - (b) Changed the origin of the Fortran interfaces `lis_vector_set_value()` and `lis_vector_get_value()` to 1.
  - (c) Changed the origin of the Fortran interface `lis_vector_set_size()` to 1.
  - (d) Changed the name of the precision flag `-precision` to `-f`.
3. Changed the specifications of the integer types:
  - (a) Replaced the type of the integer in the C programs with `LIS_INT`, which is equivalent with `int` by default. If the preprocessor macro `_LONGLONG` is defined, it is replaced with `long long int`.
  - (b) Replaced the type of the integer in the Fortran programs with `LIS_INTEGER`, which is equivalent with `integer` by default. If the preprocessor macro `LONGLONG` is defined, it is replaced with `integer*8`.

# 1 Introduction

Lis, a Library of Iterative Solvers for linear systems, is a parallel numerical library for solving the linear equations

$$Ax = b$$

and the standard eigenvalue problems

$$Ax = \lambda x$$

with real sparse matrices using the iterative methods. The solvers available in Lis are listed in Table 1 and 2, and the preconditioners are listed in Table 3. The supported matrix storage formats are listed in Table 4.

Table 1: Linear Solvers

CG	CR
BiCG	BiCR[2]
CGS	CRS[3]
BiCGSTAB	BiCRSTAB[3]
GPBiCG	GPBiCR[3]
BiCGSafe[1]	BiCRSafe[4]
BiCGSTAB(1)	TFQMR
Jacobi	Orthomin(m)
Gauss-Seidel	GMRES(m)
SOR	FGMRES(m)[5]
IDR(s)[13]	MINRES[14]

Table 2: Eigensolvers

Power
Inverse
Approximate Inverse
Rayleigh Quotient
Subspace
Lanczos
CG[18, 19]
CR[20]

Table 3: Preconditioners

Jacobi
SSOR
ILU(k)
ILUT[6, 7]
Crout ILU[8, 7]
I+S[9]
SA-AMG[10]
Hybrid[11]
SAINV[12]
Additive Schwarz
User defined

Table 4: Matrix Storage Formats

Compressed Row Storage	(CRS)
Compressed Column Storage	(CCS)
Modified Compressed Sparse Row	(MSR)
Diagonal	(DIA)
Ellpack-Itpack Generalized Diagonal	(ELL)
Jagged Diagonal	(JDS)
Block Sparse Row	(BSR)
Block Sparse Column	(BSC)
Variable Block Row	(VBR)
Dense	(DNS)
Coordinate	(COO)



## 2 Installation

This section describes the instructions for installing and testing Lis. We assume Lis being installed on a Linux cluster.

### 2.1 System Requirements

Installation of Lis requires a C compiler. The Fortran interface requires a Fortran compiler. The algebraic multigrid preconditioner requires a Fortran 90 compiler. For parallel computing environments, the OpenMP library or the MPI-1 library is used. Lis has been tested on the environments shown in Table 5 (see also Table 7).

Table 5: Major Tested Platforms

C Compilers	OS
Intel C/C++ Compiler 7.0, 8.0, 9.1, 10.1, 11.1, Intel C++ Composer XE	Linux Windows
IBM XL C/C++ V7.0, 9.0	AIX Linux
Sun WorkShop 6, Sun ONE Studio 7, Sun Studio 11, 12	Solaris
PGI C++ 6.0, 7.1, 10.5	Linux
gcc 3.3, 4.3	Linux Mac OS X Windows
Microsoft Visual C++ 2008, 2010, 2012RC	Windows
Fortran Compilers (Optional)	OS
Intel Fortran Compiler 8.1, 9.1, 10.1, 11.1, Intel Fortran Composer XE	Linux Windows
IBM XL Fortran V9.1, 11.1	AIX Linux
Sun WorkShop 6, Sun ONE Studio 7, Sun Studio 11, 12	Solaris
PGI Fortran 6.0, 7.1, 10.5	Linux
g77 3.3 gfortran 4.3, 4.4 g95 0.91	Linux Mac OS X Windows

### 2.2 Extracting Archive

Enter the following command to extract the archive, where (\$VERSION) represents the version:

```
>gunzip -c lis-($VERSION).tar.gz | tar xvf -
```

It creates a directory lis-(\$VERSION) along with its subfolders as shown in Figure 1.

### 2.3 Installing on UNIX and Compatible Systems

#### 2.3.1 Configuring Source Tree

Run the following script to configure the source tree:

- default: `>./configure`
- specify the installation destination: `>./configure --prefix=<install-dir>`

```

lis-($VERSION)
+ config
| configuration files
+ doc
| documents
+ include
| header files
+ src
| source files
+ test
| test programs
+ win32
  configuration files for Windows systems

```

Figure 1: Files contained in `lis-($VERSION).tar.gz`

Table 6 shows the major options which can be specified for the configuration. Table 7 shows the major computing environments which can be specified by `TARGET`.

Table 6: Major Configuration Options (see `./configure --help` for the complete list)

<code>--enable-omp</code>	Enable the OpenMP library
<code>--enable-mpi</code>	Enable the MPI library
<code>--enable-fortran</code>	Enable the Fortran interface
<code>--enable-saamg</code>	Enable the SA-AMG preconditioner
<code>--enable-quad</code>	Enable the quadruple precision operations
<code>--enable-longlong</code>	Enable the 64bit integer
<code>--enable-shared</code>	Enable the dynamic linking
<code>--enable-gprof</code>	Enable the GNU profiler
<code>--prefix=&lt;install-dir&gt;</code>	Specify the installation destination
<code>TARGET=&lt;target&gt;</code>	Specify the computing environment
<code>CC=&lt;c_compiler&gt;</code>	Specify the C compiler
<code>CFLAGS=&lt;c_flags&gt;</code>	Specify the options for the C compiler
<code>FC=&lt;fortran90_compiler&gt;</code>	Specify the Fortran 90 compiler
<code>FCFLAGS=&lt;fc_flags&gt;</code>	Specify the options for the Fortran 90 compiler
<code>LDFLAGS=&lt;ld_flags&gt;</code>	Specify the link options

### 2.3.2 Compiling

In the directory `lis-($VERSION)`, run the following command to generate executable files:

```
>make
```

To ensure that the library has been successfully built, enter as follows in `lis-($VERSION)`:

```
>make check
```

It runs a test script using the executable files created in `lis-($VERSION)/test`, which reads the data of the coefficient matrix and the right hand side vector from the file `test/testmat.mtx` and writes the solution of the linear equation  $Ax = b$  obtained by the BiCG method into `test/sol.txt`, and the residual history into `test/res.txt`. If the values of the elements of the solution are 1, then the result is correct. The result on the SGI Altix 3700 is shown below.

Table 7: Examples of Targets (see `lis-($VERSION)/configure.in` for details)

<target>	Equivalent options
cray_xt3_cross	<code>./configure CC=cc FC=ftn CFLAGS="-O3 -B -fastsse -tp k8-64" FCFLAGS="-O3 -fastsse -tp k8-64 -Mpreprocess" FCLDFLAGS="-Mnomain" ac_cv_sizeof_void_p=8 cross_compiling=yes --enable-mpi ax_f77_mangling="lower case, no underscore, extra underscore"</code>
fujitsu_fx10_cross	<code>./configure CC=fccpx FC=frtpx CFLAGS="-Kfast,ocl,preex -w" FCFLAGS="-Kfast,ocl,preex -Cpp -fs" FCLDFLAGS="-mlcmain=main" ac_cv_sizeof_void_p=8 cross_compiling=yes ax_f77_mangling="lower case, underscore, no extra underscore"</code>
hitachi_sr16k	<code>./configure CC=cc FC=f90 CFLAGS="-Os -noprogram" FCFLAGS="-Oss -noprogram" FCLDFLAGS="-lf90s" ac_cv_sizeof_void_p=8 ax_f77_mangling="lower case, underscore, no extra underscore"</code>
ibm_bg1_cross	<code>./configure CC=blrts_xlc FC=blrts_xlf90 CFLAGS="-O3 -qarch=440d -qtune=440 -qstrict -I/bg1/BlueLight/ppcfloor/bglsys/include" FCFLAGS="-O3 -qarch=440d -qtune=440 -qsuffix=cpp=F90 -w -I/bg1/BlueLight/ppcfloor/bglsys/include" ac_cv_sizeof_void_p=4 cross_compiling=yes --enable-mpi ax_f77_mangling="lower case, no underscore, no extra underscore"</code>
nec_es_cross	<code>./configure CC=esmpic++ FC=esmpif90 AR=esar RANLIB=true ac_cv_sizeof_void_p=8 ax_vector_machine=yes cross_compiling=yes --enable-mpi --enable-omp ax_f77_mangling="lower case, no underscore, extra underscore"</code>
nec_sx9_cross	<code>./configure CC=sxmpic++ FC=sxmpif90 AR=sxar RANLIB=true ac_cv_sizeof_void_p=8 ax_vector_machine=yes cross_compiling=yes ax_f77_mangling="lower case, no underscore, extra underscore"</code>

#### Default

```
matrix size = 100 x 100 (460 nonzero entries)
initial vector x = 0
precision : double
solver    : BiCG 2
precon    : none
storage   : CRS
lis_solve : normal end

BiCG: number of iterations      = 15 (double = 15, quad = 0)
BiCG: elapsed time             = 5.178690e-03 sec.
BiCG: preconditioner           = 1.277685e-03 sec.
BiCG: matrix creation          = 1.254797e-03 sec.
BiCG: linear solver            = 3.901005e-03 sec.
BiCG: relative residual 2-norm = 6.327297e-15
```

#### --enable-omp

```
max number of threads = 32
number of threads = 2
matrix size = 100 x 100 (460 nonzero entries)
initial vector x = 0
precision : double
solver    : BiCG 2
precon    : none
storage   : CRS
lis_solve : normal end

BiCG: number of iterations      = 15 (double = 15, quad = 0)
BiCG: elapsed time             = 8.960009e-03 sec.
BiCG: preconditioner           = 2.297878e-03 sec.
BiCG: matrix creation          = 2.072096e-03 sec.
BiCG: linear solver            = 6.662130e-03 sec.
BiCG: relative residual 2-norm = 6.221213e-15
```

```

--enable-mpi
number of processes = 2
matrix size = 100 x 100 (460 nonzero entries)
initial vector x = 0
precision : double
solver      : BiCG 2
precon      : none
storage     : CRS
lis_solve   : normal end

BiCG: number of iterations      = 15 (double = 15, quad = 0)
BiCG: elapsed time              = 2.911400e-03 sec.
BiCG: preconditioner           = 1.560780e-04 sec.
BiCG: matrix creation          = 1.459997e-04 sec.
BiCG: linear solver            = 2.755322e-03 sec.
BiCG: relative residual 2-norm = 6.221213e-15

```

### 2.3.3 Installing

In the directory `lis-($VERSION)`, enter as follows:

```
>make install
```

It copies the files to the destination directory as follows:

```

($INSTALLDIR)
+bin
|   +lsolve esolve spmvtest[1-5]
+include
|   +lis_config.h lis.h lisf.h
+lib
|   +liblis.a
+share
    +doc/lis examples/lis man

```

`lis_config.h` is the header file required to build the library, and `lis.h` and `lisf.h` are the header files required by the C and Fortran compilers, respectively. `liblis.a` is the library file. To ensure that the library has been successfully installed, enter as follows in `lis-($VERSION)`:

```
>make installcheck
```

It runs a test script using the executable files installed in `examples/lis`. `test1` and `etest1` in `examples/lis` are copied in `($INSTALLDIR)/bin` as `lsolve` and `esolve`, respectively. `examples/lis/spmvtest[1-5]` are also copied in `($INSTALLDIR)/bin`.

## 2.4 Installing on Windows Systems

Use one of the solution files or project files for the Microsoft Visual Studio in the directory `lis-($VERSION)/win32`. `lis_with_fortran.sln` is the solution file to be used with the Intel Visual Fortran Compiler.

`lis_with_fortran_mpi.sln` is the solution file to be used with the Visual Fortran and MPICH2. The header files are located in `lis-($VERSION)/include`. `lis_config.win32.h` is the header file required to build the library. `lis.h` and `lisf.h` are the header files required by the C and Fortran compilers, respectively. The library files are generated in `lis-($VERSION)/lib`. The executable files of the test programs are generated in `lis-($VERSION)/test`.

## 2.5 Testing

### 2.5.1 test1

Usage: `test1 matrix_filename rhs_setting solution_filename residual_filename [options]`

This program inputs the data of the coefficient matrix from `matrix_filename` and solves the linear equation  $Ax = b$  with the solver specified by `options`. It outputs the solution to `solution_filename` in the extended Matrix Market format and the residual history to `residual_filename` in the PLAIN format (see Appendix). The Matrix Market and extended Matrix Market formats are supported for `matrix_filename`. One of the following values can be specified by `rhs_setting`:

0	Use the right hand side vector $b$ included in the data file
1	Use $b = (1, \dots, 1)^T$
2	Use $b = A \times (1, \dots, 1)^T$
<code>rhs_filename</code>	The filename for the right hand side vector

The PLAIN and Matrix Market formats are supported for `rhs_filename`. `test1f.F` is the Fortran version of `test1.c`.

### 2.5.2 test2

Usage: `test2 m n matrix_type solution_filename residual_filename [options]`

This program solves a discretized two dimensional Poisson equation  $Ax = b$  using the five point central difference scheme, with the coefficient matrix  $A$  of size  $mn$  in the storage format specified by `matrix_type` and the solver specified by `options`. It outputs the solution to `solution_filename` in the extended Matrix Market format and the residual history to `residual_filename` in the PLAIN format. The right hand side vector is set to make the values of the elements of the solution to be 1. The values `m` and `n` represent the numbers of the grid points in each dimension.

### 2.5.3 test3

Usage: `test3 l m n matrix_type solution_filename residual_filename [options]`

This program solves a discretized three dimensional Poisson equation  $Ax = b$  using the seven point central difference scheme, with the coefficient matrix  $A$  of size  $lmn$  in the storage format specified by `matrix_type` and the solver specified by `options`. It outputs the solution to `solution_filename` in the extended Matrix Market format and the residual history to `residual_filename` in the PLAIN format. The right hand side vector is set to make the values of the elements of the solution to be 1. The values `l`, `m` and `n` represent the numbers of the grid points in each dimension.

### 2.5.4 test4

This program solves the linear equation  $Ax = b$  with a specified solver and a preconditioner, where  $A$  is a tridiagonal matrix

$$\begin{pmatrix} 2 & -1 & & & \\ -1 & 2 & -1 & & \\ & \ddots & \ddots & \ddots & \\ & & -1 & 2 & -1 \\ & & & -1 & 2 \end{pmatrix}$$

of size 12. The right hand side vector  $b$  is set to make the values of the elements of the solution  $x$  to be 1. `test4f.F` is the Fortran version of `test4.c`.

### 2.5.5 test5

Usage: test5 n gamma [options]

This program solves a linear equation  $Ax = b$ , where  $A$  is a Toeplitz matrix

$$\begin{pmatrix} 2 & 1 & & & & \\ 0 & 2 & 1 & & & \\ \gamma & 0 & 2 & 1 & & \\ & \ddots & \ddots & \ddots & \ddots & \\ & & \gamma & 0 & 2 & 1 \\ & & & \gamma & 0 & 2 \end{pmatrix}$$

of size  $n$ , with the solver specified by **options**. Note that the right hand vector is set to make the values of the elements of the solution to be 1.

### 2.5.6 etest1

Usage: etest1 matrix\_filename solution\_filename residual\_filename [options]

This program inputs the matrix data from **matrix\_filename** and solves the eigenvalue problem  $Ax = \lambda x$  with the solver specified by **options**. It outputs the associated eigenvector to **solution\_filename** in the extended Matrix Market format and the residual history to **residual\_filename** in the PLAIN format. The Matrix Market format is supported for **matrix\_filename**. **etest1f.F** is the Fortran version of **etest1.c**.

### 2.5.7 etest2

Usage: etest2 m n matrix\_type solution\_filename residual\_filename [options]

This program solves the eigenvalue problem  $Ax = \lambda x$ , where the coefficient matrix  $A$  of size  $mn$  is derived from a discretized two dimensional Helmholtz equation using the five point central difference scheme, with the coefficient matrix in the storage format specified by **matrix\_type** and the solver specified by **options**. It outputs the associated eigenvector to **solution\_filename** in the extended Matrix Market format and the residual history to **residual\_filename** in the PLAIN format. The values **m** and **n** represent the numbers of the grid points in each dimension.

### 2.5.8 etest3

Usage: etest3 l m n matrix\_type solution\_filename residual\_filename [options]

This program solves the eigenvalue problem  $Ax = \lambda x$ , where the coefficient matrix  $A$  of size  $lmn$  is derived from a discretized three dimensional Helmholtz equation using the seven point central difference scheme, with the coefficient matrix in the storage format specified by **matrix\_type** and the solver specified by **options**. It outputs the associated eigenvector to **solution\_filename** in the extended Matrix Market format and the residual history to **residual\_filename** in the PLAIN format. The values **l**, **m** and **n** represent the numbers of the grid points in each dimension.

### 2.5.9 etest4

Usage: etest4 n [options]

This program solves the eigenvalue problem  $Ax = \lambda x$  with a specified solver, where  $A$  is a tridiagonal matrix

$$A = \begin{pmatrix} 2 & -1 & & & \\ -1 & 2 & -1 & & \\ & \ddots & \ddots & \ddots & \\ & & -1 & 2 & -1 \\ & & & -1 & 2 \end{pmatrix}$$

of size  $n \times n$ . `etest4f.F` is the Fortran version of `etest4.c`.

### 2.5.10 etest5

Usage: `etest5 matrix_filename eigenvalue_filename eigenvector_filename [options]`

This program inputs the matrix data from `matrix_filename` and solves the eigenvalue problem  $Ax = \lambda x$  with the solver specified by `options`. It outputs the eigenvalues specified by `options` to `eigenvalue_filename` and the associated eigenvectors to `eigenvector_filename` in the extended Matrix Market format. The Matrix Market format is supported for `matrix_filename`.

### 2.5.11 etest6

Usage: `etest6 l m n matrix_type eigenvalue_filename eigenvector_filename [options]`

This program solves the eigenvalue problem  $Ax = \lambda x$ , where the coefficient matrix  $A$  of size  $lmn$  is derived from a discretized three dimensional Helmholtz equation using the seven point central difference scheme, with the coefficient matrix in the storage format specified by `matrix_type` and the solver specified by `options`. It outputs the eigenvalues specified by `options` to `eigenvalue_filename` and the associated eigenvectors to `eigenvector_filename` in the extended Matrix Market format. The values `l`, `m` and `n` represent the numbers of the grid points in each dimension.

### 2.5.12 spmvtest1

Usage: `spmvtest1 n iter [matrix_type]`

This program computes the multiply of a tridiagonal matrix

$$\begin{pmatrix} 2 & -1 & & & \\ -1 & 2 & -1 & & \\ & \ddots & \ddots & \ddots & \\ & & -1 & 2 & -1 \\ & & & -1 & 2 \end{pmatrix}$$

of size  $n$ , derived from a discretized one dimensional Poisson equation using the three point central difference scheme, and a vector  $(1, \dots, 1)^T$ . The FLOPS performance is measured as the average of `iter` iterations. If necessary, one of the following values can be specified by `matrix_type`:

- |      |  |
|------|--|
| 0    | Measure the performance for the available matrix storage formats |
| 1-11 | The number of the matrix storage format                          |

### 2.5.13 spmvtest2

Usage: `spmvtest2 m n iter [matrix_type]`



This program computes the multiply of a sparse matrix, derived from a discretized two dimensional Poisson equation using the five point central difference scheme, and a vector  $(1, \dots, 1)^T$ . The FLOPS performance is measured as the average of `iter` iterations. If necessary, one of the following values can be specified by `matrix_type`:

0	Measure the performance for the available matrix storage formats
1-11	The number of the matrix storage format

The values `m` and `n` represent the numbers of the grid points in each dimension.

#### 2.5.14 `spmvtest3`

Usage: `spmvtest3 l m n iter [matrix_type]`

This program computes the multiply of a sparse matrix, derived from a discretized three dimensional Poisson equation using the seven point central difference scheme, and a vector  $(1, \dots, 1)^T$ . The values `l`, `m` and `n` represent the numbers of the grid points in each dimension. The FLOPS performance is measured as the average of `iter` iterations. If necessary, one of the following values can be specified by `matrix_type`:

0	Measure the performance for the available matrix storage formats
1-11	The number of the matrix storage format

#### 2.5.15 `spmvtest4`

Usage: `spmvtest4 matrix_filename_list iter [block]`

This program inputs the matrix data from the files listed in `matrix_filename_list`, and computes the multiplies of matrices in available matrix storage formats and a vector  $(1, \dots, 1)^T$ . The FLOPS performance is measured as the average of `iter` iterations. The Matrix Market format is supported for `matrix_filename_list`. If necessary, the block size of the BSR and BSC formats can be specified by `block`.

#### 2.5.16 `spmvtest5`

Usage: `spmvtest5 matrix_filename matrix_type iter [block]`

This program inputs the matrix data from `matrix_filename` and compute the multiply of the matrix with `matrix_type` and a vector  $(1, \dots, 1)^T$ . The FLOPS performance is measured as the average of `iter` iterations. The Matrix Market format is supported for `matrix_filename`. If necessary, the block size of the BSR and BSC formats can be specified by `block`.

## 2.6 Restrictions

The current version has the following restrictions:

- Preconditioners
  - If a preconditioner other than the Jacobi or SSOR is selected and the matrix  $A$  is not in the CRS format, a new matrix is created in the CRS format for preconditioning.
  - The SA-AMG preconditioner does not support the BiCG method.
  - The SA-AMG preconditioner does not support the multithreaded environment.
  - The assembly of the matrices in the SAINV preconditioner is not parallelized.

- Quadruple precision operations
  - The Jacobi, Gauss-Seidel, SOR, and IDR(s) methods do not support the quadruple precision operations.
  - The CG and CR methods for the eigenvalue problems do not support the quadruple precision operations.
  - The Jacobi, Gauss-Seidel and SOR methods in the hybrid preconditioner do not support the quadruple precision operations.
  - The I+S and SA-AMG preconditioners do not support the quadruple precision operations.
- Matrix storage formats
  - In the multiprocessing environment, the CRS is the only accepted format for the user defined arrays.

### 3 Basic Operations

This section describes how to use the library. A program requires the following statements:

- Initialization
- Matrix creation
- Vector creation
- Solver creation
- Value assignment for matrices and vectors
- Solver assignment
- Solver execution
- Finalization

In addition, it must include one of the following `include` statements:

- C `#include "lis.h"`
- Fortran `#include "lisf.h"`

When Lis is installed in `($INSTALLDIR)`, `lis.h` and `lisf.h` are located in `($INSTALLDIR)/include`.

#### 3.1 Initializing and Finalizing

The functions for initializing and finalizing the execution environment must be called at the top and bottom of the program, respectively, as follows:

```
C
1: #include "lis.h"
2: LIS_INT main(LIS_INT argc, char* argv[])
3: {
4:     lis_initialize(&argc, &argv);
5:     ...
6:     lis_finalize();
7: }
```

```
Fortran
1: #include "lisf.h"
2:     call lis_initialize(ierr)
3:     ...
4:     call lis_finalize(ierr)
```

#### Initializing

For initializing, the following functions are used:

- C `LIS_INT lis_initialize(LIS_INT* argc, char** argv[])`
- Fortran subroutine `lis_initialize(LIS_INTEGER ierr)`

This function initializes the MPI execution environment, and specifies the options on the command line.

The default type of the integer in the C programs is `LIS_INT`, which is equivalent with `int`. If the preprocessor macro `_LONGLONG` is defined, it is replaced with `long long int`. The default type of the integer in the Fortran programs is `LIS_INTEGER`, which is equivalent with `integer`. If the preprocessor macro

LONGLONG is defined, it is replaced with `integer*8`.

### Finalizing

For finalizing, the following functions are used:

- C            `LIS_INT lis_finalize()`
- Fortran subroutine `lis_finalize(LIS_INTEGER ierr)`

## 3.2 Operating Vectors

Assume that the size of the vector  $v$  is  $global\_n$ , and the size of each partial vector stored on  $nprocs$  processing elements is  $local\_n$ . If  $global\_n$  is divisible, then  $local\_n$  is equal to  $global\_n / nprocs$ . For example, when the vector  $v$  is stored on two processing elements, as shown in Equation (3.1),  $global\_n$  and  $local\_n$  are 4 and 2, respectively.

$$v = \begin{pmatrix} 0 \\ 1 \\ 2 \\ 3 \end{pmatrix} \begin{matrix} \text{PE0} \\ \text{PE1} \end{matrix} \quad (3.1)$$

In the case of creating the vector  $v$  in Equation (3.1), the vector  $v$  itself is created for the serial and multithreaded environments, while the partial vectors are created and stored on a given number of processing elements for the multiprocessing environment.

Programs to create the vector  $v$  are as follows, where the number of the processing elements for the multiprocessing environment is assumed to be two:

C (for serial and multithreaded environments)

```
1: LIS_INT      i,n;
2: LIS_VECTOR   v;
3: n = 4;
4: lis_vector_create(0,&v);
5: lis_vector_set_size(v,0,n);          /* or lis_vector_set_size(v,n,0); */
6:
7: for(i=0;i<n;i++)
8: {
9:     lis_vector_set_value(LIS_INS_VALUE,i,(double)i,v);
10: }
```

C (for multiprocessing environment)

```
1: LIS_INT      i,n,is,ie;              /* or LIS_INT i,ln,is,ie; */
2: LIS_VECTOR   v;
3: n = 4;                                /* ln = 2; */
4: lis_vector_create(MPI_COMM_WORLD,&v);
5: lis_vector_set_size(v,0,n);          /* lis_vector_set_size(v,ln,0); */
6: lis_vector_get_range(v,&is,&ie);
7: for(i=is;i<ie;i++)
8: {
9:     lis_vector_set_value(LIS_INS_VALUE,i,(double)i,v);
10: }
```

Fortran (for serial and multithreaded environments)

```
1: LIS_INTEGER    i,n
2: LIS_VECTOR     v
3: n = 4
4: call lis_vector_create(0,v,ierr)
5: call lis_vector_set_size(v,0,n,ierr)
6:
7: do i=1,n
9:     call lis_vector_set_value(LIS_INS_VALUE,i,DBLE(i),v,ierr)
10: enddo
```

Fortran (for multiprocessing environment)

```
1: LIS_INTEGER    i,n,is,ie
2: LIS_VECTOR     v
3: n = 4
4: call lis_vector_create(MPI_COMM_WORLD,v,ierr)
5: call lis_vector_set_size(v,0,n,ierr)
6: call lis_vector_get_range(v,is,ie,ierr)
7: do i=is,ie-1
8:     call lis_vector_set_value(LIS_INS_VALUE,i,DBLE(i),v,ierr);
9: enddo
```

## Declaring Variables

As the second line shows, the declaration is stated as follows:

```
LIS_VECTOR     v;
```

## Creating Vectors

To create the vector  $v$ , the following functions are used:

- C `LIS_INT lis_vector_create(LIS_Comm comm, LIS_VECTOR *v)`
- Fortran subroutine `lis_vector_create(LIS_Comm comm, LIS_VECTOR v, LIS_INTEGER ierr)`

For the example program above, `comm` must be replaced with the MPI communicator. For the serial and multithreaded environments, the value of `comm` is ignored.

