

Lis User Manual

Version 1.2.80



The Scalable Software Infrastructure Project
<http://www.ssisc.org/>

July 12. 2012

Copyright (C) 2002-2012 The Scalable Software Infrastructure Project, supported by “Development of Software Infrastructure for Large Scale Scientific Simulation” Team, CREST, JST
Akira Nishida, Research Institute for Information Technology, Kyushu University, 6-10-1, Hakozaki, Higashi-ku, Fukuoka 812-8581 Japan
All rights reserved.

Redistribution and use in source and binary forms, with or without modification, are permitted provided that the following conditions are met:

1. Redistributions of source code must retain the above copyright notice, this list of conditions and the following disclaimer.
2. Redistributions in binary form must reproduce the above copyright notice, this list of conditions and the following disclaimer in the documentation and/or other materials provided with the distribution.
3. Neither the name of the University nor the names of its contributors may be used to endorse or promote products derived from this software without specific prior written permission.

THIS SOFTWARE IS PROVIDED BY THE SCALABLE SOFTWARE INFRASTRUCTURE PROJECT “AS IS” AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE DISCLAIMED. IN NO EVENT SHALL THE SCALABLE SOFTWARE INFRASTRUCTURE PROJECT BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.

Cover: Ogata Korin, Irises.

Contents

0	Changes from Version 1.1	1
1	Introduction	2
2	Installation	2
2.1	System Requirements	2
2.2	Extracting Archive	3
2.3	Installing on UNIX and Compatible Systems	4
2.3.1	Configuring Source Tree	4
2.3.2	Compiling	4
2.3.3	Installing	8
2.4	Installing on Windows Systems	8
2.5	Test Programs	9
2.5.1	test1	9
2.5.2	test2	9
2.5.3	test3	9
2.5.4	test4	9
2.5.5	test5	10
2.5.6	etest1	10
2.5.7	etest2	10
2.5.8	etest3	10
2.5.9	etest4	10
2.5.10	etest5	11
2.5.11	spmvttest1	11
2.5.12	spmvttest2	11
2.5.13	spmvttest3	11
2.5.14	spmvttest4	12
2.5.15	spmvttest5	12
2.6	Restrictions	13
3	Basic Operations	14
3.1	Initializing and Finalizing	15
3.2	Operating Vectors	15
3.3	Operating Matrices	18
3.4	Solving Linear Equations	24
3.5	Solving Eigenvalue Problems	27
3.6	Sample Programs	30
3.7	Compiling and Linking	32
3.8	Running	34
4	Quadruple Precision Operations	35
4.1	Using Quadruple Precision Operations	35
5	Matrix Storage Formats	37
5.1	Compressed Row Storage (CRS)	37
5.1.1	Creating Matrices (for the Serial and Multithreaded Environments)	37
5.1.2	Creating Matrices (for the Multiprocessing Environment)	38
5.1.3	Associating Arrays	38
5.2	Compressed Column Storage (CCS)	39
5.2.1	Creating Matrices (for the Serial and Multithreaded Environments)	39
5.2.2	Creating Matrices (for the Multiprocessing Environment)	40
5.2.3	Associating Arrays	40