## Assigning Sizes

To assign a size to the vector  $v$ , the following functions are used:

- C `LIS_INT lis_vector_set_size(LIS_VECTOR v, LIS_INT local_n, LIS_INT global_n)`
- Fortran subroutine `lis_vector_set_size(LIS_VECTOR v, LIS_INTEGER local_n, LIS_INTEGER global_n, LIS_INTEGER ierr)`

Either *local\_n* or *global\_n* must be provided.

In the case of the serial and multithreaded environments, *local\_n* is equal to *global\_n*. Therefore, both `lis_vector_set_size(v,n,0)` and `lis_vector_set_size(v,0,n)` create a vector of size  $n$ .

For the multiprocessing environment, `lis_vector_set_size(v,n,0)` creates a partial vector of size  $n$  on each processing element. On the other hand, `lis_vector_set_size(v,0,n)` creates a partial vector of size  $m_p$  on the processing element  $p$ . The values of  $m_p$  are determined by the library.

## Assigning Values

To assign a value to the  $i$ -th element of the vector  $v$ , the following functions are used:

- C `LIS_INT lis_vector_set(LIS_INT flag, LIS_INT i, LIS_SCALAR value, LIS_VECTOR v)`
- Fortran subroutine `lis_vector_set_value(LIS_INT flag, LIS_INT i, LIS_SCALAR value, LIS_VECTOR v, LIS_INTEGER ierr)`

For the multiprocessing environment, the  $i$ -th row of the global vector must be specified. Either

`LIS_INS_VALUE : v[i] = value`, or

`LIS_ADD_VALUE : v[i] = v[i] + value`

must be provided for `flag`.

### Duplicating Vectors

To create a vector which has the same information as the existing vector, the following functions are used:

- C `LIS_INT lis_vector_duplicate(LIS_VECTOR vin, LIS_VECTOR *vout)`
- Fortran subroutine `lis_vector_duplicate(LIS_VECTOR vin, LIS_VECTOR vout, LIS_INTEGER ierr)`

This function does not copy the values of the vector. To copy the values as well, the following functions must be called after the above functions:

- C `LIS_INT lis_vector_copy(LIS_VECTOR vsrc, LIS_VECTOR vdst)`
- Fortran subroutine `lis_vector_copy(LIS_VECTOR vsrc, LIS_VECTOR vdst, LIS_INTEGER ierr)`

### Destroying Vectors

To destroy the vector, the following functions are used:

- C `LIS_INT lis_vector_destroy(LIS_VECTOR v)`
- Fortran subroutine `lis_vector_destroy(LIS_VECTOR v, LIS_INTEGER ierr)`

## 3.3 Operating Matrices

Assume that the size of the matrix  $A$  is  $global\_n \times global\_n$ , and that the size of each row block of the matrix  $A$  stored on  $nprocs$  processing elements is  $local\_n \times global\_n$ . If  $global\_n$  is divisible, then  $local\_n$  is equal to  $global\_n / nprocs$ . For example, when the row block of the matrix  $A$  is stored on two processing elements, as shown in Equation (3.2),  $global\_n$  and  $local\_n$  are 4 and 2, respectively.

$$A = \left( \begin{array}{ccc} 2 & 1 & \\ 1 & 2 & 1 \\ 1 & 2 & 1 \\ & 1 & 2 \end{array} \right) \begin{array}{l} \text{PE0} \\ \text{PE1} \end{array} \quad (3.2)$$

A matrix in a specific storage format can be created in one of the following three ways:

#### Method 1: Define Arrays in a Specific Storage Format with Library Functions

In the case of creating the matrix  $A$  in Equation (3.2) in the CRS format, the matrix  $A$  itself is created for the serial and multithreaded environments, while the partial matrices are created and stored on the given number of processing elements for the multiprocessing environment.

Programs to create the matrix  $A$  in the CRS format are as follows, where the number of the processing elements for the multiprocessing environment is assumed to be two:

C (for serial and multithreaded environments)

```

1: LIS_INT      i,n;
2: LIS_MATRIX   A;
3: n = 4;
4: lis_matrix_create(0,&A);
5: lis_matrix_set_size(A,0,n);          /* or lis_matrix_set_size(A,n,0); */
6: for(i=0;i<n;i++) {
7:     if( i>0 ) lis_matrix_set_value(LIS_INS_VALUE,i,i-1,1.0,A);
8:     if( i<n-1 ) lis_matrix_set_value(LIS_INS_VALUE,i,i+1,1.0,A);
9:     lis_matrix_set_value(LIS_INS_VALUE,i,i,2.0,A);
10: }
11: lis_matrix_set_type(A,LIS_MATRIX_CRS);
12: lis_matrix_assemble(A);

```

C (for multiprocessing environment)

```

1: LIS_INT      i,n,gn,is,ie;
2: LIS_MATRIX   A;
3: gn = 4;          /* or n=2 */
4: lis_matrix_create(MPI_COMM_WORLD,&A);
5: lis_matrix_set_size(A,0,gn);          /* lis_matrix_set_size(A,n,0); */
6: lis_matrix_get_size(A,&n,&gn);
7: lis_matrix_get_range(A,&is,&ie);
8: for(i=is;i<ie;i++) {
9:     if( i>0 ) lis_matrix_set_value(LIS_INS_VALUE,i,i-1,1.0,A);
10:    if( i<gn-1 ) lis_matrix_set_value(LIS_INS_VALUE,i,i+1,1.0,A);
11:    lis_matrix_set_value(LIS_INS_VALUE,i,i,2.0,A);
12: }
13: lis_matrix_set_type(A,LIS_MATRIX_CRS);
14: lis_matrix_assemble(A);

```

Fortran (for serial and multithreaded environments)

```

1: LIS_INTEGER  i,n
2: LIS_MATRIX   A
3: n = 4
4: call lis_matrix_create(0,A,ierr)
5: call lis_matrix_set_size(A,0,n,ierr)
6: do i=1,n
7:     if( i>1 ) call lis_matrix_set_value(LIS_INS_VALUE,i,i-1,1.0d0,A,ierr)
8:     if( i<n ) call lis_matrix_set_value(LIS_INS_VALUE,i,i+1,1.0d0,A,ierr)
9:     call lis_matrix_set_value(LIS_INS_VALUE,i,i,2.0d0,A,ierr)
10: enddo
11: call lis_matrix_set_type(A,LIS_MATRIX_CRS,ierr)
12: call lis_matrix_assemble(A,ierr)

```

Fortran (for multiprocessing environment)

```
1: LIS_INTEGER    i,n,gn,is,ie
2: LIS_MATRIX     A
3: gn = 4
4: call lis_matrix_create(MPI_COMM_WORLD,A,ierr)
5: call lis_matrix_set_size(A,0,gn,ierr)
6: call lis_matrix_get_size(A,n,gn,ierr)
7: call lis_matrix_get_range(A,is,ie,ierr)
8: do i=is,ie-1
9:     if( i>1 ) call lis_matrix_set_value(LIS_INS_VALUE,i,i-1,1.0d0,A,ierr)
10:    if( i<gn ) call lis_matrix_set_value(LIS_INS_VALUE,i,i+1,1.0d0,A,ierr)
11:    call lis_matrix_set_value(LIS_INS_VALUE,i,i,2.0d0,A,ierr)
12: enddo
13: call lis_matrix_set_type(A,LIS_MATRIX_CRS,ierr)
14: call lis_matrix_assemble(A,ierr)
```

## Declaring Variables

As the second line shows, the declaration is stated as follows:

```
LIS_MATRIX     A;
```

## Creating Matrices

To create the matrix  $A$ , the following functions are used:

- C `LIS_INT lis_matrix_create(LIS_Comm comm, LIS_MATRIX *A)`
- Fortran subroutine `lis_matrix_create(LIS_Comm comm, LIS_MATRIX A, LIS_INTEGER ierr)`

`comm` must be replaced with the MPI communicator. For the serial and multithreaded environments, the value of `comm` is ignored.

## Assigning Sizes

To assign a size to the matrix  $A$ , the following functions are used:

- C `LIS_INT lis_matrix_set_size(LIS_MATRIX A, LIS_INT local_n, LIS_INT global_n)`
- Fortran subroutine `lis_matrix_set_size(LIS_MATRIX A, LIS_INTEGER local_n, LIS_INTEGER global_n, LIS_INTEGER ierr)`

Either *local\_n* or *global\_n* must be provided.

In the case of the serial and multithreaded environments, *local\_n* is equal to *global\_n*. Therefore, both `lis_matrix_set_size(A,n,0)` and `lis_matrix_set_size(A,0,n)` create a matrix of size  $n \times n$ .

For the multiprocessing environment, `lis_matrix_set_size(A,n,0)` creates a partial matrix of size  $n \times N$  on each processing element, where  $N$  is the total sum of  $n$ . On the other hand, `lis_matrix_set_size(A,0,n)` creates a partial matrix of size  $m_p \times n$  on the processing element  $p$ . The values of  $m_p$  are determined by the library.

## Assigning Values

To assign a value to the element at the  $i$ -th row and the  $j$ -th column of the matrix  $A$ , the following functions are used:

- C `LIS_INT lis_matrix_set_value(LIS_INT flag, LIS_INT i, LIS_INT j, LIS_SCALAR value, LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_value(LIS_INTEGER flag, LIS_INTEGER i, LIS_INTEGER j, LIS_SCALAR value, LIS_MATRIX A, LIS_INTEGER ierr)`



For the multiprocessing environment, the  $i$ -th row and the  $j$ -th column of the global matrix must be specified. Either

LIS\_INS\_VALUE :  $A(i, j) = \text{value}$ , or

LIS\_ADD\_VALUE :  $A(i, j) = A(i, j) + \text{value}$

must be provided for the parameter `flag`.

### Assigning Storage Formats

To assign a storage format to the matrix  $A$ , the following functions are used:

- C `LIS_INT lis_matrix_set_type(LIS_MATRIX A, LIS_INT matrix_type)`
- Fortran subroutine `lis_matrix_set_type(LIS_MATRIX A, LIS_INT matrix_type, LIS_INTEGER ierr)`

`matrix_type` of  $A$  is `LIS_MATRIX_CRS` when the matrix is created. The following storage formats are supported:

Storage format		<code>matrix_type</code>
Compressed Row Storage	(CRS)	{LIS_MATRIX_CRS 1}
Compressed Column Storage	(CCS)	{LIS_MATRIX_CCS 2}
Modified Compressed Sparse Row	(MSR)	{LIS_MATRIX_MSR 3}
Diagonal	(DIA)	{LIS_MATRIX_DIA 4}
Ellpack-Itpack Generalized Diagonal	(ELL)	{LIS_MATRIX_ELL 5}
Jagged Diagonal	(JDS)	{LIS_MATRIX_JDS 6}
Block Sparse Row	(BSR)	{LIS_MATRIX_BSR 7}
Block Sparse Column	(BSC)	{LIS_MATRIX_BSC 8}
Variable Block Row	(VBR)	{LIS_MATRIX_VBR 9}
Dense	(DNS)	{LIS_MATRIX_DNS 10}
Coordinate	(COO)	{LIS_MATRIX_COO 11}

### Assembling Matrices

After assigning values and storage formats, the following functions must be called:

- C `LIS_INT lis_matrix_assemble(LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_assemble(LIS_MATRIX A, LIS_INTEGER ierr)`

`lis_matrix_assemble` assembles  $A$  into the storage format specified by `lis_matrix_set_type`.

### Destroying Matrices

To destroy the matrix, the following functions are used:

- C `LIS_INT lis_matrix_destroy(LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_destroy(LIS_MATRIX A, LIS_INTEGER ierr)`

### Method 2: Define Arrays in a Specific Storage Format Directly

In the case of creating the matrix  $A$  in Equation (3.2) in the CRS format, the matrix  $A$  itself is created for the serial and multithreaded environments, while the partial matrices are created and stored on the given number of processing elements for the multiprocessing environment.

Programs to create the matrix  $A$  in the CRS format are as follows, where the number of the processing elements for the multiprocessing environment is assumed to be two:

C (for serial and multithreaded environments)

```

1: LIS_INT      i,k,n,nnz;
2: LIS_INT      *ptr,*index;
3: LIS_SCALAR    *value;
4: LIS_MATRIX    A;
5: n = 4; nnz = 10; k = 0;
6: lis_matrix_malloc_crs(n,nnz,&ptr,&index,&value);
7: lis_matrix_create(0,&A);
8: lis_matrix_set_size(A,0,n);          /* or lis_matrix_set_size(A,n,0); */
9:
10: for(i=0;i<n;i++)
11: {
12:     if( i>0 ) {index[k] = i-1; value[k] = 1; k++;}
13:     index[k] = i; value[k] = 2; k++;
14:     if( i<n-1 ) {index[k] = i+1; value[k] = 1; k++;}
15:     ptr[i+1] = k;
16: }
17: ptr[0] = 0;
18: lis_matrix_set_crs(nnz,ptr,index,value,A);
19: lis_matrix_assemble(A);

```

C (for multiprocessing environment)

```

1: LIS_INT      i,k,n,nnz,is,ie;
2: LIS_INT      *ptr,*index;
3: LIS_SCALAR    *value;
4: LIS_MATRIX    A;
5: n = 2; nnz = 5; k = 0;
6: lis_matrix_malloc_crs(n,nnz,&ptr,&index,&value);
7: lis_matrix_create(MPI_COMM_WORLD,&A);
8: lis_matrix_set_size(A,n,0);
9: lis_matrix_get_range(A,&is,&ie);
10: for(i=is;i<ie;i++)
11: {
12:     if( i>0 ) {index[k] = i-1; value[k] = 1; k++;}
13:     index[k] = i; value[k] = 2; k++;
14:     if( i<n-1 ) {index[k] = i+1; value[k] = 1; k++;}
15:     ptr[i-is+1] = k;
16: }
17: ptr[0] = 0;
18: lis_matrix_set_crs(nnz,ptr,index,value,A);
19: lis_matrix_assemble(A);

```

### Associating Arrays

To associate the arrays in the CRS format with the matrix  $A$ , the following functions are used:

- C `LIS_INT lis_matrix_set_crs(LIS_INT nnz, LIS_INT row[], LIS_INT index[], LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_crs(LIS_INTEGER nnz, LIS_INTEGER row(), LIS_INTEGER index(), LIS_SCALAR value(), LIS_MATRIX A, LIS_INTEGER ierr)`

### Method 3: Read Matrix and Vector Data from External Files

Programs to read the matrix  $A$  in Equation (3.2) in the CRS format and vector  $b$  in Equation (3.1) from an external file are as follows:

C (for serial, multithreaded and multiprocessing environments)

```
1: LIS_MATRIX      A;
2: LIS_VECTOR      b,x;
3: lis_matrix_create(LIS_COMM_WORLD,&A);
4: lis_vector_create(LIS_COMM_WORLD,&b);
5: lis_vector_create(LIS_COMM_WORLD,&x);
6: lis_matrix_set_type(A,LIS_MATRIX_CRS);
7: lis_input(A,b,x,"matvec.mtx");
```

Fortran (for serial, multithreaded and multiprocessing environments)

```
1: LIS_MATRIX      A
2: LIS_VECTOR      b,x
3: call lis_matrix_create(LIS_COMM_WORLD,A,ierr)
4: call lis_vector_create(LIS_COMM_WORLD,b,ierr)
5: call lis_vector_create(LIS_COMM_WORLD,x,ierr)
6: call lis_matrix_set_type(A,LIS_MATRIX_CRS,ierr)
7: call lis_input(A,b,x,'matvec.mtx',ierr)
```

The content of the destination file `matvec.mtx` is as follows:

```
%%MatrixMarket matrix coordinate real general
4 4 10 1 0
1 2 1.0e+00
1 1 2.0e+00
2 3 1.0e+00
2 1 1.0e+00
2 2 2.0e+00
3 4 1.0e+00
3 2 1.0e+00
3 3 2.0e+00
4 4 2.0e+00
4 3 1.0e+00
1 0.0e+00
2 1.0e+00
3 2.0e+00
4 3.0e+00
```

### Reading from External Files

To input the matrix data for  $A$  from an external file, the following functions are used:

- C `LIS_INT lis_input_matrix(LIS_MATRIX A, char *filename)`
- Fortran subroutine `lis_input(LIS_MATRIX A, character filename, LIS_INTEGER ierr)`

`filename` must be replaced with the file path. The following file formats are supported:

- Matrix Market format
- Harwell-Boeing format

To read the data for the matrix  $A$  and vectors  $b$  and  $x$  from external files, the following functions are used:

- C `LIS_INT lis_input(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR x, char *filename)`
- Fortran subroutine `lis_input(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR x, character filename, LIS_INTEGER ierr)`

filename must be replaced with the file path. The following file formats are supported:

- Extended Matrix Market format (extended to allow vector data)
- Harwell-Boeing format

### 3.4 Solving Linear Equations

A program to solve the linear equation  $Ax = b$  with a specified solver is as follows:

C (for serial, multithreaded and multiprocessing environments)

```
1: LIS_MATRIX A;
2: LIS_VECTOR b,x;
3: LIS_SOLVER solver;
4:
5: /* Create matrix and vector */
6:
7: lis_solver_create(&solver);
8: lis_solver_set_option("-i bicg -p none",solver);
9: lis_solver_set_option("-tol 1.0e-12",solver);
10: lis_solver(A,b,x,solver);
```

Fortran (for serial, multithreaded and multiprocessing environments)

```
1: LIS_MATRIX A
2: LIS_VECTOR b,x
3: LIS_SOLVER solver
4:
5: /* Create matrix and vector */
6:
7: call lis_solver_create(solver,ierr)
8: call lis_solver_set_option('-i bicg -p none',solver,ierr)
9: call lis_solver_set_option('-tol 1.0e-12',solver,ierr)
10: call lis_solver(A,b,x,solver,ierr)
```

#### Creating Solvers

To create a solver, the following functions are used:

- C `LIS_INT lis_solver_create(LIS_SOLVER *solver)`
- Fortran subroutine `lis_solver_create(LIS_SOLVER solver, LIS_INTEGER ierr)`

#### Specifying Options

To specify options, the following functions are used:

- C `LIS_INT lis_solver_set_option(char *text, LIS_SOLVER solver)`
- Fortran subroutine `lis_solver_set_option(character text, LIS_SOLVER solver, LIS_INTEGER ierr)`

or

- C `LIS_INT lis_solver_set_optionC(LIS_SOLVER solver)`
- Fortran subroutine `lis_solver_set_optionC(LIS_SOLVER solver, LIS_INTEGER ierr)`

`lis_solver_set_optionC` is a function which sets the options specified on the command line, and pass them to `solver` when the program is run.

The table below shows the available command line options, where `-i {cg|1}` means `-i cg` or `-i 1` and `-maxiter [1000]` indicates that `-maxiter` defaults to 1,000.

**Options for Linear Solvers (Default: `-i bicg`)**

Solver	Option	Auxiliary Options	
CG	<code>-i {cg 1}</code>		
BiCG	<code>-i {bicg 2}</code>		
CGS	<code>-i {cgs 3}</code>		
BiCGSTAB	<code>-i {bicgstab 4}</code>		
BiCGSTAB(l)	<code>-i {bicgstabl 5}</code>	<code>-ell [2]</code>	The degree $l$
GPBiCG	<code>-i {gpbicg 6}</code>		
TFQMR	<code>-i {tfqmr 7}</code>		
Orthomin(m)	<code>-i {orthomin 8}</code>	<code>-restart [40]</code>	The restart value $m$
GMRES(m)	<code>-i {gmres 9}</code>	<code>-restart [40]</code>	The restart value $m$
Jacobi	<code>-i {jacobi 10}</code>		
Gauss-Seidel	<code>-i {gs 11}</code>		
SOR	<code>-i {sor 12}</code>	<code>-omega [1.9]</code>	The relaxation coefficient $\omega$ ( $0 < \omega < 2$ )
BiCGSafe	<code>-i {bicgsafe 13}</code>		
CR	<code>-i {cr 14}</code>		
BiCR	<code>-i {bicr 15}</code>		
CRS	<code>-i {crs 16}</code>		
BiCRSTAB	<code>-i {bicrstab 17}</code>		
GPBiCR	<code>-i {gpbicr 18}</code>		
BiCRSafe	<code>-i {bicrsafe 19}</code>		
FGMRES(m)	<code>-i {fgmres 20}</code>	<code>-restart [40]</code>	The restart value $m$
IDR(s)	<code>-i {idrs 21}</code>	<code>-irestart [2]</code>	The restart value $s$
MINRES	<code>-i {minres 22}</code>		

**Options for Preconditioners (Default: -p none)**

Preconditioner	Option	Auxiliary Options	
None	-p {none 0}		
Jacobi	-p {jacobi 1}		
ILU(k)	-p {ilu 2}	-ilu_fill [0]	The fill level $k$
SSOR	-p {ssor 3}	-ssor_w [1.0]	The relaxation coefficient $\omega$ ( $0 < \omega < 2$ )
Hybrid	-p {hybrid 4}	-hybrid_i [sor]	The linear solver
		-hybrid_maxiter [25]	The maximum number of the iterations
		-hybrid_tol [1.0e-3]	The convergence criterion
		-hybrid_w [1.5]	The relaxation coefficient $\omega$ of the SOR ( $0 < \omega < 2$ )
		-hybrid_ell [2]	The degree $l$ of the BiCGSTAB(l)
		-hybrid_restart [40]	The restart values of the GMRES and Orthomin
I+S	-p {is 5}	-is_alpha [1.0]	The parameter $\alpha$ of the preconditioner of the $I + \alpha S^{(m)}$ type
		-is_m [3]	The parameter $m$ of the preconditioner of the $I + \alpha S^{(m)}$ type
SAINV	-p {sainv 6}	-sainv_drop [0.05]	The drop criterion
SA-AMG	-p {saamg 7}	-saamg_unsym [false]	Selects the unsymmetric version (The matrix structure must be symmetric)
		-saamg_theta [0.05 0.12]	The drop criterion $a_{ij}^2 \leq \theta^2  a_{ii}   a_{jj} $ (symmetric or unsymmetric)
Crout ILU	-p {iluc 8}	-iluc_drop [0.05]	The drop criterion
		-iluc_rate [5.0]	The ratio of the maximum fill-in
ILUT	-p {ilut 9}	-ilut_drop [0.05]	The drop criterion
		-ilut_rate [5.0]	The ratio of the maximum fill-in
Additive Schwarz	-adds true	-adds_iter [1]	The number of the iterations

### Other Options

Option	
<code>-maxiter [1000]</code>	The maximum number of the iterations
<code>-tol [1.0e-12]</code>	The convergence criterion
<code>-print [0]</code>	The display of the residual
	<code>-print {none 0}</code> None <code>-print {mem 1}</code> Save the residual history <code>-print {out 2}</code> Display the residual history <code>-print {all 3}</code> Save the residual history and display it on the screen
<code>-scale [0]</code>	The scaling (The result will overwrite the original matrix and vectors) <code>-scale {none 0}</code> No scaling <code>-scale {jacobi 1}</code> The Jacobi scaling $D^{-1}Ax = D^{-1}b$ ( $D$ represents the diagonal of $A = (a_{ij})$ ) <code>-scale {symm_diag 2}</code> The diagonal scaling $D^{-1/2}AD^{-1/2}x = D^{-1/2}b$ ( $D^{-1/2}$ represents the diagonal matrix with $1/\sqrt{a_{ii}}$ as the diagonal)
<code>-initx_zeros [true]</code>	The behavior of the initial vector $x_0$ <code>-initx_zeros {false 0}</code> Given values <code>-initx_zeros {true 1}</code> All values are set to 0
<code>-omp_num_threads [t]</code>	The number of the threads ( $t$ represents the maximum number of the threads)
<code>-storage [0]</code>	The matrix storage format
<code>-storage_block [2]</code>	The block size of the BSR and BSC
<code>-f [0]</code>	The precision of the linear solvers <code>-f {double 0}</code> Double precision <code>-f {quad 1}</code> Quadruple precision

### Solving Linear Equations

To solve the linear equation  $Ax = b$ , the following functions are used:

- C            `LIS_INT lis_solve(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR x, LIS_SOLVER solver)`
- Fortran subroutine `lis_solve(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR x, LIS_SOLVER solver, LIS_INTEGER ierr)`

### 3.5 Solving Eigenvalue Problems

A program to solve the eigenvalue problem  $Ax = \lambda x$  with a specified solver is as follows:

C (for serial, multithreaded and multiprocessing environments)

```

1: LIS_MATRIX A;
2: LIS_VECTOR x;
3: LIS_REAL eval;
4: LIS_ESOLVER esolver;
5:
6: /* Create matrix and vector */
7:
8: lis_esolver_create(&esolver);
9: lis_esolver_set_option("-e ii -i bicg -p none",esolver);
10: lis_esolver_set_option("-etol 1.0e-12 -tol 1.0e-12",esolver);
11: lis_solve(A,x,eval,esolver);

```

Fortran (for serial, multithreaded and multiprocessing environments)

```

1: LIS_MATRIX A
2: LIS_VECTOR x
3: LIS_REAL evalue
4: LIS_ESOLVER esolver
5:
6: /* Create matrix and vector */
7:
8: call lis_esolver_create(esolver,ierr)
9: call lis_esolver_set_option('-e ii -i bicg -p none',esolver,ierr)
10: call lis_esolver_set_option('-etol 1.0e-12 -tol 1.0e-12',esolver,ierr)
11: call lis_solve(A,x,evalue,esolver,ierr)

```

## Creating Eigensolvers

To create an eigensolver, the following functions are used:

- C `LIS_INT lis_esolver_create(LIS_ESOLVER *esolver)`
- Fortran subroutine `lis_esolver_create(LIS_ESOLVER esolver, LIS_INTEGER ierr)`

## Specifying Options

To specify options, the following functions are used:

- C `LIS_INT lis_esolver_set_option(char *text, LIS_ESOLVER esolver)`
- Fortran subroutine `lis_esolver_set_option(character text, LIS_ESOLVER esolver, LIS_INTEGER ierr)`

or

- C `LIS_INT lis_esolver_set_optionC(LIS_ESOLVER esolver)`
- Fortran subroutine `lis_esolver_set_optionC(LIS_ESOLVER esolver, LIS_INTEGER ierr)`

`lis_esolver_set_optionC` is a function which sets the options specified on the command line, and pass them to `esolver` when the program is run.

The table below shows the available command line options, where `-e {pi|1}` means `-e pi` or `-e 1` and `-emaxiter [1000]` indicates that `-emaxiter` defaults to 1,000.