5.3	Modified Compressed Sparse Row (MSR)	41
5.3.1	Creating Matrices (for the Serial and Multithreaded Environments)	41
5.3.2	Creating Matrices (for the Multiprocessing Environment)	42
5.3.3	Associating Arrays	42
5.4	Diagonal (DIA)	43
5.4.1	Creating Matrices (for the Serial Environment)	43
5.4.2	Creating Matrices (for the Multithreaded Environment)	44
5.4.3	Creating Matrices (for the Multiprocessing Environment)	45
5.4.4	Associating Arrays	45
5.5	Ellpack-Itpack Generalized Diagonal (ELL)	46
5.5.1	Creating Matrices (for the Serial and Multithreaded Environments)	46
5.5.2	Creating Matrices (for the Multiprocessing Environment)	47
5.5.3	Associating Arrays	47
5.6	Jagged Diagonal (JDS)	48
5.6.1	Creating Matrices (for the Serial Environment)	49
5.6.2	Creating Matrices (for the Multithreaded Environment)	50
5.6.3	Creating Matrices (for the Multiprocessing Environment)	51
5.6.4	Associating Arrays	51
5.7	Block Sparse Row (BSR)	52
5.7.1	Creating Matrices (for the Serial and Multithreaded Environments)	52
5.7.2	Creating Matrices (for the Multiprocessing Environment)	53
5.7.3	Associating Arrays	53
5.8	Block Sparse Column (BSC)	54
5.8.1	Creating Matrices (for the Serial and Multithreaded Environments)	54
5.8.2	Creating Matrices (for the Multiprocessing Environment)	55
5.8.3	Associating Arrays	55
5.9	Variable Block Row (VBR)	56
5.9.1	Creating Matrices (for the Serial and Multithreaded Environments)	56
5.9.2	Creating Matrices (for the Multiprocessing Environment)	57
5.9.3	Associating Arrays	58
5.10	Coordinate (COO)	59
5.10.1	Creating Matrices (for the Serial and Multithreaded Environments)	59
5.10.2	Creating Matrices (for the Multiprocessing Environment)	60
5.10.3	Associating Arrays	60
5.11	Dense (DNS)	61
5.11.1	Creating Matrices (for the Serial and Multithreaded Environments)	61
5.11.2	Creating Matrices (for the Multiprocessing Environment)	62
5.11.3	Associating Arrays	62
6	Functions	63
6.1	Operating Vector Elements	63
6.1.1	lis_vector_create	63
6.1.2	lis_vector_destroy	64
6.1.3	lis_vector_duplicate	64
6.1.4	lis_vector_set_size	65
6.1.5	lis_vector_get_size	65
6.1.6	lis_vector_get_range	66
6.1.7	lis_vector_set_value	66
6.1.8	lis_vector_get_value	67
6.1.9	lis_vector_set_values	67
6.1.10	lis_vector_get_values	68
6.1.11	lis_vector_scatter	69
6.1.12	lis_vector_gather	69

6.1.13	lis_vector_copy	70
6.1.14	lis_vector_set_all	70
6.2	Operating Matrix Elements	71
6.2.1	lis_matrix_create	71
6.2.2	lis_matrix_destroy	71
6.2.3	lis_matrix_duplicate	72
6.2.4	lis_matrix_malloc	72
6.2.5	lis_matrix_set_value	73
6.2.6	lis_matrix_assemble	73
6.2.7	lis_matrix_set_size	74
6.2.8	lis_matrix_get_size	74
6.2.9	lis_matrix_get_range	75
6.2.10	lis_matrix_set_type	76
6.2.11	lis_matrix_get_type	76
6.2.12	lis_matrix_set_blocksize	77
6.2.13	lis_matrix_convert	77
6.2.14	lis_matrix_copy	78
6.2.15	lis_matrix_get_diagonal	78
6.2.16	lis_matrix_set_crs	79
6.2.17	lis_matrix_set_ccs	79
6.2.18	lis_matrix_set_msr	80
6.2.19	lis_matrix_set_dia	80
6.2.20	lis_matrix_set_ell	81
6.2.21	lis_matrix_set_jds	81
6.2.22	lis_matrix_set_bsr	82
6.2.23	lis_matrix_set_bsc	82
6.2.24	lis_matrix_set_vbr	83
6.2.25	lis_matrix_set_coo	83
6.2.26	lis_matrix_set_dns	84
6.3	Operating Vectors and Matrices	85
6.3.1	lis_vector_scale	85
6.3.2	lis_vector_dot	85
6.3.3	lis_vector_nrm1	86
6.3.4	lis_vector_nrm2	86
6.3.5	lis_vector_nrmi	87
6.3.6	lis_vector_axpy	88
6.3.7	lis_vector_xpay	88
6.3.8	lis_vector_axpyz	89
6.3.9	lis_matrix_scaling	89
6.3.10	lis_matvec	90
6.3.11	lis_matvect	90
6.4	Solving Linear Equations	91
6.4.1	lis_solver_create	91
6.4.2	lis_solver_destroy	91
6.4.3	lis_solver_set_option	92
6.4.4	lis_solver_set_optionC	95
6.4.5	lis_solve	96
6.4.6	lis_solve_kernel	97
6.4.7	lis_solver_get_status	98
6.4.8	lis_solver_get_iters	98
6.4.9	lis_solver_get_itersex	99
6.4.10	lis_solver_get_time	99
6.4.11	lis_solver_get_timeex	100