**Options for Eigensolvers (Default: `-e pi`)**

Eigensolver	Option	Auxiliary Options	
Power	<code>-e {pi 1}</code>		
Inverse	<code>-e {ii 2}</code>	<code>-i [bicg]</code>	The linear solver
Approximate Inverse	<code>-e {aii 3}</code>		
Rayleigh Quotient	<code>-e {rqi 4}</code>	<code>-i [bicg]</code>	The linear solver
Subspace	<code>-e {si 5}</code>	<code>-ss [2]</code>	The size of the subspace
		<code>-m [0]</code>	The mode number
Lanczos	<code>-e {li 6}</code>	<code>-ss [2]</code>	The size of the subspace
		<code>-m [0]</code>	The mode number
CG	<code>-e {cg 7}</code>		
CR	<code>-e {cr 8}</code>		



**Options for Preconditioners (Default: -p none)**

Preconditioner	Option	Auxiliary Options	
None	-p {none 0}		
Jacobi	-p {jacobi 1}		
ILU(k)	-p {ilu 2}	-ilu_fill [0]	The fill level $k$
SSOR	-p {ssor 3}	-ssor_w [1.0]	The relaxation coefficient $\omega$ ( $0 < \omega < 2$ )
Hybrid	-p {hybrid 4}	-hybrid_i [sor]	The linear solver
		-hybrid_maxiter [25]	The maximum number of the iterations
		-hybrid_tol [1.0e-3]	The convergence criterion
		-hybrid_w [1.5]	The relaxation coefficient $\omega$ of the SOR ( $0 < \omega < 2$ )
		-hybrid_ell [2]	The degree $l$ of the BiCGSTAB(l)
		-hybrid_restart [40]	The restart values of the GMRES and Orthomin
I+S	-p {is 5}	-is_alpha [1.0]	The parameter $\alpha$ of the preconditioner of the $I + \alpha S^{(m)}$ type
		-is_m [3]	The parameter $m$ of the preconditioner of the $I + \alpha S^{(m)}$ type
SAINV	-p {sainv 6}	-sainv_drop [0.05]	The drop criterion
SA-AMG	-p {saamg 7}	-saamg_unsym [false]	Selects the unsymmetric version (The matrix structure must be symmetric)
		-saamg_theta [0.05 0.12]	The drop criterion $a_{ij}^2 \leq \theta^2  a_{ii}   a_{jj} $ (symmetric or unsymmetric)
Crout ILU	-p {iluc 8}	-iluc_drop [0.05]	The drop criterion
		-iluc_rate [5.0]	The ratio of the maximum fill-in
ILUT	-p {ilut 9}	-ilut_drop [0.05]	The drop criterion
		-ilut_rate [5.0]	The ratio of the maximum fill-in
Additive Schwarz	-adds true	-adds_iter [1]	The number of the iterations

## Other Options

Option	
<code>-emaxiter [1000]</code>	The maximum number of the iterations
<code>-etol [1.0e-12]</code>	The convergence criterion
<code>-eprint [0]</code>	The display of the residual
	<code>-eprint {none 0}</code> None
	<code>-eprint {mem 1}</code> Save the residual history
	<code>-eprint {out 2}</code> Display the residual history
	<code>-eprint {all 3}</code> Save the residual history and display it on the screen
<code>-ie [ii]</code>	The inner eigensolver used in the Lanczos and Subspace
	<code>-ie {pi 1}</code> The Power (the Subspace only)
	<code>-ie {ii 2}</code> The Inverse
	<code>-ie {aii 3}</code> The Approximate Inverse
	<code>-ie {rqi 4}</code> The Rayleigh Quotient
<code>-shift [0.0]</code>	The amount of the shift
<code>-initx_ones [true]</code>	The behavior of the initial vector $x_0$
	<code>-initx_ones {false 0}</code> Given values
	<code>-initx_ones {true 1}</code> All values are set to 1
<code>-omp_num_threads [t]</code>	The number of the threads (t represents the maximum number of the threads)
<code>-estorage [0]</code>	The matrix storage format
<code>-estorage_block [2]</code>	The block size of the BSR and BSC
<code>-ef [0]</code>	The precision of the eigensolvers
	<code>-ef {double 0}</code> Double precision
	<code>-ef {quad 1}</code> Quadruple precision

### Solving Eigenvalue Problems

To solve the eigenvalue problem  $Ax = \lambda x$ , the following functions are used:

- C `LIS_INT lis_solve(LIS_MATRIX A, LIS_VECTOR x, LIS_REAL eval, LIS_ESOLVER esolver)`
- Fortran subroutine `lis_solve(LIS_MATRIX A, LIS_VECTOR x, LIS_REAL eval, LIS_ESOLVER esolver, LIS_INTEGER ierr)`

### 3.6 Writing Programs

The following are the programs for solving the linear equation  $Ax = b$ , where the matrix  $A$  is a tridiagonal matrix

$$\begin{pmatrix} 2 & -1 & & & \\ -1 & 2 & -1 & & \\ & \ddots & \ddots & \ddots & \\ & & -1 & 2 & -1 \\ & & & -1 & 2 \end{pmatrix}$$

of size 12. The the right hand side vector  $b$  is set to make the values of the elements of the solution  $x$  is 1. The program is located in the directory `lis-($VERSION)/test`.

Test program: test4.c

```
1: #include <stdio.h>
2: #include "lis.h"
3: main(LIS_INT argc, char *argv[])
4: {
5:     LIS_INT i,n,gm,is,ie,iter;
6:     LIS_MATRIX A;
7:     LIS_VECTOR b,x,u;
8:     LIS_SOLVER solver;
9:     n = 12;
10:    lis_initialize(&argc,&argv);
11:    lis_matrix_create(LIS_COMM_WORLD,&A);
12:    lis_matrix_set_size(A,0,n);
13:    lis_matrix_get_size(A,&n,&gm)
14:    lis_matrix_get_range(A,&is,&ie)
15:    for(i=is;i<ie;i++)
16:    {
17:        if( i>0 ) lis_matrix_set_value(LIS_INS_VALUE,i,i-1,-1.0,A);
18:        if( i<gm-1 ) lis_matrix_set_value(LIS_INS_VALUE,i,i+1,-1.0,A);
19:        lis_matrix_set_value(LIS_INS_VALUE,i,i,2.0,A);
20:    }
21:    lis_matrix_set_type(A,LIS_MATRIX_CRS);
22:    lis_matrix_assemble(A);
23:
24:    lis_vector_duplicate(A,&u);
25:    lis_vector_duplicate(A,&b);
26:    lis_vector_duplicate(A,&x);
27:    lis_vector_set_all(1.0,u);
28:    lis_matvec(A,u,b);
29:
30:    lis_solver_create(&solver);
31:    lis_solver_set_optionC(solver);
32:    lis_solve(A,b,x,solver);
33:    lis_solver_get_iters(solver,&iter);
34:    printf("iter = %d\n",iter);
35:    lis_vector_print(x);
36:    lis_matrix_destroy(A);
37:    lis_vector_destroy(u);
38:    lis_vector_destroy(b);
39:    lis_vector_destroy(x);
40:    lis_solver_destroy(solver);
41:    lis_finalize();
42:    return 0;
43: }
```

Test program: test4f.F

```
1:      implicit none
2:
3: #include "lisf.h"
4:
5:      LIS_INTEGER      i,n,gn,is,ie,iter,ierr
6:      LIS_MATRIX       A
7:      LIS_VECTOR       b,x,u
8:      LIS_SOLVER       solver
9:      n = 12
10:     call lis_initialize(ierr)
11:     call lis_matrix_create(LIS_COMM_WORLD,A,ierr)
12:     call lis_matrix_set_size(A,0,n,ierr)
13:     call lis_matrix_get_size(A,n,gn,ierr)
14:     call lis_matrix_get_range(A,is,ie,ierr)
15:     do i=is,ie-1
16:         if( i>1 ) call lis_matrix_set_value(LIS_INS_VALUE,i,i-1,-1.0d0,
17:                                             A,ierr)
18:         if( i<gn ) call lis_matrix_set_value(LIS_INS_VALUE,i,i+1,-1.0d0,
19:                                             A,ierr)
20:         call lis_matrix_set_value(LIS_INS_VALUE,i,i,2.0d0,A,ierr)
21:     enddo
22:     call lis_matrix_set_type(A,LIS_MATRIX_CRD,ierr)
23:     call lis_matrix_assemble(A,ierr)
24:
25:     call lis_vector_duplicate(A,u,ierr)
26:     call lis_vector_duplicate(A,b,ierr)
27:     call lis_vector_duplicate(A,x,ierr)
28:     call lis_vector_set_all(1.0d0,u,ierr)
29:     call lis_matvec(A,u,b,ierr)
30:
31:     call lis_solver_create(solver,ierr)
32:     call lis_solver_set_optionC(solver,ierr)
33:     call lis_solve(A,b,x,solver,ierr)
34:     call lis_solver_get_iters(solver,iter,ierr)
35:     write(*,*) 'iter = ',iter
36:     call lis_vector_print(x,ierr)
37:     call lis_matrix_destroy(A,ierr)
38:     call lis_vector_destroy(b,ierr)
39:     call lis_vector_destroy(x,ierr)
40:     call lis_vector_destroy(u,ierr)
41:     call lis_solver_destroy(solver,ierr)
42:     call lis_finalize(ierr)
43:
44:     stop
45:     end
```

### 3.7 Compiling and Linking

Provided below is an example `test4.c` located in the directory `lis-($VERSION)/test`, compiled on the SGI Altix 3700 using the Intel C/C++ Compiler 8.1 (icc). Since the library includes some Fortran 90 codes when the SA-AMG preconditioner is selected, a Fortran 90 compiler must be used for the linking. The preprocessor macro `USE_MPI` must be defined for the multiprocessing environment.

For the serial environment

**Compiling**

```
>icc -c -I($INSTALLDIR)/include test4.c
```

**Linking**

```
>icc -o test4 test4.o -llis
```

**Linking (with SA-AMG)**

```
>ifort -nofor_main -o test4 test4.o -llis
```

For multithreaded environment

**Compiling**

```
>icc -c -openmp -I($INSTALLDIR)/include test4.c
```

**Linking**

```
>icc -openmp -o test4 test4.o -llis
```

**Linking (with SA-AMG)**

```
>ifort -nofor_main -openmp -o test4 test4.o -llis
```

For multiprocessing environment

**Compiling**

```
>icc -c -DUSE_MPI -I($INSTALLDIR)/include test4.c
```

**Linking**

```
>icc -o test4 test4.o -llis -lmpi
```

**Linking (with SA-AMG)**

```
>ifort -nofor_main -o test4 test4.o -llis -lmpi
```

For multithreaded and multiprocessing environments

**Compiling**

```
>icc -c -openmp -DUSE_MPI -I($INSTALLDIR)/include test4.c
```

**Linking**

```
>icc -openmp -o test4 test4.o -llis -lmpi
```

**Linking (with SA-AMG)**

```
>ifort -nofor_main -openmp -o test4 test4.o -llis -lmpi
```

Provided below is an example `test4f.F` located in the directory `lis-($VERSION)/test`, compiled on the SGI Altix 3700 using the Intel Fortran Compiler 8.1 (ifort). Since an `include` statement is used in the program, the compiler option `-fpp` is specified to use the preprocessor.

For serial environment

**Compiling**

```
>ifort -c -fpp -I($INSTALLDIR)/include test4f.F
```

**Linking**

```
>ifort -o test4 test4.o -llis
```

For multithreaded environment

**Compiling**

```
>ifort -c -fpp -openmp -I($INSTALLDIR)/include test4f.F
```

**Linking**

```
>ifort -openmp -o test4 test4.o -llis
```

For multiprocessing environment

**Compiling**

```
>ifort -c -fpp -DUSE_MPI -I($INSTALLDIR)/include test4f.F
```

**Linking**

```
>ifort -o test4 test4.o -llis -lmpi
```

For multithreaded and multiprocessing environments

**Compiling**

```
>ifort -c -fpp -openmp -DUSE_MPI -I($INSTALLDIR)/include test4f.F
```

**Linking**

```
>ifort -openmp -o test4 test4.o -llis -lmpi
```

### 3.8 Running

The test programs `test4` and `test4f` in the directory `lis-($VERSION)/test` are run as follows:

**For serial environment**

```
>./test4 -i bicgstab
```

**For multithreaded environment**

```
>env OMP_NUM_THREADS=2 ./test4 -i bicgstab
```

**For multiprocessing environment**

```
>mpirun -np 2 ./test4 -i bicgstab
```

**For multithreaded and multiprocessing environment**

```
>mpirun -np 2 env OMP_NUM_THREADS=2 ./test4 -i bicgstab
```

The following results will be returned:

```
precision : double
solver     : BiCGSTAB 4
precon     : none
storage    : CRS
lis_solve  : normal end
```

```
iter = 6
 0 1.000000e+000
 1 1.000000e+000
 2 1.000000e+000
 3 1.000000e+000
 4 1.000000e+000
 5 1.000000e+000
 6 1.000000e+000
 7 1.000000e+000
 8 1.000000e+000
 9 1.000000e+000
10 1.000000e+000
11 1.000000e+000
```

## 4 Quadruple Precision Operations

Double precision operations sometimes require a large number of iterations because of the rounding error. Lis supports "double-double", or quadruple precision operations by combining two double precision floating point numbers[15, 16]. To use the quadruple precision with the same interface as the double precision operations, both the matrix and vectors are assumed to be double precision. Lis also supports the performance acceleration of the quadruple precision operations with the SIMD instructions, such as Intel's Streaming SIMD Extensions (SSE)[24].

### 4.1 Using Quadruple Precision Operations

The test program `test5.c` solves a linear equation  $Ax = b$ , where  $A$  is a Toeplitz matrix

$$\begin{pmatrix} 2 & 1 & & & & \\ 0 & 2 & 1 & & & \\ \gamma & 0 & 2 & 1 & & \\ & \ddots & \ddots & \ddots & \ddots & \\ & & \gamma & 0 & 2 & 1 \\ & & & \gamma & 0 & 2 \end{pmatrix}.$$

The right hand vector is set to make the values of the elements of the solution to be 1. The value  $n$  is the size of the matrix  $A$ . `test5` with `-f` option is run as follows:

#### Double precision

By entering `>./test5 200 2.0 -f double`  
the following results will be returned:

```
n = 200, gamma = 2.000000
initial vector x = 0
precision : double
solver    : BiCG 2
precon    : none
storage   : CRS
lis_solve : LIS_MAXITER(code=4)

BiCG: number of iterations      = 1001 (double = 1001, quad = 0)
BiCG: elapsed time              = 2.044368e-02 sec.
BiCG: preconditioner           = 4.768372e-06 sec.
BiCG: matrix creation          = 4.768372e-06 sec.
BiCG: linear solver            = 2.043891e-02 sec.
BiCG: relative residual 2-norm = 8.917591e+01
```

#### Quadruple precision

By entering `>./test5 200 2.0 -f quad`  
the following results will be returned:

```
n = 200, gamma = 2.000000
initial vector x = 0
precision : quad
solver    : BiCG 2
precon    : none
storage   : CRS
lis_solve : normal end
```

BiCG: number of iterations = 230 (double = 230, quad = 0)  
BiCG: elapsed time = 2.267408e-02 sec.  
BiCG: preconditioner = 4.549026e-04 sec.  
BiCG: matrix creation = 5.006790e-06 sec.  
BiCG: linear solver = 2.221918e-02 sec.  
BiCG: relative residual 2-norm = 6.499145e-11



## 5 Matrix Storage Formats

This section describes the matrix storage formats supported by the library. Assume that the matrix row (column) number begins with 0 and that the number of the nonzero elements of the matrix  $A$  of size  $n \times n$  is  $nnz$ .

### 5.1 Compressed Row Storage (CRS)

The CRS format uses three arrays `ptr`, `index` and `value` to store data.

- `value` is a double precision array with a length of  $nnz$ , which stores the nonzero elements of the matrix  $A$  along the row.
- `index` is an integer array with a length of  $nnz$ , which stores the column numbers of the nonzero elements stored in the array `value`.
- `ptr` is an integer array with a length of  $n + 1$ , which stores the starting points of the rows of the arrays `value` and `index`.

#### 5.1.1 Creating Matrices (for Serial and Multithreaded Environments)

The right diagram in Figure 2 shows how the matrix  $A$  in Figure 2 is stored in the CRS format. A program to create the matrix in the CRS format is as follows:

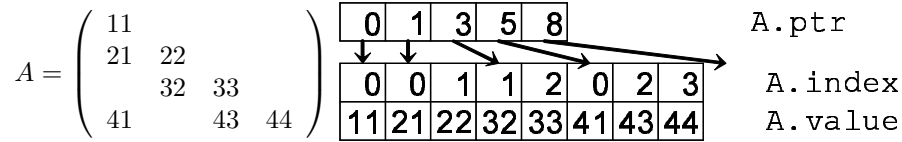


Figure 2: Data structure of CRS format (for serial and multithreaded environments).

For serial and multithreaded environments

```

1: LIS_INT      n,nnz;
2: LIS_INT      *ptr,*index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: n = 4; nnz = 8;
6: ptr  = (LIS_INT *)malloc( (n+1)*sizeof(LIS_INT) );
7: index = (LIS_INT *)malloc( nnz*sizeof(LIS_INT) );
8: value = (LIS_SCALAR *)malloc( nnz*sizeof(LIS_SCALAR) );
9: lis_matrix_create(0,&A);
10: lis_matrix_set_size(A,0,n);
11:
12: ptr[0] = 0; ptr[1] = 1; ptr[2] = 3; ptr[3] = 5; ptr[4] = 8;
13: index[0] = 0; index[1] = 0; index[2] = 1; index[3] = 1;
14: index[4] = 2; index[5] = 0; index[6] = 2; index[7] = 3;
15: value[0] = 11; value[1] = 21; value[2] = 22; value[3] = 32;
16: value[4] = 33; value[5] = 41; value[6] = 43; value[7] = 44;
17:
18: lis_matrix_set_crs(nnz,ptr,index,value,A);
19: lis_matrix_assemble(A);

```

### 5.1.2 Creating Matrices (for Multiprocessing Environment)

Figure 3 shows how the matrix  $A$  in Figure 2 is stored in the CRS format on two processing elements. A program to create the matrix in the CRS format on two processing elements is as follows:

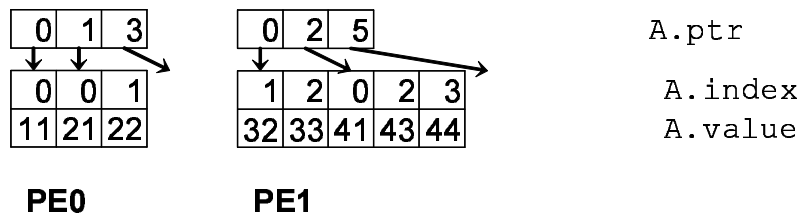


Figure 3: Data structure of CRS format (for multiprocessing environment).

For multiprocessing environment

```

1: LIS_INT      i,k,n,nnz,my_rank;
2: LIS_INT      *ptr,*index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: MPI_Comm_rank(MPI_COMM_WORLD,&my_rank);
6: if( my_rank==0 ) {n = 2; nnz = 3;}
7: else         {n = 2; nnz = 5;}
8: ptr  = (LIS_INT *)malloc( (n+1)*sizeof(LIS_INT) );
9: index = (LIS_INT *)malloc( nnz*sizeof(LIS_INT) );
10: value = (LIS_SCALAR *)malloc( nnz*sizeof(LIS_SCALAR) );
11: lis_matrix_create(MPI_COMM_WORLD,&A);
12: lis_matrix_set_size(A,n,0);
13: if( my_rank==0 ) {
14:     ptr[0] = 0; ptr[1] = 1; ptr[2] = 3;
15:     index[0] = 0; index[1] = 0; index[2] = 1;
16:     value[0] = 11; value[1] = 21; value[2] = 22;}
17: else {
18:     ptr[0] = 0; ptr[1] = 2; ptr[2] = 5;
19:     index[0] = 1; index[1] = 2; index[2] = 0; index[3] = 2; index[4] = 3;
20:     value[0] = 32; value[1] = 33; value[2] = 41; value[3] = 43; value[4] = 44;}
21: lis_matrix_set_crs(nnz,ptr,index,value,A);
22: lis_matrix_assemble(A);

```

### 5.1.3 Associating Arrays

To associate the arrays in the CRS format with the matrix  $A$ , the following functions are used:

- C            LIS\_INT lis\_matrix\_set\_crs(LIS\_INT nnz, LIS\_INT row[], LIS\_INT index[], LIS\_SCALAR value[], LIS\_MATRIX A)
- Fortran subroutine lis\_matrix\_set\_crs(LIS\_INTEGER nnz, LIS\_INTEGER row(), LIS\_INTEGER index(), LIS\_SCALAR value(), LIS\_MATRIX A, LIS\_INTEGER ierr)

## 5.2 Compressed Column Storage (CCS)

The CSS format uses three arrays `ptr`, `index` and `value` to store data.

- `value` is a double precision array with a length of  $nnz$ , which stores the values of the nonzero elements of the matrix  $A$  along the column.
- `index` is an integer array with a length of  $nnz$ , which stores the row numbers of the nonzero elements stored in the array `value`.
- `ptr` is an integer array with a length of  $n + 1$ , which stores the starting points of the rows of the arrays `value` and `index`.

### 5.2.1 Creating Matrices (for Serial and Multithreaded Environments)

The right diagram in Figure 4 shows how the matrix  $A$  in Figure 4 is stored in the CCS format. A program to create the matrix in the CCS format is as follows:

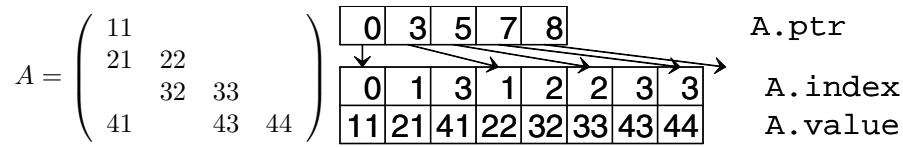


Figure 4: Data structure of CCS format (for serial and multithreaded environments).

For serial and multithreaded environments

```

1: LIS_INT      n,nnz;
2: LIS_INT      *ptr,*index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: n = 4; nnz = 8;
6: ptr = (LIS_INT *)malloc( (n+1)*sizeof(LIS_INT) );
7: index = (LIS_INT *)malloc( nnz*sizeof(LIS_INT) );
8: value = (LIS_SCALAR *)malloc( nnz*sizeof(LIS_SCALAR) );
9: lis_matrix_create(0,&A);
10: lis_matrix_set_size(A,0,n);
11:
12: ptr[0] = 0; ptr[1] = 3; ptr[2] = 5; ptr[3] = 7; ptr[4] = 8;
13: index[0] = 0; index[1] = 1; index[2] = 3; index[3] = 1;
14: index[4] = 2; index[5] = 2; index[6] = 3; index[7] = 3;
15: value[0] = 11; value[1] = 21; value[2] = 41; value[3] = 22;
16: value[4] = 32; value[5] = 33; value[6] = 43; value[7] = 44;
17:
18: lis_matrix_set_ccs(nnz,ptr,index,value,A);
19: lis_matrix_assemble(A);

```

### 5.2.2 Creating Matrices (for Multiprocessing Environment)

Figure 5 shows how the matrix  $A$  in Figure 4 is stored on two processing elements. A program to create the matrix in the CCS format on two processing elements is as follows:

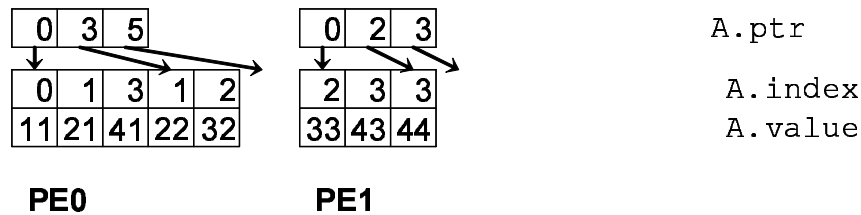


Figure 5: Data structure of CCS format (for multiprocessing environment).

For multiprocessing environment

```

1: LIS_INT      i,k,n,nnz,my_rank;
2: LIS_INT      *ptr,*index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: MPI_Comm_rank(MPI_COMM_WORLD,&my_rank);
6: if( my_rank==0 ) {n = 2; nnz = 3;}
7: else         {n = 2; nnz = 5;}
8: ptr  = (LIS_INT *)malloc( (n+1)*sizeof(LIS_INT) );
9: index = (LIS_INT *)malloc( nnz*sizeof(LIS_INT) );
10: value = (LIS_SCALAR *)malloc( nnz*sizeof(LIS_SCALAR) );
11: lis_matrix_create(MPI_COMM_WORLD,&A);
12: lis_matrix_set_size(A,n,0);
13: if( my_rank==0 ) {
14:     ptr[0] = 0; ptr[1] = 3; ptr[2] = 5;
15:     index[0] = 0; index[1] = 1; index[2] = 3; index[3] = 1; index[4] = 2;
16:     value[0] = 11; value[1] = 21; value[2] = 41; value[3] = 22; value[4] = 32;
17: } else {
18:     ptr[0] = 0; ptr[1] = 2; ptr[2] = 3;
19:     index[0] = 2; index[1] = 3; index[2] = 3;
20:     value[0] = 33; value[1] = 43; value[2] = 44;
21: lis_matrix_set_ccs(nnz,ptr,index,value,A);
22: lis_matrix_assemble(A);

```

### 5.2.3 Associating Arrays

To associate the arrays in the CCS format with the matrix  $A$ , the following functions are used:

- C `LIS_INT lis_matrix_set_ccs(LIS_INT nnz, LIS_INT row[], LIS_INT index[], LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_ccs(LIS_INTEGER nnz, LIS_INTEGER row(), LIS_INTEGER index(), LIS_SCALAR value(), LIS_MATRIX A, LIS_INTEGER ierr)`

### 5.3 Modified Compressed Sparse Row (MSR)

The MSR format uses two arrays **index** and **value** to store data. Assume that  $ndz$  represents the number of the zero elements of the diagonal.

- **value** is a double precision array with a length of  $nnz + ndz + 1$ , which stores the diagonal of the matrix  $A$  down to the  $n$ -th element. The  $n + 1$ -th element is not used. For the  $n + 2$ -th and after, the values of the nonzero elements except the diagonal of the matrix  $A$  are stored along the row.
- **index** is an integer array with a length of  $nnz + ndz + 1$ , which stores the starting points of the rows of the off-diagonal elements of the matrix  $A$  down to the  $n + 1$ -th element. For the  $n + 2$ -th and after, it stores the row numbers of the off-diagonal elements of the matrix  $A$  stored in the array **value**.

#### 5.3.1 Creating Matrices (for Serial and Multithreaded Environments)

The right diagram in Figure 6 shows how matrix  $A$  is stored in the MSR format. A program to create the matrix in the MSR format is as follows:

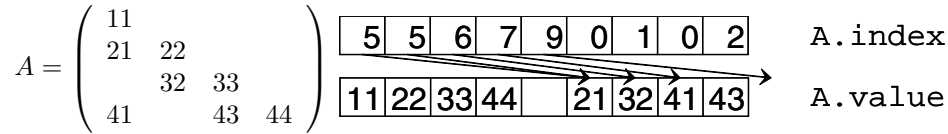


Figure 6: Data structure of MSR format (for serial and multithreaded environments).

For serial and multithreaded environments

```

1: LIS_INT      n,nnz,ndz;
2: LIS_INT      *index;
3: LIS_SCALAR    *value;
4: LIS_MATRIX    A;
5: n = 4; nnz = 8; ndz = 0;
6: index = (LIS_INT *)malloc( (nnz+ndz+1)*sizeof(LIS_INT) );
7: value = (LIS_SCALAR *)malloc( (nnz+ndz+1)*sizeof(LIS_SCALAR) );
8: lis_matrix_create(0,&A);
9: lis_matrix_set_size(A,0,n);
10:
11: index[0] = 5; index[1] = 5; index[2] = 6; index[3] = 7;
12: index[4] = 9; index[5] = 0; index[6] = 1; index[7] = 0; index[8] = 2;
13: value[0] = 11; value[1] = 22; value[2] = 33; value[3] = 44;
14: value[4] = 0; value[5] = 21; value[6] = 32; value[7] = 41; value[8] = 43;
15:
16: lis_matrix_set_msr(nnz,ndz,index,value,A);
17: lis_matrix_assemble(A);

```

### 5.3.2 Creating Matrices (for Multiprocessing Environment)

Figure 7 shows how the matrix  $A$  in Figure 6 is stored in the MSR format on two processing elements. A program to create the matrix in the MSR format on two processing element is as follows:

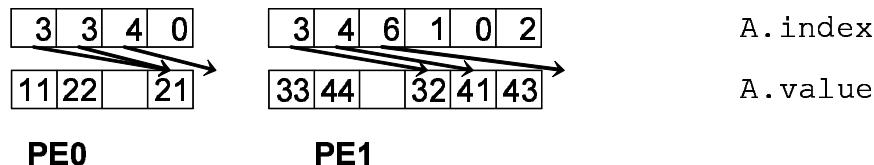


Figure 7: Data structure of MSR format (for multiprocessing environment).