6.4.12	lis_solver_get_residualnorm	100
6.4.13	lis_solver_get_rhistory	101
6.4.14	lis_solver_get_solver	102
6.4.15	lis_get_solvername	102
6.5	Solving Eigenvalue Problems	103
6.5.1	lis_esolver_create	103
6.5.2	lis_esolver_destroy	103
6.5.3	lis_esolver_set_option	104
6.5.4	lis_esolver_set_optionC	107
6.5.5	lis_solve	107
6.5.6	lis_esolver_get_status	108
6.5.7	lis_esolver_get_iters	108
6.5.8	lis_esolver_get_itersex	109
6.5.9	lis_esolver_get_time	109
6.5.10	lis_esolver_get_timeex	110
6.5.11	lis_esolver_get_residualnorm	110
6.5.12	lis_esolver_get_rhistory	111
6.5.13	lis_esolver_get_evalues	112
6.5.14	lis_esolver_get_evectors	112
6.5.15	lis_esolver_get_esolver	113
6.5.16	lis_get_esolvername	113
6.6	Operating External Files	114
6.6.1	lis_input	114
6.6.2	lis_input_vector	114
6.6.3	lis_input_matrix	115
6.6.4	lis_output	115
6.6.5	lis_output_vector	116
6.6.6	lis_output_matrix	116
6.7	Other Functions	117
6.7.1	lis_initialize	117
6.7.2	lis_finalize	117
6.7.3	lis_wtime	117
References		118
A File Formats		120
A.1	Extended Matrix Market Format	120
A.2	Harwell-Boeing Format	120
A.3	Extended Matrix Market Format for Vectors	122
A.4	PLAIN Format for Vectors	122

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`.

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 Iteration
Inverse Iteration
Approximate Inverse Iteration
Rayleigh Quotient Iteration
Subspace Iteration
Lanczos Iteration
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 compiler which supports FORTRAN 77. The AMG preconditioner requires a compiler which supports Fortran 90. For parallel computing environments, the OpenMP or MPI-1 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	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.

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

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

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>`

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

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

<code>--enable-omp</code>	Use the OpenMP library
<code>--enable-mpi</code>	Use the MPI library
<code>--enable-fortran</code>	Use the Fortran interface
<code>--enable-saamg</code>	Use the SA-AMG preconditioner
<code>--enable-quad</code>	Use the quadruple precision operation
<code>--enable-gprof</code>	Use the GNU profiler
<code>--enable-shared</code>	Build shared libraries
<code>--prefix=<install-dir></code>	Specify the installation destination
<code>TARGET=<target></code>	Specify the computing environment
<code>CC=<c_compiler></code>	Specify the C compiler
<code>CFLAGS=<c_flags></code>	Specify the options for the C compiler
<code>FC=<fortran90_compiler></code>	Specify the Fortran 90 compiler
<code>FCFLAGS=<fc_flags></code>	Specify the options for the Fortran 90 compiler
<code>LDFLAGS=<ld_flags></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 `configure` for the complete list)