For multiprocessing environment

```

1: LIS_INT      i,k,n,nnz,ndz,my_rank;
2: LIS_INT      *index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: MPI_Comm_rank(MPI_COMM_WORLD,&my_rank);
6: if( my_rank==0 ) {n = 2; nnz = 3; ndz = 0;}
7: else          {n = 2; nnz = 5; ndz = 0;}
8: index = (LIS_INT *)malloc( (nnz+ndz+1)*sizeof(LIS_INT) );
9: value = (LIS_SCALAR *)malloc( (nnz+ndz+1)*sizeof(LIS_SCALAR) );
10: lis_matrix_create(MPI_COMM_WORLD,&A);
11: lis_matrix_set_size(A,n,0);
12: if( my_rank==0 ) {
13:     index[0] = 3; index[1] = 3; index[2] = 4; index[3] = 0;
14:     value[0] = 11; value[1] = 22; value[2] = 0; value[3] = 21;}
15: else {
16:     index[0] = 3; index[1] = 4; index[2] = 6; index[3] = 1;
17:     index[4] = 0; index[5] = 2;
18:     value[0] = 33; value[1] = 44; value[2] = 0; value[3] = 32;
19:     value[4] = 41; value[5] = 43;}
20: lis_matrix_set_msr(nnz,ndz,index,value,A);
21: lis_matrix_assemble(A);

```

### 5.3.3 Associating Arrays

To associate the arrays in the MSR format with the matrix  $A$ , the following functions are used:

- C LIS\_INT lis\_matrix\_set\_msr(LIS\_INT nnz, LIS\_INT ndz, LIS\_INT index[], LIS\_SCALAR value[], LIS\_MATRIX A)
- Fortran subroutine lis\_matrix\_set\_msr(LIS\_INTEGER nnz, LIS\_INTEGER ndz, LIS\_INTEGER index(), LIS\_SCALAR value(), LIS\_MATRIX A, LIS\_INTEGER ierr)

## 5.4 Diagonal (DIA)

The DIA format uses two arrays **index** and **value** to store data. Assume that  $nnd$  represents the number of the nonzero diagonal elements of the matrix  $A$ .

- **value** is a double precision array with a length of  $nnd \times n$ , which stores the values of the nonzero diagonal elements of the matrix  $A$ .
- **index** is an integer array with a length of  $nnd$ , which stores the offsets from the main diagonal.

For the multithreaded environment, the following modifications have been made: the format uses two arrays **index** and **value** to store data. Assume that  $nprocs$  represents the number of the threads.  $nnd_p$  is the number of the nonzero diagonal elements of the partial matrix into which the row block of the matrix  $A$  is divided.  $maxnnd$  is the maximum value  $nnd_p$ .

- **value** is a double precision array with a length of  $maxnnd \times n$ , which stores the values of the nonzero diagonal elements of the matrix  $A$ .
- **index** is an integer array with a length of  $nprocs \times maxnnd$ , which stores the offsets from the main diagonal.

### 5.4.1 Creating Matrices (for Serial Environment)

The right diagram in Figure 8 shows how the matrix  $A$  in Figure 8 is stored in the DIA format. A program to create the matrix in the DIA format is as follows:

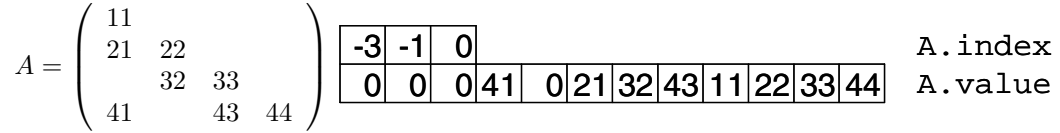


Figure 8: Data structure of DIA format (for serial environment).

For serial environment

```

1: LIS_INT      n,nnd;
2: LIS_INT      *index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: n = 4; nnd = 3;
6: index = (LIS_INT *)malloc( nnd*sizeof(LIS_INT) );
7: value = (LIS_SCALAR *)malloc( n*nnd*sizeof(LIS_SCALAR) );
8: lis_matrix_create(0,&A);
9: lis_matrix_set_size(A,0,n);
10:
11: index[0] = -3; index[1] = -1; index[2] = 0;
12: value[0] = 0; value[1] = 0; value[2] = 0; value[3] = 41;
13: value[4] = 0; value[5] = 21; value[6] = 32; value[7] = 43;
14: value[8] = 11; value[9] = 22; value[10] = 33; value[11] = 44;
15:
16: lis_matrix_set_dia(nnd,index,value,A);
17: lis_matrix_assemble(A);

```

Figure 9 shows how the matrix  $A$  in Figure 8 is stored in the DIA format on two threads. A program to create the matrix in the DIA format on two threads is as follows:

-1	0		-3	-1	0										A.index
0	21	11	22			0	41	32	43	33	44				A.value

Figure 9: Data structure of DIA format (for multithreaded environment).

• For multithreaded environment

```

1: LIS_INT      n,maxnnd,nprocs;
2: LIS_INT      *index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: n = 4; maxnnd = 3; nprocs = 2;
6: index = (LIS_INT *)malloc( maxnnd*sizeof(LIS_INT) );
7: value = (LIS_SCALAR *)malloc( n*maxnnd*sizeof(LIS_SCALAR) );
8: lis_matrix_create(0,&A);
9: lis_matrix_set_size(A,0,n);
10:
11: index[0] = -1; index[1] = 0; index[2] = 0; index[3] = -3; index[4] = -1; index[5] = 0;
12: value[0] = 0; value[1] = 21; value[2] = 11; value[3] = 22; value[4] = 0; value[5] = 0;
13: value[6] = 0; value[7] = 41; value[8] = 32; value[9] = 43; value[10] = 33; value[11] = 44;
14:
15: lis_matrix_set_dia(maxnnd,index,value,A);
16: lis_matrix_assemble(A);

```



### 5.4.3 Creating Matrices (for Multiprocessing Environment)

Figure 10 shows how the matrix  $A$  in Figure 8 is stored in the DIA format on two processing elements. A program to create the matrix in the DIA format on two processing elements is as follows:

<table><tr><td>-1</td><td>0</td></tr><tr><td>0</td><td>21</td></tr></table>	-1	0	0	21	<table><tr><td>-3</td><td>-1</td><td>0</td></tr><tr><td>0</td><td>41</td><td>32</td></tr></table>	-3	-1	0	0	41	32	A.index
-1	0											
0	21											
-3	-1	0										
0	41	32										
<table><tr><td>11</td><td>22</td></tr></table>	11	22	<table><tr><td>43</td><td>33</td><td>44</td></tr></table>	43	33	44	A.value					
11	22											
43	33	44										
PE0	PE1											

Figure 10: Data structure of DIA format (for multiprocessing environment).

For multiprocessing environment

```

1: LIS_INT      i,n,nnd,my_rank;
2: LIS_INT      *index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: MPI_Comm_rank(MPI_COMM_WORLD,&my_rank);
6: if( my_rank==0 ) {n = 2; nnd = 2;}
7: else          {n = 2; nnd = 3;}
8: index = (LIS_INT *)malloc( nnd*sizeof(LIS_INT) );
9: value = (LIS_SCALAR *)malloc( n*nnd*sizeof(LIS_SCALAR) );
10: lis_matrix_create(MPI_COMM_WORLD,&A);
11: lis_matrix_set_size(A,n,0);
12: if( my_rank==0 ) {
13:     index[0] = -1; index[1] = 0;
14:     value[0] = 0; value[1] = 21; value[2] = 11; value[3] = 22;}
15: else {
16:     index[0] = -3; index[1] = -1; index[2] = 0;
17:     value[0] = 0; value[1] = 41; value[2] = 32; value[3] = 43; value[4] = 33;
18:     value[5] = 44;}
19: lis_matrix_set_dia(nnd,index,value,A);
20: lis_matrix_assemble(A);

```

### 5.4.4 Associating Arrays

To associate the arrays in the DIA format with the matrix  $A$ , the following functions are used:

- C LIS\_INT lis\_matrix\_set\_dia(LIS\_INT nnd, LIS\_INT index[], LIS\_SCALAR value[], LIS\_MATRIX A)
- Fortran subroutine lis\_matrix\_set\_dia(LIS\_INTEGER nnd, LIS\_INTEGER index(), LIS\_SCALAR value(), LIS\_MATRIX A, LIS\_INTEGER ierr)

## 5.5 Ellpack-Itpack Generalized Diagonal (ELL)

The ELL format uses two arrays `index` and `value` to store data. Assume that `maxnzc` is the maximum value of the number of the nonzero elements in the rows of the matrix  $A$ .

- `value` is a double precision array with a length of  $maxnzc \times n$ , which stores the values of the nonzero elements of the rows of the matrix  $A$  along the column. The first column consists of the first nonzero elements of each row. If there is no nonzero elements to be stored, then 0 is stored.
- `index` is an integer array with a length of  $maxnzc \times n$ , which stores the column numbers of the nonzero elements stored in the array `value`. If the number of the nonzero elements in the  $i$ -th row is  $nnz$ , then `index[ $nnz \times n + i$ ]` stores row number  $i$ .

### 5.5.1 Creating Matrices (for Serial and Multithreaded Environments)

The right diagram in Figure 11 shows how the matrix  $A$  in Figure 11 is stored in the ELL format. A program to create the matrix in the ELL format is as follows:

$$A = \begin{pmatrix} 11 & & & & \\ 21 & 22 & & & \\ & 32 & 33 & & \\ 41 & & 43 & 44 & \end{pmatrix} \quad \begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|} \hline 0 & 0 & 1 & 0 & 0 & 1 & 2 & 2 & 0 & 1 & 2 & 3 \\ \hline 11 & 21 & 32 & 41 & 0 & 22 & 33 & 43 & 0 & 0 & 0 & 44 \\ \hline \end{array} \quad \begin{array}{l} \text{A.index} \\ \text{A.value} \end{array}$$

Figure 11: Data structure of ELL format (for serial and multithreaded environments).

For serial and multithreaded environments

```

1: LIS_INT      n,maxnzc;
2: LIS_INT      *index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: n = 4; maxnzc = 3;
6: index = (LIS_INT *)malloc( n*maxnzc*sizeof(LIS_INT) );
7: value = (LIS_SCALAR *)malloc( n*maxnzc*sizeof(LIS_SCALAR) );
8: lis_matrix_create(0,&A);
9: lis_matrix_set_size(A,0,n);
10:
11: index[0] = 0; index[1] = 0; index[2] = 1; index[3] = 0; index[4] = 0; index[5] = 1;
12: index[6] = 2; index[7] = 2; index[8] = 0; index[9] = 1; index[10] = 2; index[11] = 3;
13: value[0] = 11; value[1] = 21; value[2] = 32; value[3] = 41; value[4] = 0; value[5] = 22;
14: value[6] = 33; value[7] = 43; value[8] = 0; value[9] = 0; value[10] = 0; value[11] = 44;
15:
16: lis_matrix_set_ell(maxnzc,index,value,A);
17: lis_matrix_assemble(A);

```

### 5.5.2 Creating Matrices (for Multiprocessing Environment)

Figure 12 shows how the matrix  $A$  in Figure 11 is stored in the ELL format. A program to create the matrix in the ELL format on two processing elements is as follows:

<table><tr><td>0</td><td>0</td><td>0</td><td>1</td></tr><tr><td>11</td><td>21</td><td>0</td><td>22</td></tr></table>	0	0	0	1	11	21	0	22	<table><tr><td>1</td><td>0</td><td>2</td><td>2</td><td>2</td><td>3</td></tr><tr><td>32</td><td>41</td><td>33</td><td>43</td><td>0</td><td>44</td></tr></table>	1	0	2	2	2	3	32	41	33	43	0	44	A.index
0	0	0	1																			
11	21	0	22																			
1	0	2	2	2	3																	
32	41	33	43	0	44																	
PE0	PE1	A.value																				

Figure 12: Data structure of ELL format (for multiprocessing environment).

For multiprocessing environment

```

1: LIS_INT      i,n,maxnzs,my_rank;
2: LIS_INT      *index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: MPI_Comm_rank(MPI_COMM_WORLD,&my_rank);
6: if( my_rank==0 ) {n = 2; maxnzs = 2;}
7: else          {n = 2; maxnzs = 3;}
8: index = (LIS_INT *)malloc( n*maxnzs*sizeof(LIS_INT) );
9: value = (LIS_SCALAR *)malloc( n*maxnzs*sizeof(LIS_SCALAR) );
10: lis_matrix_create(MPI_COMM_WORLD,&A);
11: lis_matrix_set_size(A,n,0);
12: if( my_rank==0 ) {
13:     index[0] = 0; index[1] = 0; index[2] = 0; index[3] = 1;
14:     value[0] = 11; value[1] = 21; value[2] = 0; value[3] = 22;}
15: else {
16:     index[0] = 1; index[1] = 0; index[2] = 2; index[3] = 2; index[4] = 2;
17:     index[5] = 3;
18:     value[0] = 32; value[1] = 41; value[2] = 33; value[3] = 43; value[4] = 0;
19:     value[5] = 44;}
20: lis_matrix_set_ell(maxnzs,index,value,A);
21: lis_matrix_assemble(A);

```

### 5.5.3 Associating Arrays

To associate an array required by the ELL format with the matrix  $A$ , the following functions are used:

- C LIS\_INT lis\_matrix\_set\_ell(LIS\_INT maxnzs, LIS\_INT index[], LIS\_SCALAR value[], LIS\_MATRIX A)
- Fortran subroutine lis\_matrix\_set\_ell(LIS\_INTEGER maxnzs, LIS\_INTEGER index(), LIS\_SCALAR value(), LIS\_MATRIX A, LIS\_INTEGER ierr)

## 5.6 Jagged Diagonal (JDS)

The JDS format first sorts the nonzero elements of the rows in decreasing order of size, and then stores them along the column. The JDS format uses four arrays **perm**, **ptr**, **index** and **value** to store data. Assume that  $maxnzs$  represents the maximum value of the number of the nonzero elements of the matrix  $A$ .

- **perm** is an integer array with a length of  $n$ , which stores the sorted row numbers.
- **value** is a double precision array with a length of  $nnz$ , which stores the values of the jagged diagonal elements of the sorted matrix  $A$ . The first jagged diagonal consists of the values of the first nonzero elements of each row. The next jagged diagonal consists of the values of the second nonzero elements, and so on.
- **index** is an integer array with a length of  $nnz$ , which stores the row numbers of the nonzero elements stored in the array **value**.
- **ptr** is an integer array with a length of  $maxnzs + 1$ , which stores the starting points of the jagged diagonal elements.

For the multithreaded environment, the following modifications have been made: the format uses four arrays **perm**, **ptr**, **index** and **value** to store data. Assume that  $nprocs$  is the number of the threads.  $maxnzs_p$  is the number of the nonzero diagonal elements of the partial matrix into which the row block of the matrix  $A$  is divided.  $maxmaxnzs$  is the maximum value of  $maxnzs_p$ .

- **perm** is an integer array with a length of  $n$ , which stores the sorted row numbers.
- **value** is a double precision array with a length of  $nnz$ , which stores the values of the jagged diagonal elements of the sorted matrix  $A$ . The first jagged diagonal consists of the values of the first nonzero elements of each row. The next jagged diagonal consist of the values of the second nonzero elements of each row, and so on.
- **index** is an integer array with a length of  $nnz$ , which stores the row numbers of the nonzero elements stored in the array **value**.
- **ptr** is an integer array with a length of  $nprocs \times (maxmaxnzs + 1)$ , which stores the starting points of the jagged diagonal elements.

### 5.6.1 Creating Matrices (for Serial Environment)

The right diagram in Figure 13 shows how the matrix  $A$  in Figure 13 is stored in the JDS format. A program to create the matrix in the JDS format is as follows:

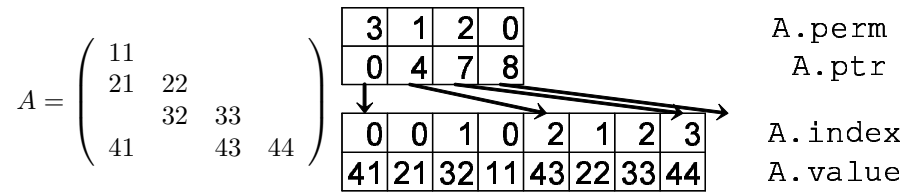


Figure 13: Data structure of JDS format (for serial environment).

For serial environment

```

1: LIS_INT      n, nnz, maxnzs;
2: LIS_INT      *perm, *ptr, *index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: n = 4; nnz = 8; maxnzs = 3;
6: perm = (LIS_INT *)malloc( n*sizeof(LIS_INT) );
7: ptr = (LIS_INT *)malloc( (maxnzs+1)*sizeof(LIS_INT) );
8: index = (LIS_INT *)malloc( nnz*sizeof(LIS_INT) );
9: value = (LIS_SCALAR *)malloc( nnz*sizeof(LIS_SCALAR) );
10: lis_matrix_create(0, &A);
11: lis_matrix_set_size(A, 0, n);
12:
13: perm[0] = 3; perm[1] = 1; perm[2] = 2; perm[3] = 0;
14: ptr[0] = 0; ptr[1] = 4; ptr[2] = 7; ptr[3] = 8;
15: index[0] = 0; index[1] = 0; index[2] = 1; index[3] = 0;
16: index[4] = 2; index[5] = 1; index[6] = 2; index[7] = 3;
17: value[0] = 41; value[1] = 21; value[2] = 32; value[3] = 11;
18: value[4] = 43; value[5] = 22; value[6] = 33; value[7] = 44;
19:
20: lis_matrix_set_jds(nnz, maxnzs, perm, ptr, index, value, A);
21: lis_matrix_assemble(A);

```

### 5.6.2 Creating Matrices (for Multithreaded Environment)

Figure 14 shows how the matrix  $A$  in Figure 13 is stored in the JDS format on two threads. A program to create the matrix in the JDS format on two threads is as follows:

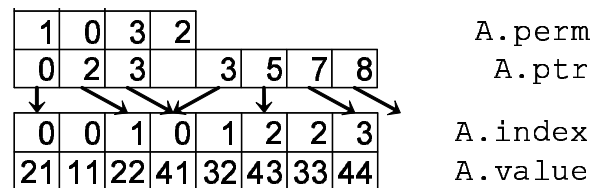


Figure 14: Data structure of JDS format (for multithreaded environment).

For multithreaded environment

```

1: LIS_INT      n, nnz, maxmaxnzs, nprocs;
2: LIS_INT      *perm, *ptr, *index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: n = 4; nnz = 8; maxmaxnzs = 3; nprocs = 2;
6: perm = (LIS_INT *)malloc( n*sizeof(LIS_INT) );
7: ptr  = (LIS_INT *)malloc( nprocs*(maxmaxnzs+1)*sizeof(LIS_INT) );
8: index = (LIS_INT *)malloc( nnz*sizeof(LIS_INT) );
9: value = (LIS_SCALAR *)malloc( nnz*sizeof(LIS_SCALAR) );
10: lis_matrix_create(0, &A);
11: lis_matrix_set_size(A, 0, n);
12:
13: perm[0] = 1; perm[1] = 0; perm[2] = 3; perm[3] = 2;
14: ptr[0]  = 0; ptr[1]  = 2; ptr[2]  = 3; ptr[3]  = 0;
15: ptr[4]  = 3; ptr[5]  = 5; ptr[6]  = 7; ptr[7]  = 8;
16: index[0] = 0; index[1] = 0; index[2] = 1; index[3] = 0;
17: index[4] = 1; index[5] = 2; index[6] = 2; index[7] = 3;
18: value[0] = 21; value[1] = 11; value[2] = 22; value[3] = 41;
19: value[4] = 32; value[5] = 43; value[6] = 33; value[7] = 44;
20:
21: lis_matrix_set_jds(nnz, maxmaxnzs, perm, ptr, index, value, A);
22: lis_matrix_assemble(A);

```

### 5.6.3 Creating Matrices (for Multiprocessing Environment)

Figure 15 shows how the matrix  $A$  in Figure 13 is stored in the JDS format on two processing elements. A program to create the matrix in the JDS format on two processing elements is as follows:

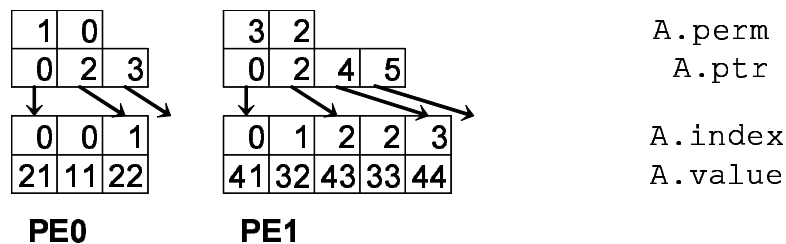


Figure 15: Data structure of JDS format (for multiprocessing environment).

For multiprocessing environment

```

1: LIS_INT      i,n,nnz,maxnzs,my_rank;
2: LIS_INT      *perm,*ptr,*index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: MPI_Comm_rank(MPI_COMM_WORLD,&my_rank);
6: if( my_rank==0 ) {n = 2; nnz = 3; maxnzs = 2;}
7: else         {n = 2; nnz = 5; maxnzs = 3;}
8: perm = (LIS_INT *)malloc( n*sizeof(LIS_INT) );
9: ptr  = (LIS_INT *)malloc( (maxnzs+1)*sizeof(LIS_INT) );
10: index = (LIS_INT *)malloc( nnz*sizeof(LIS_INT) );
11: value = (LIS_SCALAR *)malloc( nnz*sizeof(LIS_SCALAR) );
12: lis_matrix_create(MPI_COMM_WORLD,&A);
13: lis_matrix_set_size(A,n,0);
14: if( my_rank==0 ) {
15:     perm[0] = 1; perm[1] = 0;
16:     ptr[0] = 0; ptr[1] = 2; ptr[2] = 3;
17:     index[0] = 0; index[1] = 0; index[2] = 1;
18:     value[0] = 21; value[1] = 11; value[2] = 22;}
19: else {
20:     perm[0] = 3; perm[1] = 2;
21:     ptr[0] = 0; ptr[1] = 2; ptr[2] = 4; ptr[3] = 5;
22:     index[0] = 0; index[1] = 1; index[2] = 2; index[3] = 2; index[4] = 3;
23:     value[0] = 41; value[1] = 32; value[2] = 43; value[3] = 33; value[4] = 44;}
24: lis_matrix_set_jds(nnz,maxnzs,perm,ptr,index,value,A);
25: lis_matrix_assemble(A);

```

### 5.6.4 Associating Arrays

To associate an array required by the JDS format with the matrix  $A$ , the following functions are used:

- C            LIS\_INT lis\_matrix\_set\_jds(LIS\_INT nnz, LIS\_INT maxnzs, LIS\_INT perm[], LIS\_INT ptr[], LIS\_INT index[], LIS\_SCALAR value[], LIS\_MATRIX A)
- Fortran subroutine lis\_matrix\_set\_jds(LIS\_INTEGER nnz, LIS\_INTEGER maxnzs, LIS\_INTEGER ptr(), integer index(), LIS\_SCALAR value(), LIS\_MATRIX A, LIS\_INTEGER ierr)

## 5.7 Block Sparse Row (BSR)

The BSR format breaks down the matrix  $A$  into partial matrices called blocks, with a size of  $r \times c$ . The BSR format stores the nonzero blocks, in which at least one nonzero element exists, with the similar format as the CRS. Assume that  $nr = n/r$  and  $nnzb$  are the numbers of the nonzero blocks of  $A$ . The BSR format uses three arrays **bp**tr, **bin**dex and **val**ue to store data.

- **value** is a double precision array with a length of  $nnzb \times r \times c$ , which stores the values of the elements of the nonzero blocks.
- **bin**dex is an integer array with a length of  $nnzb$ , which stores the block column numbers of the nonzero blocks.
- **bp**tr is an integer array with a length of  $nr + 1$ , which stores the starting points of the block rows in the array **bin**dex.

### 5.7.1 Creating Matrices (for Serial and Multithreaded Environments)

The right diagram in Figure 16 shows how the matrix  $A$  in Figure 16 is stored in the BSR format. A program to create the matrix in the BSR format is as follows:

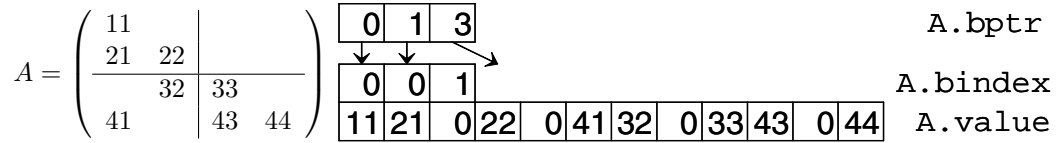


Figure 16: Data structure of BSR format (for serial and multithreaded environments).

For serial and multithreaded environments

```

1: LIS_INT      n, bnr, bnc, nr, nc, bnnz;
2: LIS_INT      *bp
```

tr, \*bindex;
3: LIS\_SCALAR \*value;
4: LIS\_MATRIX A;
5: n = 4; bnr = 2; bnc = 2; bnnz = 3; nr = (n-1)/bnr+1; nc = (n-1)/bnc+1;
6: bptr = (LIS\_INT \*)malloc( (nr+1)\*sizeof(LIS\_INT) );
7: bindex = (LIS\_INT \*)malloc( bnnz\*sizeof(LIS\_INT) );
8: value = (LIS\_SCALAR \*)malloc( bnr\*bnc\*bnnz\*sizeof(LIS\_SCALAR) );
9: lis\_matrix\_create(0,&A);
10: lis\_matrix\_set\_size(A,0,n);
11:
12: bptr[0] = 0; bptr[1] = 1; bptr[2] = 3;
13: bindex[0] = 0; bindex[1] = 0; bindex[2] = 1;
14: value[0] = 11; value[1] = 21; value[2] = 0; value[3] = 22;
15: value[4] = 0; value[5] = 41; value[6] = 32; value[7] = 0;
16: value[8] = 33; value[9] = 43; value[10] = 0; value[11] = 44;
17:
18: lis\_matrix\_set\_bsr(bnr, bnc, bnnz, bptr, bindex, value, A);
19: lis\_matrix\_assemble(A);



### 5.7.2 Creating Matrices (for Multiprocessing Environment)

Figure 17 shows how the matrix  $A$  in Figure 16 is stored in the BSR format on two processing elements. A program to create the matrix in the BSR format on two processing elements is as follows:

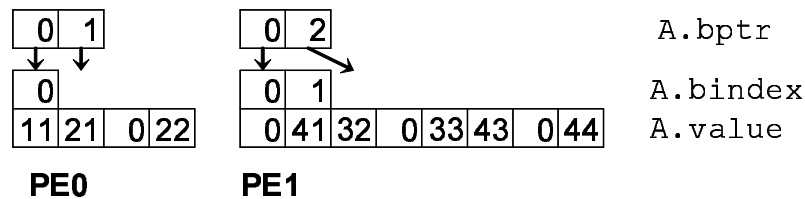


Figure 17: Data structure of BSR format (for multiprocessing environment).