<target>	Equivalent options
cray_xt3	<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_pq	<code>./configure CC=fcc FC=frt ac_cv_sizeof_void_p=8 CFLAGS="-O3 -Kfast,ocl,preex" FFLAGS="-O3 -Kfast,ocl,preex -Cpp" FCFLAGS="-O3 -Kfast,ocl,preex -Cpp -Am" ax_f77_mangling="lower case, underscore, no extra underscore"</code>
hitachi	<code>./configure CC=cc FC=f90 FCLDFLAGS="-lf90s" ac_cv_sizeof_void_p=8 CFLAGS="-Os -noparallel" FCFLAGS="-Oss -noparallel" ax_f77_mangling="lower case, underscore, no extra underscore"</code>
ibm_bg1	<code>./configure CC=blrts_xlc FC=blrts_xlf90 CFLAGS="-O3 -qarch=440d -qtune=440 -qstrict -I/bg1/BlueLight/ppcfloor/bglsys/include" FFFLAGS="-O3 -qarch=440d -qtune=440 -qsuffix=cpp=F -qfixed=72 -w -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	<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)
+include
|   +lis_config.h lis.h lisf.h
+lib
    +liblis.a
```

`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.

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 Test Programs

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` and the residual history to `residual_filename`. The extended Matrix Market format, which is extended to allow vector data, is supported (see Appendix). One of the following values can be used for `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` and the residual history to `residual_filename`. 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` and the residual history to `residual_filename`. 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** and the residual history to **residual_filename**. The Matrix Market format is supported. **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** and the residual history to **residual_filename**. 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** and the residual history to **residual_filename**. 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 evalfile evecfile`

This program solves the eigenvalue problem $Ax = \lambda x$ with the subspace iteration, 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 12×12 . It outputs 2 extreme eigenvalues of the smallest magnitude to `evalfile` and the associated eigenvectors to `evecfile` in the extended Matrix Market format (see Appendix).

2.5.11 spmvtest1

Usage: `spmvtest1 n iter`

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 for available matrix storage formats.

2.5.12 spmvtest2

Usage: `spmvtest2 m n iter`

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 values m and n represent the numbers of the grid points in the vertical and horizontal directions. The FLOPS performance is measured as the average of *iter* iterations for available matrix storage formats.

2.5.13 spmvtest3

Usage: `spmvtest3 l m n iter`

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 for available matrix storage formats.

2.5.14 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 twice as the average of *iter* iterations. If necessary, the block size of the BSR and BSC can be specified by *block*.

2.5.15 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 twice as the average of *iter* iterations. If necessary, the block size of the BSR and BSC 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: int main(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_initialize(int* argc, char** argv[])`
- Fortran subroutine `lis_initialize(integer ierr)`

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

Finalizing

For finalizing, the following functions are used:

- C `int lis_finalize()`
- Fortran subroutine `lis_finalize(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 the serial and multithreaded environments) —

```
1: 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 the multiprocessing environment) —

```
1: int          i,n,is,ie;                /*or 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 the serial and multithreaded environments) —

```
1: 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
8:     call lis_vector_set_value(LIS_INS_VALUE,i,DBLE(i),v,ierr)
9: enddo
```

Fortran (for the multiprocessing environment) —

```
1: 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 `int lis_vector_create(LIS_Comm comm, LIS_VECTOR *v)`
- Fortran subroutine `lis_vector_create(LIS_Comm comm, LIS_VECTOR v, 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 `int lis_vector_set_size(LIS_VECTOR v, int local_n, int global_n)`
- Fortran subroutine `lis_vector_set_size(LIS_VECTOR v, integer local_n, integer global_n, 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 `int lis_vector_set(int flag, int i, LIS_SCALAR value, LIS_VECTOR v)`
- Fortran subroutine `lis_vector_set_value(int flag, int i, LIS_SCALAR value, LIS_VECTOR v, 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 `int lis_vector_duplicate(LIS_VECTOR vin, LIS_VECTOR *vout)`
- Fortran subroutine `lis_vector_duplicate(LIS_VECTOR vin, LIS_VECTOR vout, 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 `int lis_vector_copy(LIS_VECTOR vsrc, LIS_VECTOR vdst)`

- Fortran subroutine `lis_vector_copy(LIS_VECTOR vsrc, LIS_VECTOR vdst, integer ierr)`

Destroying Vectors

To destroy the vector, the following functions are used:

- C `int lis_vector_destroy(LIS_VECTOR v)`
- Fortran subroutine `lis_vector_destroy(LIS_VECTOR v, 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 the serial and multithreaded environments)

```
1: 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 the multiprocessing environment)

```
1: 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_CRD);
14: lis_matrix_assemble(A);
```

Fortran (for the serial and multithreaded environments)

```
1: 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_CRD,ierr)
12: call lis_matrix_assemble(A,ierr)
```

Fortran (for the multiprocessing environment)

```
1: 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_CRD,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 `int lis_matrix_create(LIS_Comm comm, LIS_MATRIX *A)`
- Fortran subroutine `lis_matrix_create(LIS_Comm comm, LIS_MATRIX A, 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 `int lis_matrix_set_size(LIS_MATRIX A, int local_n, int global_n)`
- Fortran subroutine `lis_matrix_set_size(LIS_MATRIX A, integer local_n, integer global_n, 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 `int lis_matrix_set_value(int flag, int i, int j, LIS_SCALAR value, LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_value(integer flag, integer i, integer j, LIS_SCALAR value, LIS_MATRIX A, 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 `int lis_matrix_set_type(LIS_MATRIX A, int matrix_type)`
- Fortran subroutine `lis_matrix_set_type(LIS_MATRIX A, int matrix_type, integer ierr)`

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

Storage formats		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}

Assembling Matrices

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

- C `int lis_matrix_assemble(LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_assemble(LIS_MATRIX A, 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 `int lis_matrix_destroy(LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_destroy(LIS_MATRIX A, 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 the serial and multithreaded environments)

```

1: int          i,k,n,nnz;
2: 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 the multiprocessing environment)

```

1: int          i,k,n,nnz,is,ie;
2: 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 `int lis_matrix_set_crs(int nnz, int row[], int index[], LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_crs(integer nnz, integer row(), integer index(), LIS_SCALAR value(), LIS_MATRIX A, 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 the 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 the 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 `int lis_input_matrix(LIS_MATRIX A, char *filename)`
- Fortran subroutine `lis_input(LIS_MATRIX A, character filename, 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 `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, 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 the 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 the 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 `int lis_solver_create(LIS_SOLVER *solver)`
- Fortran subroutine `lis_solver_create(LIS_SOLVER solver, integer ierr)`

Specifying Options

To specify options, the following functions are used:

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

or

- C `int lis_solver_set_optionC(LIS_SOLVER solver)`

- Fortran subroutine `lis_solver_set_optionC(LIS_SOLVER solver, 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.

Specifying Linear Solvers (Default: `-i bicg`)

Method	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 ω ($0 < \omega < 2$)
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>		

Specifying 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 ω ($0 < \omega < 2$)
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 ω 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 α 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	
-maxiter [1000]	The maximum number of the iterations
-tol [1.0e-12]	The convergence criterion
-print [0]	The display of the residual -print {none 0} None -print {mem 1} Saves the residual history -print {out 2} Displays the residual history -print {all 3} Saves the residual history and displays it on the screen
-scale [0]	The scaling (The result will overwrite the original matrix and vectors) -scale {none 0} No scaling -scale {jacobi 1} The Jacobi scaling $D^{-1}Ax = D^{-1}b$ (D represents the diagonal of $A = (a_{ij})$) -scale {symm_diag 2} 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)
-initx_zeros [true]	The behavior of the initial vector x_0 -initx_zeros {false 0} Given values -initx_zeros {true 1} All values are set to 0
-omp_num_threads [t]	The number of the threads (t represents the maximum number of the threads)
-storage [0]	The matrix storage format
-storage_block [2]	The block size of the BSR and BSC

Precision (Default: -f double)