For multiprocessing environment

```

1: LIS_INT      n, bnr, bnc, nr, nc, bnnz, my_rank;
2: LIS_INT      *bptr, *bindex;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);
6: if( my_rank==0 ) {n = 2; bnr = 2; bnc = 2; bnnz = 1; nr = (n-1)/bnr+1; nc = (n-1)/bnc+1;}
7: else          {n = 2; bnr = 2; bnc = 2; bnnz = 2; nr = (n-1)/bnr+1; nc = (n-1)/bnc+1;}
8: bptr  = (LIS_INT *)malloc( (nr+1)*sizeof(LIS_INT) );
9: bindex = (LIS_INT *)malloc( bnnz*sizeof(LIS_INT) );
10: value = (LIS_SCALAR *)malloc( bnr*bnc*bnnz*sizeof(LIS_SCALAR) );
11: lis_matrix_create(MPI_COMM_WORLD, &A);
12: lis_matrix_set_size(A, n, 0);
13: if( my_rank==0 ) {
14:     bptr[0] = 0; bptr[1] = 1;
15:     bindex[0] = 0;
16:     value[0] = 11; value[1] = 21; value[2] = 0; value[3] = 22;}
17: else {
18:     bptr[0] = 0; bptr[1] = 2;
19:     bindex[0] = 0; bindex[1] = 1;
20:     value[0] = 0; value[1] = 41; value[2] = 32; value[3] = 0;
21:     value[4] = 33; value[5] = 43; value[6] = 0; value[7] = 44;}
22: lis_matrix_set_bsr(bnr, bnc, bnnz, bptr, bindex, value, A);
23: lis_matrix_assemble(A);

```

### 5.7.3 Associating Arrays

To associate the arrays in the BSR format with the matrix  $A$ , the following functions are used:

- C LIS\_INT lis\_matrix\_set\_bsr(LIS\_INT bnr, LIS\_INT bnc, LIS\_INT bnnz, LIS\_INT bptr[], LIS\_INT bindex[], LIS\_SCALAR value[], LIS\_MATRIX A)
- Fortran subroutine lis\_matrix\_set\_bsr(LIS\_INTEGER bnr, LIS\_INTEGER bnc, LIS\_INTEGER bnnz, LIS\_INTEGER bptr(), LIS\_INTEGER bindex(), LIS\_SCALAR value(), LIS\_MATRIX A, LIS\_INTEGER ierr)

## 5.8 Block Sparse Column (BSC)

The BSC format breaks down the matrix  $A$  into partial matrices called blocks, with a size of  $r \times c$ . The BSC format stores the nonzero blocks, in which at least one nonzero element exists, in the similar format as the CCS. Assume that  $nc = n/c$  and  $nnzb$  are the numbers of the nonzero blocks of  $A$ . The BSC format uses three arrays **bp**tr, **bin**dex and **value** to store data.

- **value** is a double precision array with a length of  $nnzb \times r \times c$ , which stores the values of the elements of the nonzero blocks.
- **bin**dex is an integer array with a length of  $nnzb$ , which stores the block row numbers of the nonzero blocks.
- **bp**tr is an integer array with a length of  $nc+1$ , which stores the starting points of the block columns in the array **bin**dex.

### 5.8.1 Creating Matrices (for Serial and Multithreaded Environments)

The right diagram in Figure 18 shows how the matrix  $A$  in Figure 18 is stored in the BSC format. A program to create the matrix in the BSC format is as follows:

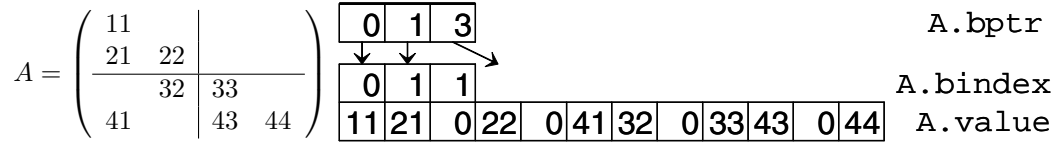


Figure 18: Data structure of BSC format (for serial and multithreaded environments).

For serial and multithreaded environments

```

1: LIS_INT      n, bnr, bnc, nr, nc, bnnz;
2: LIS_INT      *bp[tr], *bin[de]x;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: n = 4; bnr = 2; bnc = 2; bnnz = 3; nr = (n-1)/bnr+1; nc = (n-1)/bnc+1;
6: bp[tr] = (LIS_INT *)malloc( (nc+1)*sizeof(LIS_INT) );
7: bin[de]x = (LIS_INT *)malloc( bnnz*sizeof(LIS_INT) );
8: value = (LIS_SCALAR *)malloc( bnr*bnc*bnnz*sizeof(LIS_SCALAR) );
9: lis_matrix_create(0, &A);
10: lis_matrix_set_size(A, 0, n);
11:
12: bp[tr][0] = 0; bp[tr][1] = 1; bp[tr][2] = 3;
13: bin[de]x[0] = 0; bin[de]x[1] = 1; bin[de]x[2] = 1;
14: value[0] = 11; value[1] = 21; value[2] = 0; value[3] = 22;
15: value[4] = 0; value[5] = 41; value[6] = 32; value[7] = 0;
16: value[8] = 33; value[9] = 43; value[10] = 0; value[11] = 44;
17:
18: lis_matrix_set_bsc(bnr, bnc, bnnz, bp[tr], bin[de]x, value, A);
19: lis_matrix_assemble(A);

```

### 5.8.2 Creating Matrices (for Multiprocessing Environment)

Figure 19 shows how the matrix  $A$  in Figure 18 is stored in the BSC format on two processing elements. A program to create the matrix in the BSC format on two processing elements is as follows:

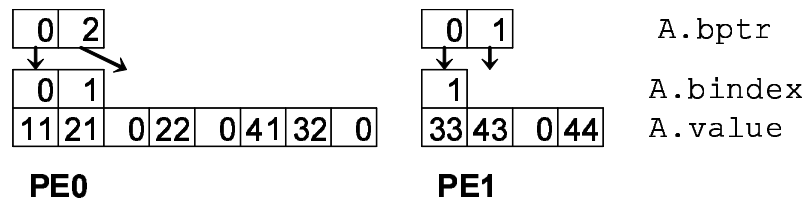


Figure 19: Data structure of BSC format (for multiprocessing environment).

For multiprocessing environment

```

1: LIS_INT      n, bnr, bnc, nr, nc, bnnz, my_rank;
2: LIS_INT      *bptr, *bindex;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);
6: if( my_rank==0 ) {n = 2; bnr = 2; bnc = 2; bnnz = 2; nr = (n-1)/bnr+1; nc = (n-1)/bnc+1;}
7: else          {n = 2; bnr = 2; bnc = 2; bnnz = 1; nr = (n-1)/bnr+1; nc = (n-1)/bnc+1;}
8: bptr  = (LIS_INT *)malloc( (nr+1)*sizeof(LIS_INT) );
9: bindex = (LIS_INT *)malloc( bnnz*sizeof(LIS_INT) );
10: value = (LIS_SCALAR *)malloc( bnr*bnc*bnnz*sizeof(LIS_SCALAR) );
11: lis_matrix_create(MPI_COMM_WORLD, &A);
12: lis_matrix_set_size(A, n, 0);
13: if( my_rank==0 ) {
14:     bptr[0] = 0; bptr[1] = 2;
15:     bindex[0] = 0; bindex[1] = 1;
16:     value[0] = 11; value[1] = 21; value[2] = 0; value[3] = 22;
17:     value[4] = 0; value[5] = 41; value[6] = 32; value[7] = 0;
18: } else {
19:     bptr[0] = 0; bptr[1] = 1;
20:     bindex[0] = 1;
21:     value[0] = 33; value[1] = 43; value[2] = 0; value[3] = 44;
22: lis_matrix_set_bsc(bnr, bnc, bnnz, bptr, bindex, value, A);
23: lis_matrix_assemble(A);

```

### 5.8.3 Associating Arrays

To associate the arrays in the BSC format with the matrix  $A$ , the following functions are used:

- C `LIS_INT lis_matrix_set_bsc(LIS_INT bnr, LIS_INT bnc, LIS_INT bnnz, LIS_INT bptr[], LIS_INT bindex[], LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_bsc(LIS_INTEGER bnr, LIS_INTEGER bnc, LIS_INTEGER bnnz, LIS_INTEGER bptr(), LIS_INTEGER bindex(), LIS_SCALAR value(), LIS_MATRIX A, LIS_INTEGER ierr)`

## 5.9 Variable Block Row (VBR)

The VBR format is the generalized version of the BSR format. The division points of the rows and columns are given by the arrays `row` and `col`. The VBR format stores the nonzero blocks (the blocks in which at least one nonzero element exists) in the similar format as the CRS. Assume that  $nr$  and  $nc$  are the numbers of row and column divisions, respectively, and that  $nnzb$  denotes the number of the nonzero blocks of  $A$ , and  $nnz$  denotes the total number of the elements of the nonzero blocks. The VBR format uses six arrays `bptr`, `bindex`, `row`, `col`, `ptr` and `value` to store data.

- `row` is an integer array with a length of  $nr + 1$ , which stores the starting row number of the block rows.
- `col` is an integer array with a length of  $nc + 1$ , which stores the starting column number of the block columns.
- `bindex` is an integer array with a length of  $nnzb$ , which stores the block column numbers of the nonzero blocks.
- `bptr` is an integer array with a length of  $nr + 1$ , which stores the starting points of the block rows in the array `bindex`.
- `value` is a double precision array with a length of  $nnz$ , which stores the values of the elements of the nonzero blocks.
- `ptr` is an integer array with a length of  $nnzb + 1$ , which stores the starting points of the nonzero blocks in the array `value`.

### 5.9.1 Creating Matrices (for Serial and Multithreaded Environments)

The right diagram in Figure 20 shows how the matrix  $A$  in Figure 20 is stored in the VBR format. A program to create the matrix in the VBR format is as follows:

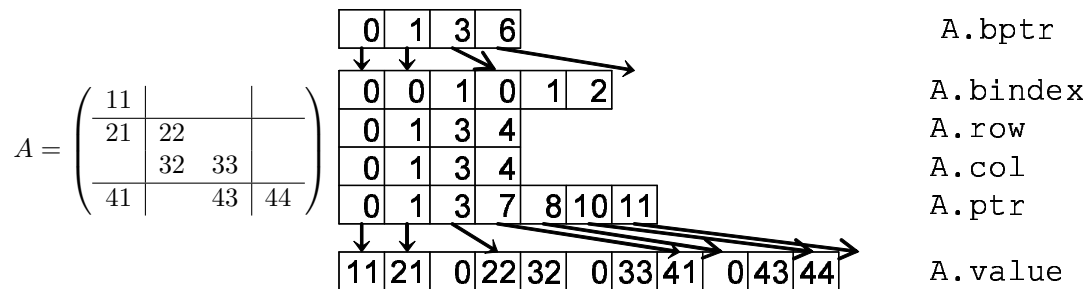


Figure 20: Data structure of VBR format (for serial and multithreaded environments).

For serial and multithreaded environments

```

1: LIS_INT      n,nnz,nr,nc,bnnz;
2: LIS_INT      *row,*col,*ptr,*bptr,*bindex;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: n = 4; nnz = 11; bnnz = 6; nr = 3; nc = 3;
6: bptr = (LIS_INT *)malloc( (nr+1)*sizeof(LIS_INT) );
7: row = (LIS_INT *)malloc( (nr+1)*sizeof(LIS_INT) );
8: col = (LIS_INT *)malloc( (nc+1)*sizeof(LIS_INT) );
9: ptr = (LIS_INT *)malloc( (bnnz+1)*sizeof(LIS_INT) );
10: bindex = (LIS_INT *)malloc( bnnz*sizeof(LIS_INT) );
11: value = (LIS_SCALAR *)malloc( nnz*sizeof(LIS_SCALAR) );
12: lis_matrix_create(0,&A);
13: lis_matrix_set_size(A,0,n);
14:
15: bptr[0] = 0; bptr[1] = 1; bptr[2] = 3; bptr[3] = 6;
16: row[0] = 0; row[1] = 1; row[2] = 3; row[3] = 4;
17: col[0] = 0; col[1] = 1; col[2] = 3; col[3] = 4;
18: bindex[0] = 0; bindex[1] = 0; bindex[2] = 1; bindex[3] = 0;
19: bindex[4] = 1; bindex[5] = 2;
20: ptr[0] = 0; ptr[1] = 1; ptr[2] = 3; ptr[3] = 7;
21: ptr[4] = 8; ptr[5] = 10; ptr[6] = 11;
22: value[0] = 11; value[1] = 21; value[2] = 0; value[3] = 22;
23: value[4] = 32; value[5] = 0; value[6] = 33; value[7] = 41;
24: value[8] = 0; value[9] = 43; value[10] = 44;
25:
26: lis_matrix_set_vbr(nnz,nr,nc,bnnz,row,col,ptr,bptr,bindex,value,A);
27: lis_matrix_assemble(A);

```

### 5.9.2 Creating Matrices (for Multiprocessing Environment)

Figure 21 shows how the matrix  $A$  in Figure 20 is stored in the VBR format on two processing elements. A program to create the matrix in the VBR format on two processing elements is as follows:

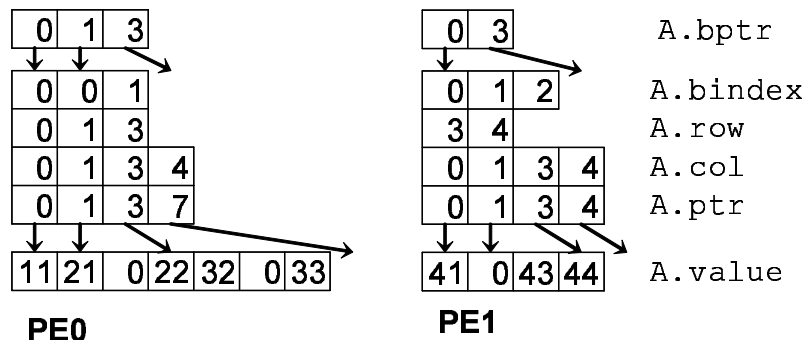


Figure 21: Data structure of VBR format (for multiprocessing environment).

For multiprocessing environment

```

1: LIS_INT      n, nnz, nr, nc, bnnz, my_rank;
2: LIS_INT      *row, *col, *ptr, *bptr, *bindex;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);
6: if( my_rank==0 ) { n = 2; nnz = 7; bnnz = 3; nr = 2; nc = 3; }
7: else          { n = 2; nnz = 4; bnnz = 3; nr = 1; nc = 3; }
8: bptr  = (LIS_INT *)malloc( (nr+1)*sizeof(LIS_INT) );
9: row   = (LIS_INT *)malloc( (nr+1)*sizeof(LIS_INT) );
10: col  = (LIS_INT *)malloc( (nc+1)*sizeof(LIS_INT) );
11: ptr   = (LIS_INT *)malloc( (bnnz+1)*sizeof(LIS_INT) );
12: bindex = (LIS_INT *)malloc( bnnz*sizeof(LIS_INT) );
13: value = (LIS_SCALAR *)malloc( nnz*sizeof(LIS_SCALAR) );
14: lis_matrix_create(MPI_COMM_WORLD, &A);
15: lis_matrix_set_size(A, n, 0);
16: if( my_rank==0 ) {
17:     bptr[0] = 0; bptr[1] = 1; bptr[2] = 3;
18:     row[0] = 0; row[1] = 1; row[2] = 3;
19:     col[0] = 0; col[1] = 1; col[2] = 3; col[3] = 4;
20:     bindex[0] = 0; bindex[1] = 0; bindex[2] = 1;
21:     ptr[0] = 0; ptr[1] = 1; ptr[2] = 3; ptr[3] = 7;
22:     value[0] = 11; value[1] = 21; value[2] = 0; value[3] = 22;
23:     value[4] = 32; value[5] = 0; value[6] = 33; }
24: else {
25:     bptr[0] = 0; bptr[1] = 3;
26:     row[0] = 3; row[1] = 4;
27:     col[0] = 0; col[1] = 1; col[2] = 3; col[3] = 4;
28:     bindex[0] = 0; bindex[1] = 1; bindex[2] = 2;
29:     ptr[0] = 0; ptr[1] = 1; ptr[2] = 3; ptr[3] = 4;
30:     value[0] = 41; value[1] = 0; value[2] = 43; value[3] = 44; }
31: lis_matrix_set_vbr(nnz, nr, nc, bnnz, row, col, ptr, bptr, bindex, value, A);
32: lis_matrix_assemble(A);

```

### 5.9.3 Associating Arrays

To associate the arrays in the VBR format with the matrix  $A$ , the following functions are used:

- C `LIS_INT lis_matrix_set_vbr(LIS_INT nnz, LIS_INT nr, LIS_INT nc, LIS_INT bnnz, LIS_INT row[], LIS_INT col[], LIS_INT ptr[], LIS_INT bptr[], LIS_INT bindex[], LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_vbr(LIS_INTEGER nnz, LIS_INTEGER nr, LIS_INTEGER nc, LIS_INTEGER bnnz, LIS_INTEGER row(), LIS_INTEGER col(), LIS_INTEGER ptr(), LIS_INTEGER bptr(), LIS_INTEGER bindex(), LIS_SCALAR value(), LIS_MATRIX A, LIS_INTEGER ierr)`

## 5.10 Coordinate (COO)

The COO format uses three arrays `row`, `col` and `value` to store data.

- `value` is a double precision array with a length of `nnz`, which stores the values of the nonzero elements.
- `row` is an integer array with a length of `nnz`, which stores the row numbers of the nonzero elements.
- `col` is an integer array with a length of `nnz`, which stores the column numbers of the nonzero elements.

### 5.10.1 Creating Matrices (for Serial and Multithreaded Environments)

The right diagram in Figure 22 shows how the matrix  $A$  in Figure 22 is stored in the COO format. A program to create the matrix in the COO format is as follows:

$$A = \begin{pmatrix} 11 & & & \\ 21 & 22 & & \\ & 32 & 33 & \\ 41 & & 43 & 44 \end{pmatrix} \quad \begin{array}{|c|c|c|c|c|c|c|c|} \hline 0 & 1 & 3 & 1 & 2 & 2 & 3 & 3 \\ \hline 0 & 0 & 0 & 1 & 1 & 2 & 2 & 3 \\ \hline 11 & 21 & 41 & 22 & 32 & 33 & 43 & 44 \\ \hline \end{array} \quad \begin{array}{l} A.\text{row} \\ A.\text{col} \\ A.\text{value} \end{array}$$

Figure 22: Data structure of COO format (for serial and multithreaded environments).

For serial and multithreaded environments

```

1: LIS_INT      n,nnz;
2: LIS_INT      *row,*col;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: n = 4; nnz = 8;
6: row = (LIS_INT *)malloc( nnz*sizeof(LIS_INT) );
7: col = (LIS_INT *)malloc( nnz*sizeof(LIS_INT) );
8: value = (LIS_SCALAR *)malloc( nnz*sizeof(LIS_SCALAR) );
9: lis_matrix_create(0,&A);
10: lis_matrix_set_size(A,0,n);
11:
12: row[0] = 0; row[1] = 1; row[2] = 3; row[3] = 1;
13: row[4] = 2; row[5] = 2; row[6] = 3; row[7] = 3;
14: col[0] = 0; col[1] = 0; col[2] = 0; col[3] = 1;
15: col[4] = 1; col[5] = 2; col[6] = 2; col[7] = 3;
16: value[0] = 11; value[1] = 21; value[2] = 41; value[3] = 22;
17: value[4] = 32; value[5] = 33; value[6] = 43; value[7] = 44;
18:
19: lis_matrix_set_coo(nnz,row,col,value,A);
20: lis_matrix_assemble(A);

```



### 5.10.2 Creating Matrices (for Multiprocessing Environment)

Figure 23 shows how the matrix  $A$  in Figure 22 is stored in the COO format on two processing elements. A program to create the matrix in the COO format on two processing elements is as follows:

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Figure 23: Data structure of COO format (for multiprocessing environment).

For multiprocessing environment

```

1: LIS_INT      n,nnz,my_rank;
2: LIS_INT      *row,*col;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: MPI_Comm_rank(MPI_COMM_WORLD,&my_rank);
6: if( my_rank==0 ) {n = 2; nnz = 3;}
7: else         {n = 2; nnz = 5;}
8: row  = (LIS_INT *)malloc( nnz*sizeof(LIS_INT) );
9: col  = (LIS_INT *)malloc( nnz*sizeof(LIS_INT) );
10: value = (LIS_SCALAR *)malloc( nnz*sizeof(LIS_SCALAR) );
11: lis_matrix_create(MPI_COMM_WORLD,&A);
12: lis_matrix_set_size(A,n,0);
13: if( my_rank==0 ) {
14:     row[0] = 0; row[1] = 1; row[2] = 1;
15:     col[0] = 0; col[1] = 0; col[2] = 1;
16:     value[0] = 11; value[1] = 21; value[2] = 22;}
17: else {
18:     row[0] = 3; row[1] = 2; row[2] = 2; row[3] = 3; row[4] = 3;
19:     col[0] = 0; col[1] = 1; col[2] = 2; col[3] = 2; col[4] = 3;
20:     value[0] = 41; value[1] = 32; value[2] = 33; value[3] = 43; value[4] = 44;}
21: lis_matrix_set_coo(nnz,row,col,value,A);
22: lis_matrix_assemble(A);

```

### 5.10.3 Associating Arrays

To associate the arrays in the COO format with the matrix  $A$ , the following functions are used:

- C `LIS_INT lis_matrix_set_coo(LIS_INT nnz, LIS_INT row[], LIS_INT col[], LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_coo(LIS_INTEGER nnz, LIS_INTEGER row(), LIS_INTEGER col(), LIS_SCALAR value(), LIS_MATRIX A, LIS_INTEGER ierr)`

## 5.11 Dense (DNS)

The DNS format uses one array `value` to store data.

- `value` is a double precision array with a length of  $n \times n$ , which stores the values of the elements with priority given to the columns.

### 5.11.1 Creating Matrices (for Serial and Multithreaded Environments)

The right diagram in Figure 24 shows how the matrix  $A$  in Figure 24 is stored in the DNS format. A program to create the matrix in the DNS format is as follows:

$$A = \begin{pmatrix} 11 & & & \\ 21 & 22 & & \\ & 32 & 33 & \\ 41 & & 43 & 44 \end{pmatrix} \quad \begin{array}{|c|c|c|c|c|c|c|c|} \hline 11 & 21 & 0 & 41 & 0 & 22 & 32 & 0 \\ \hline 0 & 0 & 33 & 43 & 0 & 0 & 0 & 44 \\ \hline \end{array} \quad \text{A.Value}$$

Figure 24: Data structure of DNS format (for serial and multithreaded environments).

For serial and multithreaded environments

```

1: LIS_INT      n;
2: LIS_SCALAR   *value;
3: LIS_MATRIX   A;
4: n = 4;
5: value = (LIS_SCALAR *)malloc( n*n*sizeof(LIS_SCALAR) );
6: lis_matrix_create(0,&A);
7: lis_matrix_set_size(A,0,n);
8:
9: value[0] = 11; value[1] = 21; value[2] = 0; value[3] = 41;
10: value[4] = 0; value[5] = 22; value[6] = 32; value[7] = 0;
11: value[8] = 0; value[9] = 0; value[10] = 33; value[11] = 43;
12: value[12] = 0; value[13] = 0; value[14] = 0; value[15] = 44;
13:
14: lis_matrix_set_dns(value,A);
15: lis_matrix_assemble(A);

```

### 5.11.2 Creating Matrices (for Multiprocessing Environment)

Figure 25 shows how the matrix  $A$  in Figure 24 is stored in the DNS format on two processing elements. A program to create the matrix in the DNS format on two processing elements is as follows:

11	21	0	22	0	41	32	0	A.Value
0	0	0	0	33	43	0	44	
<b>PE0</b>				<b>PE1</b>				

Figure 25: Data structure of DNS format (for multiprocessing environment).

For multiprocessing environment

```

1: LIS_INT      n,my_rank;
2: LIS_SCALAR   *value;
3: LIS_MATRIX   A;
4: MPI_Comm_rank(MPI_COMM_WORLD,&my_rank);
5: if( my_rank==0 ) {n = 2;}
6: else         {n = 2;}
7: value = (LIS_SCALAR *)malloc( n*n*sizeof(LIS_SCALAR) );
8: lis_matrix_create(MPI_COMM_WORLD,&A);
9: lis_matrix_set_size(A,n,0);
10: if( my_rank==0 ) {
11:     value[0] = 11; value[1] = 21; value[2] = 0; value[3] = 22;
12:     value[4] = 0; value[5] = 0; value[6] = 0; value[7] = 0;}
13: else {
14:     value[0] = 0; value[1] = 41; value[2] = 32; value[3] = 0;
15:     value[4] = 33; value[5] = 43; value[6] = 0; value[7] = 44;}
16: lis_matrix_set_dns(value,A);
17: lis_matrix_assemble(A);

```

### 5.11.3 Associating Arrays

To associate the arrays in the DNS format with the matrix  $A$ , the following functions are used:

- C LIS\_INT lis\_matrix\_set\_dns(LIS\_SCALAR value[], LIS\_MATRIX A)
- Fortran subroutine lis\_matrix\_set\_dns(LIS\_SCALAR value(), LIS\_MATRIX A, LIS\_INTEGER ierr)

## 6 Functions

This section describes the functions which can be employed by the user. The return codes of the functions in C and the values of `ierr` in Fortran are as follows:

<code>LIS_SUCCESS(0)</code>	Normal termination
<code>LIS_ILL_OPTION(1)</code>	Illegal option
<code>LIS_BREAKDOWN(2)</code>	Breakdown
<code>LIS_OUT_OF_MEMORY(3)</code>	Out of working memory
<code>LIS_MAXITER(4)</code>	Maximum number of iterations
<code>LIS_NOT_IMPLEMENTED(5)</code>	Not implemented
<code>LIS_ERR_FILE_IO(6)</code>	File I/O error

## 6.1 Operating Vector Elements

Assume that the size of the vector  $v$  is  $global\_n$  and that the size of the partial vectors stored on  $nprocs$  processing elements is  $local\_n$ .  $global\_n$  and  $local\_n$  are called the global size and the local size, respectively.

### 6.1.1 `lis_vector_create`

```
C      LIS_INT lis_vector_create(LIS_Comm comm, LIS_VECTOR *v)
Fortran subroutine lis_vector_create(LIS_Comm comm, LIS_VECTOR v, LIS_INTEGER ierr)
```

#### Description

Create the vector  $v$

#### Input

<code>LIS_Comm</code>	The MPI communicator
-----------------------	----------------------

#### Output

<code>v</code>	The vector
<code>ierr</code>	The return code

#### Note

For the serial and multithreaded environments, the value of `comm` is ignored.

### 6.1.2 `lis_vector_destroy`

```
C      LIS_INT lis_vector_destroy(LIS_VECTOR v)
Fortran subroutine lis_vector_destroy(LIS_VECTOR v, LIS_INTEGER ierr)
```

#### Description

Destroy the vector  $v$

#### Input

<code>v</code>	The vector to be destroyed
----------------	----------------------------

#### Output

<code>ierr</code>	The return code
-------------------	-----------------

### 6.1.3 lis\_vector\_duplicate

```
C      LIS_INT lis_vector_duplicate(void *vin, LIS_VECTOR *vout)
Fortran subroutine lis_vector_duplicate(LIS_VECTOR vin, LIS_VECTOR vout,
      LIS_INTEGER ierr)
```

#### Description

Create the vector  $v_{out}$  which has the same information as  $v_{in}$

#### Input

`vin`                                      The source vector

#### Output

`vout`                                     The destination vector

`ierr`                                     The return code

#### Note

The function `lis_vector_duplicate` does not copy the values, but only allocates the memory. To copy the values as well, the function `lis_vector_copy` must be called after this function.

### 6.1.4 lis\_vector\_set\_size

```
C      LIS_INT lis_vector_set_size(LIS_VECTOR v, LIS_INT local_n,
      LIS_INTEGER global_n)
Fortran subroutine lis_vector_set_size(LIS_VECTOR v, LIS_INTEGER local_n,
      LIS_INTEGER global_n, LIS_INTEGER ierr)
```

#### Description

Assign the size of the vector  $v$

#### Input

`v`                                        The vector

`local_n`                                The size of the partial vector

`global_n`                               The size of the global vector

#### Output

`ierr`                                     The return code

#### Note

Either `local_n` or `global_n` must be provided.

In the case of the serial and multithreaded environments, `local_n` is equal to `global_n`. Therefore, both `lis_vector_set_size(v,n,0)` and `lis_vector_set_size(v,0,n)` create a vector of size  $n$ .

For the multiprocessing environment, `lis_vector_set_size(v,n,0)` creates a partial vector of size  $n$  on each processing element. On the other hand, `lis_vector_set_size(v,0,n)` creates a partial vector of size  $m_p$  on the processing element  $p$ . The values of  $m_p$  are determined by the library.

```
C      LIS_INT lis_vector_get_size(LIS_VECTOR v, LIS_INT *local_n,
C      LIS_INT *global_n)
Fortran subroutine lis_vector_get_size(LIS_VECTOR v, LIS_INTEGER local_n,
LIS_INTEGER global_n, LIS_INTEGER ierr)
```

Get the size of the vector  $v$

v The vector

<code>local_n</code>	The size of the partial vector
<code>global_n</code>	The size of the global vector
<code>ierr</code>	The return code

In the case of the serial and multithreaded environments, *local\_n* is equal to *global\_n*.

```
C      LIS_INT lis_vector_get_range(LIS_VECTOR v, LIS_INT *is, LIS_INT *ie)
Fortran subroutine lis_vector_get_range(LIS_VECTOR v, LIS_INTEGER is,
      LIS_INTEGER ie, LIS_INTEGER ierr)
```

Get the location of the partial vector  $v$  in the global vector

v The partial vector

<b>is</b>	The location where the partial vector $v$ starts in the global vector
<b>ie</b>	The next location where the partial vector $v$ ends in the global vector
<b>ierr</b>	The return code

For the serial and multithreaded environments, a vector of size  $n$  results in  $is = 0$  and  $ie = n$ .

### 6.1.7 lis\_vector\_set\_value

```
C      LIS_INT lis_vector_set_value(LIS_INT flag, LIS_INT i, LIS_SCALAR value,  
                                  LIS_VECTOR v)  
Fortran subroutine lis_vector_set_value(LIS_INTEGER flag, LIS_INTEGER i,  
                                       LIS_SCALAR value, LIS_VECTOR v, LIS_INTEGER ierr)
```

#### Description

Assign the scalar *value* to the *i*-th row of the vector *v*

#### Input

flag	LIS_INS.VALUE : $v[i] = value$ LIS_ADD.VALUE : $v[i] = v[i] + value$
i	The location where the value is assigned
value	The scalar value to be assigned
v	The destination vector

#### Output

v	The vector with the scalar <i>value</i> assigned to the <i>i</i> -th row
ierr	The return code

#### Note

For the multiprocessing environment, the *i*-th row of the global vector must be specified instead of the *i*-th row of the partial vector.

### 6.1.8 lis\_vector\_get\_value

```
C      LIS_INT lis_vector_get_value(LIS_VECTOR v, LIS_INT i, LIS_SCALAR *value)  
Fortran subroutine lis_vector_get_value(LIS_VECTOR v, LIS_INTEGER i,  
                                       LIS_SCALAR value, LIS_INTEGER ierr)
```

#### Description

Get the value of the *i*-th row of the vector *v*

#### Input

i	The location where the value is assigned
v	The destination vector

#### Output

value	The value of the <i>i</i> -th row
ierr	The return code

#### Note

For the multiprocessing environment, the *i*-th row of the global vector must be specified.



### 6.1.9 lis\_vector\_set\_values

```
C      LIS_INT lis_vector_set_values(LIS_INT flag, LIS_INT count,
      LIS_INT index[], LIS_SCALAR value[], LIS_VECTOR v)
Fortran subroutine lis_vector_set_values(LIS_INTEGER flag, LIS_INTEGER count,
      LIS_INTEGER index(), LIS_SCALAR value(), LIS_VECTOR v, LIS_INTEGER ierr)
```

#### Description

Assign the scalar values `value[i]` to the `index[i]`-th rows of the vector *v*

#### Input

<code>flag</code>	<code>LIS_INS.VALUE : v[index[i]] = value[i]</code> <code>LIS_ADD.VALUE : v[index[i]] = v[index[i]] + value[i]</code>
<code>count</code>	The number of the elements of the array which stores the scalar values to be assigned
<code>index</code>	The array which stores the location where the scalar values are assigned
<code>value</code>	The array which stores the scalar values to be assigned
<code>v</code>	The destination vector

#### Output

<code>v</code>	The vector with the scalar <code>value[i]</code> assigned to the <code>index[i]</code> -th row
<code>ierr</code>	The return code

#### Note

For the multiprocessing environment, the `index[i]`-th row of the global vector must be specified instead of the `index[i]`-th row of the partial vector.

### 6.1.10 lis\_vector\_get\_values

```
C      LIS_INT lis_vector_get_values(LIS_VECTOR v, LIS_INT start, LIS_INT count,
                                   LIS_SCALAR value[])
Fortran subroutine lis_vector_get_values(LIS_VECTOR v, LIS_INTEGER start,
                                   LIS_INTEGER count, LIS_SCALAR value(), LIS_INTEGER ierr)
```

#### Description

Get the scalar values of the  $start + i$ -th row of the vector  $v$ , where  $i = 0, 1, \dots, count - 1$

#### Input

<code>start</code>	The starting location
<code>count</code>	The number of the values to get
<code>v</code>	The destination vector

#### Output

<code>value</code>	The vector to store the scalar values
<code>ierr</code>	The return code

#### Note

For the multiprocessing environment, the  $start + i$ -th row of the global vector must be specified.

### 6.1.11 lis\_vector\_scatter

```
C      LIS_INT lis_vector_scatter(LIS_SCALAR value[], LIS_VECTOR v)
Fortran subroutine lis_vector_scatter(LIS_SCALAR value(), LIS_VECTOR v,
                                   LIS_INTEGER ierr)
```

#### Description

Assign the scalar values of the  $i$ -th row of the vector  $v$ , where  $i = 0, 1, \dots, global\_n - 1$

#### Input

<code>value</code>	The array which stores the scalar values to be assigned
--------------------	---

#### Output

<code>v</code>	The destination vector
<code>ierr</code>	The return code

#### Note

```
C      LIS_INT lis_vector_gather(LIS_VECTOR v, LIS_SCALAR value[])
Fortran subroutine lis_vector_gather(LIS_VECTOR v, LIS_SCALAR value(),
      LIS_INTEGER ierr)
```

Get the scalar values of the  $i$ -th row of the vector  $v$ , where  $i = 0, 1, \dots, global\_n - 1$

**v** The source vector

value	The vector to store the scalar values
-------	---------------------------------------

ierr	The return code
------	-----------------

```
C      LIS_INT lis_vector_copy(LIS_VECTOR x, LIS_VECTOR y)
Fortran subroutine lis_vector_copy(LIS_VECTOR x, LIS_VECTOR y, LIS_INTEGER ierr)
```

Copy the values of the vector elements

<b>x</b>	The source vector
----------	-------------------

y                      The destination vector

ierr	The return code
------	-----------------

```
C      LIS_INT lis_vector_set_all(LIS_SCALAR value, LIS_VECTOR x)
Fortran subroutine lis_vector_set_all(LIS_SCALAR value, LIS_VECTOR x,
                                     LIS_INTEGER ierr)
```

Assign the scalar *value* to the all elements of the vector *v*

value	The scalar value to be assigned
0	0
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	9
10	10
11	11
12	12
13	13
14	14
15	15
16	16
17	17
18	18
19	19
20	20
21	21
22	22
23	23
24	24
25	25
26	26
27	27
28	28
29	29
30	30
31	31
32	32
33	33
34	34
35	35
36	36
37	37
38	38
39	39
40	40
41	41
42	42
43	43
44	44
45	45
46	46
47	47
48	48
49	49
50	50
51	51
52	52
53	53
54	54
55	55
56	56
57	57
58	58
59	59
60	60
61	61
62	62
63	63
64	64
65	65
66	66
67	67
68	68
69	69
70	70
71	71
72	72
73	73
74	74
75	75
76	76
77	77
78	78
79	79
80	80
81	81
82	82
83	83
84	84
85	85
86	86
87	87
88	88
89	89
90	90
91	91
92	92
93	93
94	94
95	95
96	96
97	97
98	98
99	99

**v** The destination vector

v	The vector with the <i>value</i> assigned to the all elements
---	---

ierr	The return code
------	-----------------

## 6.2 Operating Matrix Elements

Assume that the size of the matrix  $A$  is  $global\_n \times global\_n$  and that the size of each partial matrix stored on  $nprocs$  processing elements is  $local\_n \times global\_n$ . Here,  $global\_n$  and  $local\_n$  are called the number of the rows of the global matrix and the number of the rows of the partial matrix, respectively.

### 6.2.1 lis\_matrix\_create

```
C      LIS_INT lis_matrix_create(LIS_Comm comm, LIS_MATRIX *A)
Fortran subroutine lis_matrix_create(LIS_Comm comm, LIS_MATRIX A, LIS_INTEGER ierr)
```

#### Description

Create the matrix  $A$

#### Input

LIS_Comm	The MPI communicator
----------	----------------------

#### Output

A	The matrix
ierr	The return code

#### Note

For the sequential and the multithreaded environments, the value of `comm` is ignored.

### 6.2.2 lis\_matrix\_destroy

```
C      LIS_INT lis_matrix_destroy(LIS_MATRIX A)
Fortran subroutine lis_matrix_destroy(LIS_MATRIX A, LIS_INTEGER ierr)
```

#### Description

Destroy the matrix  $A$

#### Input

A	The matrix to be destroyed
---	----------------------------

#### Output

ierr	The return code
------	-----------------

### 6.2.3 lis\_matrix\_duplicate

```
C      LIS_INT lis_matrix_duplicate(LIS_MATRIX Ain, LIS_MATRIX *Aout)
Fortran subroutine lis_matrix_duplicate(LIS_MATRIX Ain, LIS_MATRIX Aout,
      LIS_INTEGER ierr)
```

#### Description

Create the matrix  $A_{out}$  which has the same information as the original  $A_{in}$

#### Input

**Ain**                                      The source matrix

#### Output

**Aout**                                      The destination matrix

**ierr**                                      The return code

#### Note

The function `lis_matrix_duplicate` does not copy the values of the elements of the matrix, but only allocates the memory. To copy the values of the elements as well, the function `lis_matrix_copy` must be called after this function.

### 6.2.4 lis\_matrix\_malloc

```
C      LIS_INT lis_matrix_malloc(LIS_MATRIX A, LIS_INT nnz_row, LIS_INT nnz[])
Fortran subroutine lis_matrix_malloc(LIS_MATRIX A, LIS_INTEGER nnz_row,
      LIS_INTEGER nnz[], LIS_INTEGER ierr)
```

#### Description

Allocate the memory for the matrix  $A$

#### Input

**A**    The matrix

**nnz\_row**                                   The average number of the nonzero elements

**nnz**                                        The array of numbers of the nonzero elements in each row

#### Output

**ierr**                                      The return code

#### Note

Either `nnz_row` or `nnz` must be provided.

### 6.2.5 lis\_matrix\_set\_value

```
C      LIS_INT lis_matrix_set_value(LIS_INT flag, LIS_INT i, LIS_INT j,
                                   LIS_SCALAR value, LIS_MATRIX A)
Fortran subroutine lis_matrix_set_value(LIS_INTEGER flag, LIS_INTEGER i,
                                       LIS_INTEGER j, LIS_SCALAR value, LIS_MATRIX A, LIS_INTEGER ierr)
```

#### Description

Assign the scalar *value* to the  $(i, j)$ -th element of the matrix *A*

#### Input

flag	LIS_INS.VALUE : $A(i, j) = value$ LIS_ADD.VALUE : $A(i, j) = A(i, j) + value$
i	The row number of the matrix
j	The column number of the matrix
value	The value to be assigned
A	The matrix

#### Output

A	The matrix
ierr	The return code

#### Note

For the multiprocessing environment, the  $i$ -th row and the  $j$ -th column of the global matrix must be specified.

The function `lis_matrix_set_value` stores the assigned value in a temporary internal format. Therefore, after `lis_matrix_set_value` is called, the function `lis_matrix_assemble` must be called.

### 6.2.6 lis\_matrix\_assemble

```
C      LIS_INT lis_matrix_assemble(LIS_MATRIX A)
Fortran subroutine lis_matrix_assemble(LIS_MATRIX A, LIS_INTEGER ierr)
```

#### Description

Assemble the matrix *A* into the specified storage format

#### Input

A	The matrix
---	------------

#### Output

A	The matrix assembled into the specified storage format
ierr	The return code

### 6.2.7 lis\_matrix\_set\_size

```
C      LIS_INT lis_matrix_set_size(LIS_MATRIX A, LIS_INT local_n,  
                                LIS_INT global_n)  
Fortran subroutine lis_matrix_set_size(LIS_MATRIX A, LIS_INTEGER local_n,  
                                LIS_INTEGER global_n, LIS_INTEGER ierr)
```

#### Description

Assign the size of the matrix  $A$

#### Input

$A$	The matrix
$local\_n$	The number of the rows of the partial matrix
$global\_n$	The number of the rows of the global matrix

#### Output

$ierr$	The return code
--------	-----------------

#### Note

Either  $local\_n$  or  $global\_n$  must be provided.

In the case of the serial and multithreaded environments,  $local\_n$  is equal to  $global\_n$ . Therefore, both `lis_matrix_set_size(A,n,0)` and `lis_matrix_set_size(A,0,n)` create a matrix of size  $n \times n$ .

For the multiprocessing environment, `lis_matrix_set_size(A,n,0)` creates a partial matrix of size  $n \times N$  on each processing element, where  $N$  is the total sum of  $n$ . On the other hand, `lis_matrix_set_size(A,0,n)` creates a partial matrix of size  $m_p \times n$  on the processing element  $p$ . The values of  $m_p$  are determined by the library.

### 6.2.8 lis\_matrix\_get\_size

```
C      LIS_INT lis_matrix_get_size(LIS_MATRIX A, LIS_INT *local_n,  
                                LIS_INT *global_n)  
Fortran subroutine lis_matrix_get_size(LIS_MATRIX A, LIS_INTEGER local_n,  
                                LIS_INTEGER global_n, LIS_INTEGER ierr)
```

#### Description

Get the size of the matrix  $A$

#### Input

$A$	The matrix
-----	------------

#### Output

$local\_n$	The number of the rows of the partial matrix
$global\_n$	The number of the rows of the global matrix
$ierr$	The return code

#### Note

In case of the serial and multithreaded environments,  $local\_n$  is equal to  $global\_n$ .

### 6.2.9 lis\_matrix\_get\_range

```
C      LIS_INT lis_matrix_get_range(LIS_MATRIX A, LIS_INT *is, LIS_INT *ie)
Fortran subroutine lis_matrix_get_range(LIS_MATRIX A, LIS_INTEGER is,
      LIS_INTEGER ie, LIS_INTEGER ierr)
```

#### Description

Get the location of the partial matrix  $A$  in the global matrix

#### Input

<b>A</b>	The partial matrix
----------	--------------------

#### Output

<b>is</b>	The location where the partial matrix $A$ starts in the global matrix
<b>ie</b>	The next location where the partial matrix $A$ ends in the global matrix
<b>ierr</b>	The return code

#### Note

For the serial and multithreaded environments, a matrix of  $n \times n$  results in  $is = 0$  and  $ie = n$ .



### 6.2.10 lis\_matrix\_set\_type

```
C      LIS_INT lis_matrix_set_type(LIS_MATRIX A, LIS_INT matrix_type)
Fortran subroutine lis_matrix_set_type(LIS_MATRIX A, LIS_INTEGER matrix_type,
      LIS_INTEGER ierr)
```

#### Description

Assign the storage format

#### Input

A	The matrix
matrix_type	The storage format

#### Output

ierr	The return code
------	-----------------

#### Note

matrix\_type of A is LIS\_MATRIX\_CRS when the matrix is created. The table below shows the available storage formats for matrix\_type.

Storage format		matrix_type
Compressed Row Storage	(CRS)	{LIS_MATRIX_CRS 1}
Compressed Column Storage	(CCS)	{LIS_MATRIX_CCS 2}
Modified Compressed Sparse Row	(MSR)	{LIS_MATRIX_MSR 3}
Diagonal	(DIA)	{LIS_MATRIX_DIA 4}
Ellpack-Itpack Generalized Diagonal	(ELL)	{LIS_MATRIX_ELL 5}
Jagged Diagonal	(JDS)	{LIS_MATRIX_JDS 6}
Block Sparse Row	(BSR)	{LIS_MATRIX_BSR 7}
Block Sparse Column	(BSC)	{LIS_MATRIX_BSC 8}
Variable Block Row	(VBR)	{LIS_MATRIX_VBR 9}
Dense	(DNS)	{LIS_MATRIX_DNS 10}
Coordinate	(COO)	{LIS_MATRIX_COO 11}

### 6.2.11 lis\_matrix\_get\_type

```
C      LIS_INT lis_matrix_get_type(LIS_MATRIX A, LIS_INT *matrix_type)
Fortran subroutine lis_matrix_get_type(LIS_MATRIX A, LIS_INTEGER matrix_type,
      LIS_INTEGER ierr)
```

#### Description

Get the storage format

#### Input

A	The matrix
---	------------

#### Output

matrix_type	The storage format
ierr	The return code

### 6.2.12 lis\_matrix\_set\_blocksize

```
C      LIS_INT lis_matrix_set_blocksize(LIS_MATRIX A, LIS_INT bnr, LIS_INT bnc,
        LIS_INT row[], LIS_INT col[])
Fortran subroutine lis_matrix_set_blocksize(LIS_MATRIX A, LIS_INTEGER bnr,
        LIS_INTEGER bnc, LIS_INTEGER row[], LIS_INTEGER col[], LIS_INTEGER ierr)
```

#### Description

Assign the block size of the BSR, BSC, and VBR

#### Input

A	The matrix
bnr	The row block size of the BSR (BSC) format or the number of the row blocks of the VBR format
bnc	The column block size of the BSR (BSC) format or the number of the column blocks of the VBR format
row	The array of the row division information about the VBR format
col	The array of the column division information about the VBR format

#### Output

ierr	The return code
------	-----------------

### 6.2.13 lis\_matrix\_convert

```
C      LIS_INT lis_matrix_convert(LIS_MATRIX Ain, LIS_MATRIX Aout)
Fortran subroutine lis_matrix_convert(LIS_MATRIX Ain, LIS_MATRIX Aout,
        LIS_INTEGER ierr)
```

#### Description

Convert the matrix  $A_{in}$  into  $A_{out}$  of the format specified by `lis_matrix_set_type`

#### Input

Ain	The source matrix
-----	-------------------

#### Output

Aout	The destination matrix
ierr	The return code

#### Note

The storage format of the  $A_{out}$  is set by `lis_matrix_set_type`. The block size of the BSR, BSC, and VBR is set by `lis_matrix_set_blocksize`.

The conversions indicated by one in the table below are performed directly, and the other ones are performed via the indicated formats. The conversions with no indication are performed via the CRS format.

Src \ Dst	CRS	CCS	MSR	DIA	ELL	JDS	BSR	BSC	VBR	DNS	COO
CRS		1	1	1	1	1	1	CCS	1	1	1
COO	1	1	1	CRS	CRS	CRS	CRS	CCS	CRS	CRS	

### 6.2.14 lis\_matrix\_copy

```
C      LIS_INT lis_matrix_copy(LIS_MATRIX Ain, LIS_MATRIX Aout)
Fortran subroutine lis_matrix_copy(LIS_MATRIX Ain, LIS_MATRIX Aout,
      LIS_INTEGER ierr)
```

#### Description

Copy the values of the matrix elements

#### Input

Ain	The source matrix
-----	-------------------

#### Output

Aout	The destination matrix
ierr	The return code

### 6.2.15 lis\_matrix\_get\_diagonal

```
C      LIS_INT lis_matrix_get_diagonal(LIS_MATRIX A, LIS_VECTOR d)
Fortran subroutine lis_matrix_get_diagonal(LIS_MATRIX A, LIS_VECTOR d,
      LIS_INTEGER ierr)
```

#### Description

Store the diagonal elements of the matrix  $A$  to the vector  $d$

#### Input

A	The matrix
---	------------

#### Output

d	The vector which stores the diagonal elements of the matrix
ierr	The return code

### 6.2.16 lis\_matrix\_set\_crs

```
C      LIS_INT lis_matrix_set_crs(LIS_INT nnz, LIS_INT ptr[], LIS_INT index[],
                                LIS_SCALAR value[], LIS_MATRIX A)
Fortran subroutine lis_matrix_set_crs(LIS_INTEGER nnz, LIS_INTEGER row(),
                                LIS_INTEGER index(), LIS_SCALAR value(), LIS_MATRIX A, LIS_INTEGER ierr)
```

#### Description

Associate the arrays in the CRS format with the matrix *A*

#### Input

<code>nnz</code>	The number of nonzero elements
<code>ptr, index, value</code>	The arrays in the CRS format
<code>A</code>	The matrix

#### Output

<code>A</code>	The matrix associated with the arrays
----------------	---------------------------------------

#### Note

After `lis_matrix_set_crs` is called, the function `lis_matrix_assemble` must be called.

### 6.2.17 lis\_matrix\_set\_ccs

```
C      LIS_INT lis_matrix_set_ccs(LIS_INT nnz, LIS_INT ptr[], LIS_INT index[],
                                LIS_SCALAR value[], LIS_MATRIX A)
Fortran subroutine lis_matrix_set_ccs(LIS_INTEGER nnz, LIS_INTEGER row(),
                                LIS_INTEGER index(), LIS_SCALAR value(), LIS_MATRIX A, LIS_INTEGER ierr)
```

#### Description

Associate the arrays in the CCS format with the matrix *A*

#### Input

<code>nnz</code>	The number of the nonzero elements
<code>ptr, index, value</code>	The arrays in the CCS format
<code>A</code>	The matrix

#### Output

<code>A</code>	The matrix associated with the arrays
----------------	---------------------------------------

#### Note

After `lis_matrix_set_ccs` is called, the function `lis_matrix_assemble` must be called.

### 6.2.18 lis\_matrix\_set\_msr

```
C      LIS_INT lis_matrix_set_msr(LIS_INT nnz, LIS_INT ndz, LIS_INT index[],
                                LIS_SCALAR value[], LIS_MATRIX A)
Fortran subroutine lis_matrix_set_msr(LIS_INTEGER nnz, LIS_INTEGER ndz,
                                LIS_INTEGER index(), LIS_SCALAR value(), LIS_MATRIX A, LIS_INTEGER ierr)
```

#### Description

Associate the arrays in the MSR format with the matrix  $A$

#### Input

<code>nnz</code>	The number of the nonzero elements
<code>ndz</code>	The number of the nonzero elements in the diagonal
<code>index, value</code>	The arrays in the MSR format
<code>A</code>	The matrix

#### Output

<code>A</code>	The matrix associated with the arrays
----------------	---------------------------------------

#### Note

After `lis_matrix_set_msr` is called, the function `lis_matrix_assemble` must be called.

### 6.2.19 lis\_matrix\_set\_dia

```
C      LIS_INT lis_matrix_set_dia(LIS_INT nnd, LIS_INT index[],
                                LIS_SCALAR value[], LIS_MATRIX A)
Fortran subroutine lis_matrix_set_dia(LIS_INTEGER nnd, LIS_INTEGER index(),
                                LIS_SCALAR value(), LIS_MATRIX A, LIS_INTEGER ierr)
```

#### Description

Associate the arrays in the DIA format with the matrix  $A$

#### Input

<code>nnd</code>	The number of the nonzero diagonal elements
<code>index, value</code>	The arrays in the DIA format
<code>A</code>	The matrix

#### Output

<code>A</code>	The matrix associated with the arrays
----------------	---------------------------------------

#### Note

After `lis_matrix_set_dia` is called, the function `lis_matrix_assemble` must be called.

### 6.2.20 lis\_matrix\_set\_ell

```
C      LIS_INT lis_matrix_set_ell(LIS_INT maxnzs, LIS_INT index[],
                                LIS_SCALAR value[], LIS_MATRIX A)
Fortran subroutine lis_matrix_set_ell(LIS_INTEGER maxnzs,
                                LIS_INTEGER index(), LIS_SCALAR value(), LIS_MATRIX A,
                                LIS_INTEGER ierr)
```

#### Description

Associate the arrays in the ELL format with the matrix  $A$

#### Input

maxnzs	The maximum number of the nonzero elements in each row
index, value	The arrays in the ELL format
A	The matrix

#### Output

A	The matrix associated with the arrays
---	---------------------------------------

#### Note

After `lis_matrix_set_ell` is called, the function `lis_matrix_assemble` must be called.

### 6.2.21 lis\_matrix\_set\_jds

```
C      LIS_INT lis_matrix_set_jds(LIS_INT nnz, LIS_INT maxnzs, LIS_INT perm[],
                                LIS_INT ptr[], LIS_INT index[], LIS_SCALAR value[], LIS_MATRIX A)
Fortran subroutine lis_matrix_set_jds(LIS_INTEGER nnz, LIS_INTEGER maxnzs,
                                LIS_INTEGER ptr(), LIS_INTEGER index(), LIS_SCALAR value(),
                                LIS_MATRIX A, LIS_INTEGER ierr)
```

#### Description

Associate the arrays in the JDS format with the matrix  $A$

#### Input

nnz	The number of the nonzero elements
maxnzs	The maximum number of the nonzero elements in each row
perm, ptr, index, value	The arrays in the JDS format
A	The matrix

#### Output

A	The matrix associated with the arrays
---	---------------------------------------

#### Note

After `lis_matrix_set_jds` is called, the function `lis_matrix_assemble` must be called.

### 6.2.22 lis\_matrix\_set\_bsr

```
C      LIS_INT lis_matrix_set_bsr(LIS_INT bnr, LIS_INT bnc, LIS_INT bnnz,  
                                LIS_INT bptr[], LIS_INT bindex[], LIS_SCALAR value[], LIS_MATRIX A)  
Fortran subroutine lis_matrix_set_bsr(LIS_INTEGER bnr, LIS_INTEGER bnc,  
                                LIS_INTEGER bnnz, LIS_INTEGER bptr(), LIS_INTEGER bindex(),  
                                LIS_SCALAR value(), LIS_MATRIX A, LIS_INTEGER ierr)
```

#### Description

Associate the arrays in the BSR format with the matrix  $A$

#### Input

bnr	The row block size
bnc	The column block size
bnnz	The number of the nonzero blocks
bptr, bindex, value	The arrays in the BSR format
A	The matrix

#### Output

A	The matrix associated with the arrays
---	---------------------------------------

#### Note

After `lis_matrix_set_bsr` is called, the function `lis_matrix_assemble` must be called.

### 6.2.23 lis\_matrix\_set\_bsc

```
C      LIS_INT lis_matrix_set_bsc(LIS_INT bnr, LIS_INT bnc, LIS_INT bnnz,  
                                LIS_INT bptr[], LIS_INT bindex[], LIS_SCALAR value[], LIS_MATRIX A)  
Fortran subroutine lis_matrix_set_bsc(LIS_INTEGER bnr, LIS_INTEGER bnc,  
                                LIS_INTEGER bnnz, LIS_INTEGER bptr(), LIS_INTEGER bindex(),  
                                LIS_SCALAR value(), LIS_MATRIX A, LIS_INTEGER ierr)
```

#### Description

Associate the arrays in the BSC format with the matrix  $A$

#### Input

bnr	The row block size
bnc	The column block size
bnnz	The number of the nonzero blocks
bptr, bindex, value	The arrays in the BSC format
A	The matrix

#### Output

A	The matrix associated with the arrays
---	---------------------------------------

#### Note

After `lis_matrix_set_bsc` is called, the function `lis_matrix_assemble` must be called.

### 6.2.24 lis\_matrix\_set\_vbr

```
C      LIS_INT lis_matrix_set_vbr(LIS_INT nnz, LIS_INT nr, LIS_INT nc,
      LIS_INT bnnz, LIS_INT row[], LIS_INT col[], LIS_INT ptr[],
      LIS_INT bptr[], LIS_INT bindex[], LIS_SCALAR value[],
      LIS_MATRIX A)
Fortran subroutine lis_matrix_set_vbr(LIS_INTEGER nnz, LIS_INTEGER nr,
      LIS_INTEGER nc, LIS_INTEGER bnnz, LIS_INTEGER row(),
      LIS_INTEGER col(), LIS_INTEGER ptr(), LIS_INTEGER bptr(),
      LIS_INTEGER bindex(), LIS_SCALAR value(), LIS_MATRIX A,
      LIS_INTEGER ierr)
```

#### Description

Associate the arrays in the VBR format with the matrix  $A$

#### Input

nnz	The number of the all nonzero elements
nr	The number of the row blocks
nc	The number of the column blocks
bnnz	The number of the nonzero blocks
row, col, ptr, bptr, bindex, value	The arrays in the VBR format
A	The matrix

#### Output

A	The matrix associated with the arrays
---	---------------------------------------

#### Note

After `lis_matrix_set_vbr` is called, the function `lis_matrix_assemble` must be called.

### 6.2.25 lis\_matrix\_set\_coo

```
C      LIS_INT lis_matrix_set_coo(LIS_INT nnz, LIS_INT row[], LIS_INT col[],
      LIS_SCALAR value[], LIS_MATRIX A)
Fortran subroutine lis_matrix_set_coo(LIS_INTEGER nnz, LIS_INTEGER row(),
      LIS_INTEGER col(), LIS_SCALAR value(), LIS_MATRIX A, LIS_INTEGER ierr)
```

#### Description

Associate the arrays in the COO format with the matrix  $A$

#### Input

nnz	The number of the nonzero elements
row, col, value	The arrays in the COO format
A	The matrix

#### Output

A	The matrix associated with the arrays
---	---------------------------------------

#### Note

After `lis_matrix_set_coo` is called, the function `lis_matrix_assemble` must be called.



### 6.2.26 lis\_matrix\_set\_dns

```
C      LIS_INT lis_matrix_set_dns(LIS_SCALAR value[], LIS_MATRIX A)
Fortran subroutine lis_matrix_set_dns(LIS_SCALAR value(), LIS_MATRIX A,
      LIS_INTEGER ierr)
```

#### Description

Associate the array in the DNS format with the matrix  $A$

#### Input

value	The array in the DNS format
A	The matrix

#### Output

A	The matrix associated with the array
---	--------------------------------------

#### Note

After `lis_matrix_set_dns` is called, the function `lis_matrix_assemble` must be called.

## 6.3 Operating Vectors and Matrices

### 6.3.1 lis\_vector\_scale

```
C      LIS_INT lis_vector_scale(LIS_SCALAR alpha, LIS_VECTOR x)
Fortran subroutine lis_vector_scale(LIS_SCALAR alpha, LIS_VECTOR x,
                                   LIS_INTEGER ierr)
```

#### Description

Multiply the vector  $x$  by the scalar  $\alpha$

#### Input

alpha	The scalar value $\alpha$
x	The vector to be multiplied

#### Output

x	The vector multiplied by $\alpha$
ierr	The return code

### 6.3.2 lis\_vector\_dot

```
C      LIS_INT lis_vector_dot(LIS_VECTOR x, LIS_VECTOR y, LIS_SCALAR *val)
Fortran subroutine lis_vector_dot(LIS_VECTOR x, LIS_VECTOR y, LIS_SCALAR val,
                                   LIS_INTEGER ierr)
```

#### Description

Calculate the inner product  $x^T y$

#### Input

x	The vector
y	The vector

#### Output

val	The inner product value
ierr	The return code

### 6.3.3 lis\_vector\_nrm1

```
C      LIS_INT lis_vector_nrm1(LIS_VECTOR x, LIS_SCALAR *val)
Fortran subroutine lis_vector_nrm1(LIS_VECTOR x, LIS_SCALAR val, LIS_INTEGER ierr)
```

#### Description

Calculate the 1-norm of the vector  $x$

#### Input

<code>x</code>	The vector
----------------	------------

#### Output

<code>val</code>	The 1-norm of the vector
------------------	--------------------------

<code>ierr</code>	The return code
-------------------	-----------------

### 6.3.4 lis\_vector\_nrm2

```
C      LIS_INT lis_vector_nrm2(LIS_VECTOR x, LIS_SCALAR *val)
Fortran subroutine lis_vector_nrm2(LIS_VECTOR x, LIS_SCALAR val, LIS_INTEGER ierr)
```

#### Description

Calculate the 2-norm of the vector  $x$

#### Input

<code>x</code>	The vector
----------------	------------

#### Output

<code>val</code>	The 2-norm of the vector
------------------	--------------------------

<code>ierr</code>	The return code
-------------------	-----------------

### 6.3.5 lis\_vector\_nrmi

```
C      LIS_INT lis_vector_nrmi(LIS_VECTOR x, LIS_SCALAR *val)
Fortran subroutine lis_vector_nrmi(LIS_VECTOR x, LIS_SCALAR val, LIS_INTEGER ierr)
```

#### Description

Calculate the infinity norm of the vector  $x$

#### Input

<code>x</code>	The vector
----------------	------------

#### Output

<code>val</code>	The infinity norm of the vector
------------------	---------------------------------

<code>ierr</code>	The return code
-------------------	-----------------

### 6.3.6 lis\_vector\_axpy

```
C      LIS_INT lis_vector_axpy(LIS_SCALAR alpha, LIS_VECTOR x, LIS_VECTOR y)
Fortran subroutine lis_vector_axpy(LIS_SCALAR alpha, LIS_VECTOR x, LIS_VECTOR y,
                                   LIS_INTEGER ierr)
```

#### Description

Calculate the vector sum  $y = \alpha x + y$

#### Input

alpha	The scalar value
x, y	The vectors

#### Output

y	$\alpha x + y$ (the vector $y$ is overwritten)
ierr	The return code

### 6.3.7 lis\_vector\_xpay

```
C      LIS_INT lis_vector_xpay(LIS_VECTOR x, LIS_SCALAR alpha, LIS_VECTOR y)
Fortran subroutine lis_vector_xpay(LIS_VECTOR x, LIS_SCALAR alpha, LIS_VECTOR y,
                                   LIS_INTEGER ierr)
```

#### Description

Calculate the vector sum  $y = x + \alpha y$

#### Input

alpha	The scalar value
x, y	The vectors

#### Output

y	$x + \alpha y$ (the vector $y$ is overwritten)
ierr	The return code

### 6.3.8 lis\_vector\_axpyz

```
C      LIS_INT lis_vector_axpyz(LIS_SCALAR alpha, LIS_VECTOR x, LIS_VECTOR y,  
                               LIS_VECTOR z)  
Fortran subroutine lis_vector_axpyz(LIS_SCALAR alpha, LIS_VECTOR x, LIS_VECTOR y,  
                                   LIS_VECTOR z, LIS_INTEGER ierr)
```

#### Description

Calculate the vector sum  $z = \alpha x + y$

#### Input

alpha	The scalar value
x, y	The vectors

#### Output

z	$x + \alpha y$
ierr	The return code

### 6.3.9 lis\_matrix\_scaling

```
C      LIS_INT lis_matrix_scaling(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR d,  
                                LIS_INT action)  
Fortran subroutine lis_matrix_scaling(LIS_MATRIX A, LIS_VECTOR b,  
                                    LIS_VECTOR d, LIS_INTEGER action, LIS_INTEGER ierr)
```

#### Description

Scale the matrix  $A$

#### Input

A	The matrix
b	The vector
action	<b>LIS_SCALE_JACOBI</b> : Jacobi scaling $D^{-1}Ax = D^{-1}b$ , where $D$ represents the diagonal of $A = (a_{ij})$ <b>LIS_SCALE_SYMM_DIAG</b> : Diagonal scaling $D^{-1/2}AD^{-1/2}x = D^{-1/2}b$ , where $D^{-1/2}$ represents a diagonal matrix with $1/\sqrt{a_{ii}}$ as the diagonal

#### Output

d	The vector which stores the diagonal elements of $D^{-1}$ or $D^{-1/2}$
ierr	The return code

### 6.3.10 lis\_matvec

```
C      LIS_INT lis_matvec(LIS_MATRIX A, LIS_VECTOR x, LIS_VECTOR y)
Fortran subroutine lis_matvec(LIS_MATRIX A, LIS_VECTOR x, LIS_VECTOR y,
                             LIS_INTEGER ierr)
```

#### Description

Calculate the matrix vector product  $y = Ax$

#### Input

A	The matrix
x	The vector

#### Output

y	$Ax$
ier	The return code

### 6.3.11 lis\_matvect

```
C      LIS_INT lis_matvect(LIS_MATRIX A, LIS_VECTOR x, LIS_VECTOR y)
Fortran subroutine lis_matvect(LIS_MATRIX A, LIS_VECTOR x, LIS_VECTOR y,
                              LIS_INTEGER ierr)
```

#### Description

Calculate the transposed matrix vector product  $y = A^T x$

#### Input

A	The matrix
x	The vector

#### Output

y	$A^T x$
ier	The return code

## 6.4 Solving Linear Equations

### 6.4.1 lis\_solver\_create

```
C      LIS_INT lis_solver_create(LIS_SOLVER *solver)
Fortran subroutine lis_solver_create(LIS_SOLVER solver, LIS_INTEGER ierr)
```

#### Description

Create the solver

#### Input

None

#### Output

<code>solver</code>	The solver
<code>ierr</code>	The return code

#### Note

`solver` has the information on the solver, the preconditioner, etc.

### 6.4.2 lis\_solver\_destroy

```
C      LIS_INT lis_solver_destroy(LIS_SOLVER solver)
Fortran subroutine lis_solver_destroy(LIS_SOLVER solver, LIS_INTEGER ierr)
```

#### Description

Destroy the solver

#### Input

<code>solver</code>	The solver to be destroyed
---------------------	----------------------------

#### Output

<code>ierr</code>	The return code
-------------------	-----------------

```
C      LIS_INT lis_solver_set_option(char *text, LIS_SOLVER solver)
Fortran subroutine lis_solver_set_option(character text, LIS_SOLVER solver,
      LIS_INTEGER ierr)
```

Set the options for the solver

text	The command line options
------	--------------------------

<b>solver</b>	The solver
<b>ierr</b>	The return code

The table below shows the available command line options, where `-i {cg|1}` means `-i cg` or `-i 1` and `-maxiter [1000]` indicates that `-maxiter` defaults to 1,000.

Solver	Option	Auxiliary Options	
CG	-i {cg 1}		
BiCG	-i {bicg 2}		
CGS	-i {cgs 3}		
BiCGSTAB	-i {bicgstab 4}		
BiCGSTAB(l)	-i {bicgstabl 5}	-ell [2]	The degree $l$
GPBiCG	-i {gpbicg 6}		
TFQMR	-i {tfqmr 7}		
Orthomin(m)	-i {orthomin 8}	-restart [40]	The restart value $m$
GMRES(m)	-i {gmres 9}	-restart [40]	The restart value $m$
Jacobi	-i {jacobi 10}		
Gauss-Seidel	-i {gs 11}		
SOR	-i {sor 12}	-omega [1.9]	The relaxation coefficient $\omega$ ( $0 < \omega < 2$ )
BiCGSafe	-i {bicgsafe 13}		
CR	-i {cr 14}		
BiCR	-i {bicr 15}		
CRS	-i {crs 16}		
BiCRSTAB	-i {bicrstab 17}		
GPBiCR	-i {gpbicr 18}		
BiCRSafe	-i {bicrsafe 19}		
FGMRES(m)	-i {fgmres 20}	-restart [40]	The restart value $m$
IDR(s)	-i {idrs 21}	-irestart [2]	The restart value $s$
MINRES	-i {minres 22}		



**Options for Preconditioners (Default: -p none)**

Preconditioner	Option	Auxiliary Options	
None	-p {none 0}		
Jacobi	-p {jacobi 1}		
ILU(k)	-p {ilu 2}	-ilu_fill [0]	The fill level $k$
SSOR	-p {ssor 3}	-ssor_w [1.0]	The relaxation coefficient $\omega$ ( $0 < \omega < 2$ )
Hybrid	-p {hybrid 4}	-hybrid_i [sor]	The linear solver
		-hybrid_maxiter [25]	The maximum number of the iterations
		-hybrid_tol [1.0e-3]	The convergence criterion
		-hybrid_w [1.5]	The relaxation coefficient $\omega$ of the SOR ( $0 < \omega < 2$ )
		-hybrid_ell [2]	The degree $l$ of the BiCGSTAB(l)
		-hybrid_restart [40]	The restart values of the GMRES and Orthomin
I+S	-p {is 5}	-is_alpha [1.0]	The parameter $\alpha$ of the preconditioner of the $I + \alpha S^{(m)}$ type
		-is_m [3]	The parameter $m$ of the preconditioner of the $I + \alpha S^{(m)}$ type
SAINV	-p {sainv 6}	-sainv_drop [0.05]	The drop criterion
SA-AMG	-p {saamg 7}	-saamg_unsym [false]	Selects the unsymmetric version (The matrix structure must be symmetric)
		-saamg_theta [0.05 0.12]	The drop criterion $a_{ij}^2 \leq \theta^2  a_{ii}   a_{jj} $ (symmetric or unsymmetric)
Crout ILU	-p {iluc 8}	-iluc_drop [0.05]	The drop criterion
		-iluc_rate [5.0]	The ratio of the maximum fill-in
ILUT	-p {ilut 9}	-ilut_drop [0.05]	The drop criterion
		-ilut_rate [5.0]	The ratio of the maximum fill-in
Additive Schwarz	-adds true	-adds_iter [1]	The number of the iterations

## Other Options

Option	
<code>-maxiter [1000]</code>	The maximum number of the iterations
<code>-tol [1.0e-12]</code>	The convergence criterion
<code>-print [0]</code>	The display of the residual
	<code>-print {none 0}</code> None
	<code>-print {mem 1}</code> Save the residual history
	<code>-print {out 2}</code> Display the residual history
	<code>-print {all 3}</code> Save the residual history and display it on the screen
<code>-scale [0]</code>	The scaling (The result will overwrite the original matrix and vectors)
	<code>-scale {none 0}</code> No scaling
	<code>-scale {jacobi 1}</code> The Jacobi scaling $D^{-1}Ax = D^{-1}b$ ( $D$ represents the diagonal of $A = (a_{ij})$ )
	<code>-scale {symm_diag 2}</code> The diagonal scaling $D^{-1/2}AD^{-1/2}x = D^{-1/2}b$ ( $D^{-1/2}$ represents the diagonal matrix with $1/\sqrt{a_{ii}}$ as the diagonal)
<code>-initx_zeros [true]</code>	The behavior of the initial vector $x_0$
	<code>-initx_zeros {false 0}</code> Given values
	<code>-initx_zeros {true 1}</code> All values are set to 0
<code>-omp_num_threads [t]</code>	The number of the threads ( $t$ represents the maximum number of the threads)
<code>-storage [0]</code>	The matrix storage format
<code>-storage_block [2]</code>	The block size of the BSR and BSC
<code>-f [0]</code>	The precision of the linear solvers
	<code>-f {double 0}</code> Double precision
	<code>-f {quad 1}</code> Quadruple precision

#### 6.4.4 lis\_solver\_set\_optionC

```
C      LIS_INT lis_solver_set_optionC(LIS_SOLVER solver)
Fortran subroutine lis_solver_set_optionC(LIS_SOLVER solver, LIS_INTEGER ierr)
```

##### Description

Set the options for the solver on the command line

##### Input

None

##### Output

<code>solver</code>	The solver
<code>ierr</code>	The return code

#### 6.4.5 lis\_solve

```
C      LIS_INT lis_solve(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR x,
                        LIS_SOLVER solver)
Fortran subroutine lis_solve(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR x,
                        LIS_SOLVER solver, LIS_INTEGER ierr)
```

##### Description

Solve the linear equation  $Ax = b$  with the specified solver

##### Input

<code>A</code>	The coefficient matrix
<code>b</code>	The right hand side vector
<code>x</code>	The initial vector
<code>solver</code>	The solver

##### Output

<code>x</code>	The solution
<code>solver</code>	The number of iterations, execution time, etc.
<code>ierr</code>	The return code

#### 6.4.6 lis\_solve\_kernel

```
C      LIS_INT lis_solve_kernel(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR x,  
                             LIS_SOLVER solver, LIS_PRECON, precon)  
Fortran subroutine lis_solve_kernel(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR x,  
                                  LIS_SOLVER solver, LIS_PRECON precon, LIS_INTEGER ierr)
```

##### Description

Solve the linear equation  $Ax = b$  with the specified solver and the predefined preconditioner

##### Input

<code>A</code>	The coefficient matrix
<code>b</code>	The right hand side vector
<code>x</code>	The initial vector
<code>solver</code>	The solver
<code>precon</code>	The preconditioner

##### Output

<code>x</code>	The solution
<code>solver</code>	The number of the iterations, the execution time, etc.
<code>ierr</code>	The return code

##### Note

See `lis-($VERSION)/src/esolver/lis_esolver_ii.c`, which computes the smallest eigenvalue by calling `lis_solve_kernel` multiple times, for example.

#### 6.4.7 lis\_solver\_get\_status

```
C      LIS_INT lis_solver_get_status(LIS_SOLVER solver, LIS_INT *status)
Fortran subroutine lis_solver_get_status(LIS_SOLVER solver, LIS_INTEGER status,
      LIS_INTEGER ierr)
```

##### Description

Get the status from the solver

##### Input

<code>solver</code>	The solver
---------------------	------------

##### Output

<code>status</code>	The number of iterations
<code>ierr</code>	The return code

#### 6.4.8 lis\_solver\_get\_iters

```
C      LIS_INT lis_solver_get_iters(LIS_SOLVER solver, LIS_INT *iters)
Fortran subroutine lis_solver_get_iters(LIS_SOLVER solver, LIS_INTEGER iters,
      LIS_INTEGER ierr)
```

##### Description

Get the number of iterations from the solver

##### Input

<code>solver</code>	The solver
---------------------	------------

##### Output

<code>iters</code>	The number of iterations
<code>ierr</code>	The return code

#### 6.4.9 lis\_solver\_get\_itersex

```
C      LIS_INT lis_solver_get_itersex(LIS_SOLVER solver, LIS_INT *iters,  
                                     LIS_INT *iters_double, LIS_INT *iters_quad)  
Fortran subroutine lis_solver_get_itersex(LIS_SOLVER solver, LIS_INTEGER iters,  
                                         LIS_INTEGER iters_double, LIS_INTEGER iters_quad, LIS_INTEGER ierr)
```

##### Description

Get the number of iterations from the solver

##### Input

<code>solver</code>	The solver
---------------------	------------

##### Output

<code>iters</code>	The number of the iterations
<code>iters_double</code>	The number of the double precision iterations
<code>iters_quad</code>	The number of the quadruple precision iterations
<code>ierr</code>	The return code

#### 6.4.10 lis\_solver\_get\_time

```
C      LIS_INT lis_solver_get_time(LIS_SOLVER solver, double *times)  
Fortran subroutine lis_solver_get_time(LIS_SOLVER solver, real*8 times,  
                                       LIS_INTEGER ierr)
```

##### Description

Get the execution time from the solver

##### Input

<code>solver</code>	The solver
---------------------	------------

##### Output

<code>times</code>	The time in seconds of the execution
<code>ierr</code>	The return code

```

C      LIS_INT lis_solver_get_timeex(LIS_SOLVER solver, double *times,
      double *itimes, double *ptimes, double *p_c_times, double *p_i_times)
Fortran subroutine lis_solver_get_timeex(LIS_SOLVER solver, real*8 times,
      real*8 itimes, real*8 ptimes, real*8 p_c_times, real*8 p_i_times,
      LIS_INTEGER ierr)

```

Get the execution time from the solver

solver	The solver
gurobi	Gurobi Optimizer
cbc	CBC
glpk	GLPK
scipy	SciPy
cvxopt	CVXOPT
cvxpy	CVXPY
qpoas	QPOAS
qpoas5	QPOAS5
qpoas6	QPOAS6
qpoas7	QPOAS7
qpoas8	QPOAS8
qpoas9	QPOAS9
qpoas10	QPOAS10
qpoas11	QPOAS11
qpoas12	QPOAS12
qpoas13	QPOAS13
qpoas14	QPOAS14
qpoas15	QPOAS15
qpoas16	QPOAS16
qpoas17	QPOAS17
qpoas18	QPOAS18
qpoas19	QPOAS19
qpoas20	QPOAS20
qpoas21	QPOAS21
qpoas22	QPOAS22
qpoas23	QPOAS23
qpoas24	QPOAS24
qpoas25	QPOAS25
qpoas26	QPOAS26
qpoas27	QPOAS27
qpoas28	QPOAS28
qpoas29	QPOAS29
qpoas30	QPOAS30
qpoas31	QPOAS31
qpoas32	QPOAS32
qpoas33	QPOAS33
qpoas34	QPOAS34
qpoas35	QPOAS35
qpoas36	QPOAS36
qpoas37	QPOAS37
qpoas38	QPOAS38
qpoas39	QPOAS39
qpoas40	QPOAS40
qpoas41	QPOAS41
qpoas42	QPOAS42
qpoas43	QPOAS43
qpoas44	QPOAS44
qpoas45	QPOAS45
qpoas46	QPOAS46
qpoas47	QPOAS47
qpoas48	QPOAS48
qpoas49	QPOAS49
qpoas50	QPOAS50
qpoas51	QPOAS51
qpoas52	QPOAS52
qpoas53	QPOAS53
qpoas54	QPOAS54
qpoas55	QPOAS55
qpoas56	QPOAS56
qpoas57	QPOAS57
qpoas58	QPOAS58
qpoas59	QPOAS59
qpoas60	QPOAS60
qpoas61	QPOAS61
qpoas62	QPOAS62
qpoas63	QPOAS63
qpoas64	QPOAS64
qpoas65	QPOAS65
qpoas66	QPOAS66
qpoas67	QPOAS67
qpoas68	QPOAS68
qpoas69	QPOAS69
qpoas70	QPOAS70
qpoas71	QPOAS71
qpoas72	QPOAS72
qpoas73	QPOAS73
qpoas74	QPOAS74
qpoas75	QPOAS75
qpoas76	QPOAS76
qpoas77	QPOAS77
qpoas78	QPOAS78
qpoas79	QPOAS79
qpoas80	QPOAS80
qpoas81	QPOAS81
qpoas82	QPOAS82
qpoas83	QPOAS83
qpoas84	QPOAS84
qpoas85	QPOAS85
qpoas86	QPOAS86
qpoas87	QPOAS87
qpoas88	QPOAS88
qpoas89	QPOAS89
qpoas90	QPOAS90
qpoas91	QPOAS91
qpoas92	QPOAS92
qpoas93	QPOAS93
qpoas94	QPOAS94
qpoas95	QPOAS95
qpoas96	QPOAS96
qpoas97	QPOAS97
qpoas98	QPOAS98
qpoas99	QPOAS99
qpoas100	QPOAS100
qpoas101	QPOAS101
qpoas102	QPOAS102
qpoas103	QPOAS103
qpoas104	QPOAS104
qpoas105	QPOAS105
qpoas106	QPOAS106
qpoas107	QPOAS107
qpoas108	QPOAS108
qpoas109	QPOAS109
qpoas110	QPOAS110
qpoas111	QPOAS111
qpoas112	QPOAS112
qpoas113	QPOAS113
qpoas114	QPOAS114
qpoas115	QPOAS115
qpoas116	QPOAS116
qpoas117	QPOAS117
qpoas118	QPOAS118
qpoas119	QPOAS119
qpoas120	QPOAS120
qpoas121	QPOAS121
qpoas122	QPOAS122
qpoas123	QPOAS123
qpoas124	QPOAS124
qpoas125	QPOAS125
qpoas126	QPOAS126
qpoas127	QPOAS127
qpoas128	QPOAS128
qpoas129	QPOAS129
qpoas130	QPOAS130
qpoas131	QPOAS131
qpoas132	QPOAS132
qpoas133	QPOAS133
qpoas134	QPOAS134
qpoas135	QPOAS135
qpoas136	QPOAS136
qpoas137	QPOAS137
qpoas138	QPOAS138
qpoas139	QPOAS139
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qpoas141	QPOAS141
qpoas142	QPOAS142
qpoas143	QPOAS143
qpoas144	QPOAS144
qpoas145	QPOAS145
qpoas146	QPOAS146
qpoas147	QPOAS147
qpoas148	QPOAS148
qpoas149	QPOAS149
qpoas150	QPOAS150
qpoas151	QPOAS151
qpoas152	QPOAS152
qpoas153	QPOAS153
qpoas154	QPOAS154
qpoas155	QPOAS155
qpoas156	QPOAS156
qpoas157	QPOAS157
qpoas158	QPOAS158
qpoas159	QPOAS159
qpoas160	QPOAS160
qpoas161	QPOAS161
qpoas162	QPOAS162
qpoas163	QPOAS163
q	

<code>times</code>	The total time in seconds
<code>itimes</code>	The time in seconds of the iteration
<code>ptimes</code>	The time in seconds of the preconditioning
<code>p_c_times</code>	The time in seconds of the creation of the preconditioner
<code>p_i_times</code>	The time in seconds of the iteration in the preconditioner
<code>ierr</code>	The return code

```
C      LIS_INT lis_solver_get_residualnorm(LIS_SOLVER solver, LIS_REAL *residual)
Fortran subroutine lis_solver_get_residualnorm(LIS_SOLVER solver,
        LIS_REAL residual, LIS_INTEGER ierr)
```

Calculate the relative residual norm  $\|b - Ax\|_2 / \|b\|_2$  from the solution  $x$

solver	The solver
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	9
10	10
11	11
12	12
13	13
14	14
15	15
16	16
17	17
18	18
19	19
20	20
21	21
22	22
23	23
24	24
25	25
26	26
27	27
28	28
29	29
30	30
31	31
32	32
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34	34
35	35
36	36
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38	38
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40	40
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43	43
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54	54
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59	59
60	60
61	61
62	62
63	63
64	64
65	65
66	66
67	67
68	68
69	69
70	70
71	71
72	72
73	73
74	74
75	75
76	76
77	77
78	78
79	79
80	80
81	81
82	82
83	83
84	84
85	85
86	86
87	87
88	88
89	89
90	90
91	91
92	92
93	93
94	94
95	95
96	96
97	97
98	98
99	99
100	100

<b>residual</b>	The relative residual norm $\ b - Ax\ _2/\ b\ _2$
<b>ierr</b>	The return code

#### 6.4.13 lis\_solver\_get\_rhistory

```
C      LIS_INT lis_solver_get_rhistory(VECTOR v)
Fortran subroutine lis_solver_get_rhistory(LIS_VECTOR v, LIS_INTEGER ierr)
```

##### Description

Store the residual norm history of the solver

##### Input

None

##### Output

<code>v</code>	The vector
<code>ierr</code>	The return code

##### Note

The vector  $v$  must be created in advance with the function `lis_vector_create`. When the vector  $v$  is shorter than the residual history, it stores the residual history in order to the vector  $v$ .



#### 6.4.14 lis\_solver\_get\_solver

```
C      LIS_INT lis_solver_get_solver(LIS_SOLVER solver, LIS_INT *nsol)
Fortran subroutine lis_solver_get_solver(LIS_SOLVER solver, LIS_INTEGER nsol,
      LIS_INTEGER ierr)
```

##### Description

Get the solver number from the solver

##### Input

`solver`                                      The solver

##### Output

`nsol`                                         The solver number

`ierr`                                         The return code

##### Note

The number of the solver is as follows:

Solver	Number	Solver	Number
CG	1	SOR	12
BiCG	2	BiCGSafe	13
CGS	3	CR	14
BiCGSTAB	4	BiCR	15
BiCGSTAB(l)	5	CRS	16
GPBiCG	6	BiCRSTAB	17
TFQMR	7	GPBiCR	18
Orthomin(m)	8	BiCRSafe	19
GMRES(m)	9	FGMRES(m)	20
Jacobi	10	IDR(s)	21
Gauss-Seidel	11	MINRES	22

#### 6.4.15 lis\_solver\_get\_precon

```
C      LIS_INT lis_solver_get_precon(LIS_SOLVER solver, LIS_INT *precon_type)
Fortran subroutine lis_solver_get_precon(LIS_SOLVER solver, LIS_INTEGER precon_type,
      LIS_INTEGER ierr)
```

##### Description

Get the preconditioner number from the solver

##### Input

`solver`                                      The solver

##### Output

`precon_type`                                  The preconditioner number

`ierr`    The return code

##### Note

The number of the preconditioner is as follows:

Preconditioner	Number
none	0
Jacobi	1
ILU(k)	2
SSOR	3
Hybrid	4
I+S	5
SAINV	6
SA-AMG	7
Crout ILU	8
ILUT	9

#### 6.4.16 lis\_get\_solvername

```
C      LIS_INT lis_get_solvername(LIS_INT nsol, char *name)
Fortran subroutine lis_get_solvername(LIS_INTEGER nsol, character name,
      LIS_INTEGER ierr)
```

##### Description

Get the solver name from the solver number

##### Input

nsol	The solver number
------	-------------------

##### Output

name	The solver name
ierr	The return code

#### 6.4.17 lis\_get\_preconname

```
C      LIS_INT lis_get_preconname(LIS_INT precon_type, char *name)
Fortran subroutine lis_get_preconname(LIS_INTEGER precon_type, character name,
      LIS_INTEGER ierr)
```

##### Description

Get the preconditioner name from the preconditioner number

##### Input

precon_type	The preconditioner number
-------------	---------------------------

##### Output

name	The preconditioner name
ierr	The return code

## 6.5 Solving Eigenvalue Problems

### 6.5.1 lis\_esolver\_create

```
C      LIS_INT lis_esolver_create(LIS_ESOLVER *esolver)
Fortran subroutine lis_esolver_create(LIS_ESOLVER esolver, LIS_INTEGER ierr)
```

#### Description

Create the eigensolver

#### Input

None

#### Output

esolver	The eigensolver
ierr	The return code

#### Note

esolver has the information on the eigensolver, the preconditioner, etc.

### 6.5.2 lis\_esolver\_destroy

```
C      LIS_INT lis_esolver_destroy(LIS_ESOLVER esolver)
Fortran subroutine lis_esolver_destroy(LIS_ESOLVER esolver, LIS_INTEGER ierr)
```

#### Description

Destroy the eigensolver

#### Input

esolver	The eigensolver to be destroyed
---------	---------------------------------

#### Output

ierr	The return code
------	-----------------

### 6.5.3 lis\_esolver\_set\_option

```
C      LIS_INT lis_esolver_set_option(char *text, LIS_ESOLVER esolver)
Fortran subroutine lis_esolver_set_option(character text, LIS_ESOLVER esolver,
      LIS_INTEGER ierr)
```

#### Description

Set the options for the eigensolver

#### Input

`text`                                      The command line options

#### Output

`esolver`                                    The eigensolver

`ierr`                                        The return code

#### Note

The table below shows the available command line options, where `-e {pi|1}` means `-e pi` or `-e 1` and `-emaxiter [1000]` indicates that `-emaxiter` defaults to 1,000.

Options for Eigensolvers (Default: <code>-e pi</code> )			
Eigensolver	Option	Auxiliary Options	
Power	<code>-e {pi 1}</code>		
Inverse	<code>-e {ii 2}</code>	<code>-i [bicg]</code>	The linear solver
Approximate Inverse	<code>-e {aii 3}</code>		
Rayleigh Quotient	<code>-e {rqi 4}</code>	<code>-i [bicg]</code>	The linear solver
Subspace	<code>-e {si 5}</code>	<code>-ss [2]</code>	The size of the subspace
		<code>-m [0]</code>	The mode number
Lanczos	<code>-e {li 6}</code>	<code>-ss [2]</code>	The size of the subspace
		<code>-m [0]</code>	The mode number
CG	<code>-e {cg 7}</code>		
CR	<code>-e {cr 8}</code>		

**Options for Preconditioners (Default: -p none)**

Preconditioner	Option	Auxiliary Options	
None	-p {none 0}		
Jacobi	-p {jacobi 1}		
ILU(k)	-p {ilu 2}	-ilu_fill [0]	The fill level $k$
SSOR	-p {ssor 3}	-ssor_w [1.0]	The relaxation coefficient $\omega$ ( $0 < \omega < 2$ )
Hybrid	-p {hybrid 4}	-hybrid_i [sor]	The linear solver
		-hybrid_maxiter [25]	The maximum number of the iterations
		-hybrid_tol [1.0e-3]	The convergence criterion
		-hybrid_w [1.5]	The relaxation coefficient $\omega$ of the SOR ( $0 < \omega < 2$ )
		-hybrid_ell [2]	The degree $l$ of the BiCGSTAB(l)
		-hybrid_restart [40]	The restart values of the GMRES and Orthomin
I+S	-p {is 5}	-is_alpha [1.0]	The parameter $\alpha$ of the preconditioner of the $I + \alpha S^{(m)}$ type
		-is_m [3]	The parameter $m$ of the preconditioner of the $I + \alpha S^{(m)}$ type
SAINV	-p {sainv 6}	-sainv_drop [0.05]	The drop criterion
SA-AMG	-p {saamg 7}	-saamg_unsym [false]	Selects the unsymmetric version (The matrix structure must be symmetric)
		-saamg_theta [0.05 0.12]	The drop criterion $a_{ij}^2 \leq \theta^2  a_{ii}   a_{jj} $ (symmetric or unsymmetric)
Crout ILU	-p {iluc 8}	-iluc_drop [0.05]	The drop criterion
		-iluc_rate [5.0]	The ratio of the maximum fill-in
ILUT	-p {ilut 9}	-ilut_drop [0.05]	The drop criterion
		-ilut_rate [5.0]	The ratio of the maximum fill-in
Additive Schwarz	-adds true	-adds_iter [1]	The number of the iterations

## Other Options

Option	
<code>-emaxiter [1000]</code>	The maximum number of the iterations
<code>-etol [1.0e-12]</code>	The convergence criterion
<code>-eprint [0]</code>	The display of the residual
	<code>-eprint {none 0}</code> None
	<code>-eprint {mem 1}</code> Save the residual history
	<code>-eprint {out 2}</code> Display the residual history
	<code>-eprint {all 3}</code> Save the residual history and display it on the screen
<code>-ie [ii]</code>	The inner eigensolver used in the Lanczos and Subspace
	<code>-ie {pi 1}</code> The Power (the Subspace only)
	<code>-ie {ii 2}</code> The Inverse
	<code>-ie {aii 3}</code> The Approximate Inverse
	<code>-ie {rqi 4}</code> The Rayleigh Quotient
<code>-shift [0.0]</code>	The amount of the shift
<code>-initx_ones [true]</code>	The behavior of the initial vector $x_0$
	<code>-initx_ones {false 0}</code> Given values
	<code>-initx_ones {true 1}</code> All values are set to 1
<code>-omp_num_threads [t]</code>	The number of the threads ( $t$ represents the maximum number of the threads)
<code>-estorage [0]</code>	The matrix storage format
<code>-estorage_block [2]</code>	The block size of the BSR and BSC
<code>-ef [0]</code>	The precision of the eigensolvers
	<code>-ef {double 0}</code> Double precision
	<code>-ef {quad 1}</code> Quadruple precision

#### 6.5.4 lis\_esolver\_set\_optionC

```
C      LIS_INT lis_esolver_set_optionC(LIS_ESOLVER esolver)
Fortran subroutine lis_esolver_set_optionC(LIS_ESOLVER esolver, LIS_INTEGER ierr)
```

##### Description

Set the options for the eigensolver on the command line

##### Input

None

##### Output

<code>esolver</code>	The eigensolver
<code>ierr</code>	The return code

#### 6.5.5 lis\_solve

```
C      LIS_INT lis_solve(LIS_MATRIX A, LIS_VECTOR x,
      LIS_REAL eval, LIS_ESOLVER esolver)
Fortran subroutine lis_solve(LIS_MATRIX A, LIS_VECTOR x,
      LIS_REAL eval, LIS_ESOLVER esolver, LIS_INTEGER ierr)
```

##### Description

Solve the eigenvalue problem  $Ax = \lambda x$  with the specified eigensolver

##### Input

<code>A</code>	The matrix
<code>x</code>	The initial vector
<code>esolver</code>	The eigensolver

##### Output

<code>eval</code>	The eigenvalue of the mode specified by the <code>-m [0]</code> option
<code>x</code>	The associated eigenvector
<code>esolver</code>	The number of the iterations, the execution time, etc.
<code>ierr</code>	The return code



### 6.5.6 lis\_esolver\_get\_status

```
C      LIS_INT lis_esolver_get_status(LIS_ESOLVER esolver, LIS_INT *status)
Fortran subroutine lis_esolver_get_status(LIS_ESOLVER esolver, LIS_INTEGER status,
      LIS_INTEGER ierr)
```

#### Description

Get the status from the eigensolver

#### Input

esolver	The eigensolver
---------	-----------------

#### Output

status	The number of the iterations
ierr	The return code

### 6.5.7 lis\_esolver\_get\_iters

```
C      LIS_INT lis_esolver_get_iters(LIS_ESOLVER esolver, LIS_INT *iters)
Fortran subroutine lis_esolver_get_iters(LIS_ESOLVER esolver, LIS_INTEGER iters,
      LIS_INTEGER ierr)
```

#### Description

Get the number of iterations from the eigensolver

#### Input

esolver	The eigensolver
---------	-----------------

#### Output

iters	The number of the iterations
ierr	The return code

### 6.5.8 lis\_esolver\_get\_itersex

```
C      LIS_INT lis_esolver_get_itersex(LIS_ESOLVER esolver, LIS_INT *iters,  
                                      LIS_INT *iters_double, LIS_INT *iters_quad)  
Fortran subroutine lis_esolver_get_itersex(LIS_ESOLVER esolver, LIS_INTEGER iters,  
                                          LIS_INTEGER iters_double, LIS_INTEGER iters_quad, LIS_INTEGER ierr)
```

#### Description

Get the number of iterations from the eigensolver

#### Input

esolver	The eigensolver
---------	-----------------

#### Output

iters	The number of the iterations
iters_double	The number of the double precision iterations
iters_quad	The number of the quadruple precision iterations
ierr	The return code

### 6.5.9 lis\_esolver\_get\_time

```
C      LIS_INT lis_esolver_get_time(LIS_ESOLVER esolver, double *times)  
Fortran subroutine lis_esolver_get_time(LIS_ESOLVER esolver, real*8 times,  
                                       LIS_INTEGER ierr)
```

#### Description

Get the execution time from the eigensolver

#### Input

esolver	The eigensolver
---------	-----------------

#### Output

times	The time in seconds of the execution
ierr	The return code

### 6.5.10 lis\_esolver\_get\_timeex

```
C      LIS_INT lis_esolver_get_timeex(LIS_ESOLVER esolver, double *times,
                                     double *itimes, double *ptimes, double *p_c_times, double *p_i_times)
Fortran subroutine lis_esolver_get_timeex(LIS_ESOLVER esolver, real*8 times,
                                     real*8 itimes, real*8 ptimes, real*8 p_c_times, real*8 p_i_times,
                                     LIS_INTEGER ierr)
```

#### Description

Get the execution time from the eigensolver

#### Input

esolver	The eigensolver
---------	-----------------

#### Output

times	The total time in seconds
itimes	The time in seconds of the iteration
ptimes	The time in seconds of the preconditioning
p_c_times	The time in seconds of the creation of the preconditioner
p_i_times	The time in seconds of the iteration in the preconditioner
ierr	The return code

### 6.5.11 lis\_esolver\_get\_residualnorm

```
C      LIS_INT lis_esolver_get_residualnorm(LIS_ESOLVER esolver,
                                     LIS_REAL *residual)
Fortran subroutine lis_esolver_get_residualnorm(LIS_ESOLVER esolver,
                                     LIS_REAL residual, LIS_INTEGER ierr)
```

#### Description

Calculate the relative residual norm  $\|\lambda x - Ax\|_2/\lambda$  from eigenvector  $x$

#### Input

esolver	The eigensolver
---------	-----------------

#### Output

residual	The relative residual norm $\ \lambda x - Ax\ _2/\lambda$
ierr	The return code

### 6.5.12 lis\_esolver\_get\_rhistory

```
C      LIS_INT lis_esolver_get_rhistory(VECTOR v)
Fortran subroutine lis_esolver_get_rhistory(LIS_VECTOR v, LIS_INTEGER ierr)
```

#### Description

Store the residual norm history of the eigensolver

#### Input

None

#### Output

<code>v</code>	The vector
<code>ierr</code>	The return code

#### Note

The vector  $v$  must be created in advance with the function `lis_vector_create`. When the vector  $v$  is shorter than the residual history, it stores the residual history in order to the vector  $v$ .

### 6.5.13 lis\_esolver\_get\_evalues

```
C      LIS_INT lis_esolver_get_evalues(LIS_ESOLVER esolver, LIS_VECTOR v)
Fortran subroutine lis_esolver_get_evalues(LIS_ESOLVER esolver,
      LIS_VECTOR v, LIS_INTEGER ierr)
```

#### Description

Store the eigenvalues in the vector  $v$

#### Input

esolver	The eigensolver
---------	-----------------

#### Output

v	The vector which stores the eigenvalues
ierr	The return code

#### Note

The vector  $v$  must be created in advance with the function `lis_vector_create`.

### 6.5.14 lis\_esolver\_get\_evecs

```
C      LIS_INT lis_esolver_get_evecs(LIS_ESOLVER esolver, LIS_MATRIX A)
Fortran subroutine lis_esolver_get_evecs(LIS_ESOLVER esolver,
      LIS_MATRIX A, LIS_INTEGER ierr)
```

#### Description

Store the eigenvectors in the matrix  $A$

#### Input

esolver	The eigensolver
---------	-----------------

#### Output

A	The matrix in the CRS format which stores the eigenvectors
ierr	The return code

#### Note

The matrix  $A$  must be created in advance with the function `lis_matrix_create`.

### 6.5.15 lis\_esolver\_get\_esolver

```
C      LIS_INT lis_esolver_get_esolver(LIS_ESOLVER esolver, LIS_INT *nesol)
Fortran subroutine lis_esolver_get_esolver(LIS_ESOLVER esolver,
      LIS_INTEGER nesol, LIS_INTEGER ierr)
```

#### Description

Get the eigensolver number from the eigensolver

#### Input

esolver                      The eigensolver

#### Output

nesol                        The eigensolver number

ierr                         The return code

#### Note

The number of the eigensolver is as follows:

Eigensolver	Number
Power	1
Inverse	2
Approximate Inverse	3
Rayleigh Quotient	4
Subspace	5
Lanczos	6
CG	7
CR	8

### 6.5.16 lis\_get\_esolvername

```
C      LIS_INT lis_get_esolvername(LIS_INT nesol, char *ename)
Fortran subroutine lis_get_esolvername(LIS_INTEGER nesol, character ename,
      LIS_INTEGER ierr)
```

#### Description

Get the eigensolver name from the eigensolver number

#### Input

nesol                        The eigensolver number

#### Output

name                         The eigensolver name

ierr                         The return code

## 6.6 Operating External Files

### 6.6.1 lis\_input

```
C      LIS_INT lis_input(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR x, char *filename)
Fortran subroutine lis_input(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR x,
                           character filename, LIS_INTEGER ierr)
```

#### Description

Read the matrix and vector data from the external file

#### Input

filename	The source file
----------	-----------------

#### Output

A	The matrix in the specified storage format
b	The right hand side vector
x	The solution
ierr	The return code

#### Note

The supported file formats are shown below:

- The Matrix Market format (extended to allow vector data)
- The Harwell-Boeing format

### 6.6.2 lis\_input\_vector

```
C      LIS_INT lis_input_vector(LIS_VECTOR v, char *filename)
Fortran subroutine lis_input_vector(LIS_VECTOR v, character filename,
                                   LIS_INTEGER ierr)
```

#### Description

Read the vector data from the external file

#### Input

filename	The source file
----------	-----------------

#### Output

v	The vector
ierr	The return code

#### Note

The following formats are supported:

- The PLAIN format
- The Matrix Market format

### 6.6.3 lis\_input\_matrix

```
C      LIS_INT lis_input_matrix(LIS_MATRIX A, char *filename)
Fortran subroutine lis_input_matrix(LIS_MATRIX A, LIS_VECTOR x,
      character filename, LIS_INTEGER ierr)
```

## Description

Read the matrix data from the external file

## Input

<code>filename</code>	The source file
-----------------------	-----------------

## Output

A The matrix in the specified storage format

x	The solution
---	--------------

ierr	The return code
------	-----------------

### Note

The supported file formats are shown below:

- The Matrix Market format (extended to allow vector data)
- The Harwell-Boeing format

### 6.6.4 lis\_output

```
C      LIS_INT lis_output(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR x,
      LIS_INT format, char *filename)
Fortran subroutine lis_output(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR x,
      LIS_INTEGER format, character path, LIS_INTEGER ierr)
```

### Description

Write the matrix and vector data into the external file

## Input

A The Matrix

<b>b</b>	The right hand side vector (If no vector is written to the external file, then NULL must be input.)
----------	---

<b>x</b>	The solution (If no vector is written to the external file, then NULL must be input.)
----------	---

format	The file format
--------	-----------------

LIS\_FMT\_MM The Matrix Market format

filename	The destination file
----------	----------------------

## Output

ierr	The return code
------	-----------------



### 6.6.5 lis\_output\_vector

```
C      LIS_INT lis_output_vector(LIS_VECTOR v, LIS_INT format, char *filename)
Fortran subroutine lis_output_vector(LIS_VECTOR v, LIS_INTEGER format,
      character filename, LIS_INTEGER ierr)
```

#### Description

Write the vector data into the external file

#### Input

v	The vector	
format	The file format	
	LIS_FMT_PLAIN	The PLAIN format
	LIS_FMT_MM	The Matrix Market format
filename	The destination file	

#### Output

ierr	The return code
------	-----------------

### 6.6.6 lis\_output\_matrix

```
C      LIS_INT lis_output_matrix(LIS_MATRIX A, LIS_INT format, char *filename)
Fortran subroutine lis_output_matrix(LIS_MATRIX A, LIS_ format, character path,
      LIS_INTEGER ierr)
```

#### Description

Write the matrix data into the external file

#### Input

A	The matrix	
format	The file format	
	LIS_FMT_MM	The Matrix Market format
filename	The destination file	

#### Output

ierr	The return code
------	-----------------

## 6.7 Other Functions

### 6.7.1 lis\_initialize

```
C      LIS_INT lis_initialize(LIS_INT* argc, char** argv[])
Fortran subroutine lis_initialize(LIS_INTEGER ierr)
```

#### Description

Initialize the execution environment

#### Input

argc	The number of the command line arguments
argv	The command line argument

#### Output

ierr	The return code
------	-----------------

### 6.7.2 lis\_finalize

```
C      LIS_INT lis_finalize()
Fortran subroutine lis_finalize(LIS_INTEGER ierr)
```

#### Description

Finalize the execution environment

#### Input

None

#### Output

ierr	The return code
------	-----------------

### 6.7.3 lis\_wtime

```
C      double lis_wtime()
Fortran function lis_wtime()
```

#### Description

Measure the elapsed time

#### Input

None

#### Output

The elapsed time in seconds from the given point is returned as the double precision number

#### Note

To measure the processing time, call `lis_wtime` to get the starting time, call it again to get the ending time, and calculate the difference.

### 6.7.4 CHKERR

```
C      void CHKERR(LIS_INT ierr)
Fortran subroutine CHKERR(LIS_INTEGER ierr)
```

#### Description

Check the value of the return code

#### Input

<code>ierr</code>	The return code
-------------------	-----------------

#### Output

None

#### Note

If the value of the return code is not 0, it calls `lis_finalize` and terminates the program.

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## A File Formats

This section describes the file formats available for the library.

### A.1 Extended Matrix Market Format

The Matrix Market format[37] does not support the vector data. The extended Matrix Market format is the extension of the Matrix Market format to handle the matrix and vector data. Assume that the number of the nonzero elements of the matrix  $A = (a_{ij})$  of size  $M \times N$  is  $L$  and that  $a_{ij} = A(I, J)$ . The format is as follows:

```
%%MatrixMarket matrix coordinate real general <-- Header
%
%                                     <--+
%                                     | Comment lines with 0 or more lines
%                                     <--+
M N L B X                             <-- Numbers of rows, columns, and
I1 J1 A(I1,J1)                       <--+   nonzero elements (0 or 1) (0 or 1)
I2 J2 A(I2,J2)                       | Row and column number values
. . .                                 | The index is one origin
IL JL A(IL,JL)                       <--+
I1 B(I1)                             <--+
I2 B(I2)                             | Exists only when B=1
. . .                               | Row number value
IM B(IM)                             <--+
I1 X(I1)                             <--+
I2 X(I2)                             | Exists only when X=1
. . .                               | Row number value
IM X(IM)                             <--+
```

The extended Matrix Market format for the matrix  $A$  and the vector  $b$  in Equation (A.1) is as follows:

$$A = \begin{pmatrix} 2 & 1 & & \\ 1 & 2 & 1 & \\ & 1 & 2 & 1 \\ & & 1 & 2 \end{pmatrix} \quad b = \begin{pmatrix} 0 \\ 1 \\ 2 \\ 3 \end{pmatrix} \quad (\text{A.1})$$

```
%%MatrixMarket matrix coordinate real general
4 4 10 1 0
1 2 1.00e+00
1 1 2.00e+00
2 3 1.00e+00
2 1 1.00e+00
2 2 2.00e+00
3 4 1.00e+00
3 2 1.00e+00
3 3 2.00e+00
4 4 2.00e+00
4 3 1.00e+00
1 0.00e+00
2 1.00e+00
3 2.00e+00
4 3.00e+00
```

### A.2 Harwell-Boeing Format

The Harwell-Boeing format inputs and outputs the matrix in the CCS storage format. Assume that the array `value` stores the values of the nonzero elements of the matrix  $A$ , the array `index` stores the row

indices of the nonzero elements and the array `ptr` stores pointers to the top of each column in the arrays `value` and `index`. The format is as follows:

```

Line 1 (A72,A8)
  1 - 72 Title
  73 - 80 Key
Line 2 (5I14)
  1 - 14 Total number of lines excluding header
  15 - 28 Number of lines for ptr
  29 - 42 Number of lines for index
  43 - 56 Number of lines for value
  57 - 70 Number of lines for right hand side vectors
Line 3 (A3,11X,4I14)
  1 - 3 Matrix type
      Col.1: R Real matrix
            C Complex matrix (Not supported)
            P Pattern only (Not supported)
      Col.2: S Symmetric
            U Unsymmetric
            H Hermitian (Not supported)
            Z Skew symmetric (Not supported)
            R Rectangular (Not supported)
      Col.3: A Assembled
            E Elemental matrices (Not supported)
  4 - 14 Blank space
  15 - 28 Number of rows
  29 - 42 Number of columns
  43 - 56 Number of nonzero elements
  57 - 70 0
Line 4 (2A16,2A20)
  1 - 16 Format for ptr
  17 - 32 Format for index
  33 - 52 Format for value
  53 - 72 Format for right hand side vectors
Line 5 (A3,11X,2I14) Only presents if there are right hand side vectors
  1   Right hand side vector type
      F for full storage
      M for same format as matrix (Not supported)
  2   G if a starting vector is supplied
  3   X if an exact solution is supplied
  4 - 14 Blank space
  15 - 28 Number of right hand side vectors
  29 - 42 Number of nonzero elements

```

The Harwell-Boeing format for the matrix  $A$  and the vector  $b$  in Equation (A.1) is as follows:

```

1-----10-----20-----30-----40-----50-----60-----70-----80
Harwell-Boeing format sample                                     Lis
      8              1              1              4              2
RUA              4              4              10             4
(11i7)          (13i6)          (3e26.18)          (3e26.18)
F              1              0
      1      3      6      9
      1      2      1      2      3      2      3      4      3      4
2.00000000000000000000E+00 1.00000000000000000000E+00 1.00000000000000000000E+00
2.00000000000000000000E+00 1.00000000000000000000E+00 1.00000000000000000000E+00
2.00000000000000000000E+00 1.00000000000000000000E+00 1.00000000000000000000E+00
2.00000000000000000000E+00

```

```
0.000000000000000000E+00  1.000000000000000000E+00  2.000000000000000000E+00
3.000000000000000000E+00
```

### A.3 Extended Matrix Market Format for Vectors

The extended Matrix Market format for vectors is the extension of the Matrix Market format to handle the vector data. Assume that the vector  $b = (b_i)$  is a vector of size  $N$  and that  $b_i = B(I)$ . The format is as follows:

```
%%MatrixMarket vector coordinate real general  <--  Header
%
%
%
%
N
I1 B(I1)
I2 B(I2)
. . .
IN B(IN)
```

<-- Number of rows  
<-- Row number value  
| The index is one origin  
<--

The extended Matrix Market format for the vector  $b$  in Equation (A.1) is as follows:

```
%%MatrixMarket vector coordinate real general
4
1  0.00e+00
2  1.00e+00
3  2.00e+00
4  3.00e+00
```

### A.4 PLAIN Format for Vectors

The PLAIN format for vectors is designed to write vector values in order. Assume that the vector  $b = (b_i)$  is a vector of size  $N$  and that  $b_i$  is equal to  $B(I)$ . The format is as follows:

```
B(1)
B(2)
. . .
B(N)
```

<--+  
| Vector value  
|  
<--+

The PLAIN format for the vector  $b$  in Equation (A.1) is as follows:

```
0.00e+00
1.00e+00
2.00e+00
3.00e+00
```