Precision	Option	Auxiliary Options
DOUBLE	-f {double 0}	
QUAD	-f {quad 1}	

Solving Linear Equations

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

- C `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, 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 the 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 the 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: 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,eval,esolver,ierr)
```

Creating Eigensolvers

To create an eigensolver, the following functions are used:

- C `int lis_esolver_create(LIS_ESOLVER *esolver)`
- Fortran subroutine `lis_esolver_create(LIS_ESOLVER esolver, integer ierr)`

Specifying Options

To specify options, the following functions are used:

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

or

- C `int lis_esolver_set_optionC(LIS_ESOLVER esolver)`
- Fortran subroutine `lis_esolver_set_optionC(LIS_ESOLVER esolver, 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.

Specifying Eigensolvers (Default: `-e pi`)

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

Specifying 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 ω ($0 < \omega < 2$)
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 ω 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 α 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	
-emaxiter [1000]	The maximum number of the iterations
-etol [1.0e-12]	The convergence criterion
-eprint [0]	The display of the residual
	-eprint {none 0} None
	-eprint {mem 1} Saves the residual history
	-eprint {out 2} Displays the residual history
	-eprint {all 3} Saves the residual history and displays it on the screen
-ie [ii]	The inner eigensolver used in the Lanczos iteration and the subspace iteration
	-ie {pi 1} The power iteration (Subspace Iteration only)
	-ie {ii 2} The inverse iteration
	-ie {aai 3} The approximate inverse iteration
	-ie {rqi 4} The Rayleigh quotient iteration
-shift [0.0]	The amount of the shift
-initx_ones [true]	The behavior of the initial vector x_0
	-initx_ones {false 0} Given values
	-initx_ones {true 1} All values are set to 1
-omp_num_threads [t]	The number of the threads (t represents the maximum number of the threads)
-estorage [0]	The matrix storage format
-estorage_block [2]	The block size of the BSR and BSC

Precision (Default: <code>-ef double</code>)		
Precision	Option	Auxiliary Options
DOUBLE	<code>-ef {double 0}</code>	
QUAD	<code>-ef {quad 1}</code>	

Solving Eigenvalue Problems

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

- C `int lis_solve(LIS_MATRIX A, LIS_VECTOR x, LIS_REAL eval, LIS_ESOLVER solver)`
- Fortran subroutine `lis_solve(LIS_MATRIX A, LIS_VECTOR x, LIS_REAL eval, LIS_ESOLVER solver, integer ierr)`

3.6 Sample 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(int argc, char *argv[])
4: {
5:     int i,n,gn,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,&gn);
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<gn-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:      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_CRS,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 `USE_MPI` macro must be used 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 the 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 the 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 the multithreaded and multiprocessing environment

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 the serial environment

Compiling

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

Linking

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

for the multithreaded environment

Compiling

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

Linking

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

for the multiprocessing environment

Compiling

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

Linking

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

for the multithreaded and multiprocessing environment

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 the serial environment

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

for the multithreaded environment

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

for the multiprocessing environment

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

for the 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) and IBM's Fused Multiply-Add (FMA)[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 the 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:

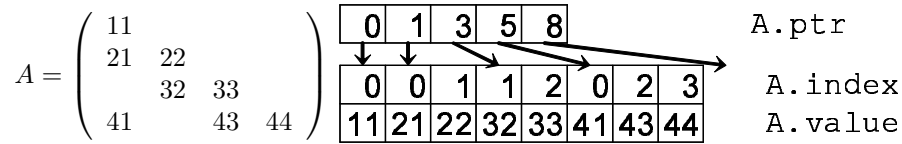


Figure 2: The data structure of the CRS format (for the serial and multithreaded environments).

for the serial and multithreaded environments

```

1: int          n,nnz;
2: int          *ptr,*index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: n = 4; nnz = 8;
6: ptr = (int *)malloc( (n+1)*sizeof(int) );
7: index = (int *)malloc( nnz*sizeof(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);

```

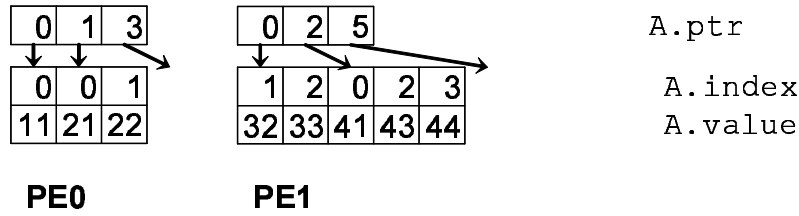


Figure 3: The data structure of the CRS format (for the multiprocessing environment).

5.1.2 Creating Matrices (for the 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:

for the multiprocessing environment

```

1: int      i,k,n,nnz,my_rank;
2: 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 = (int *)malloc( (n+1)*sizeof(int) );
9: index = (int *)malloc( nnz*sizeof(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 `int lis_matrix_set_crs(int nnz, int row[], int index[], LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_crs(integer nnz, integer row(), integer index(), LIS_SCALAR value(), LIS_MATRIX A, 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 the 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:

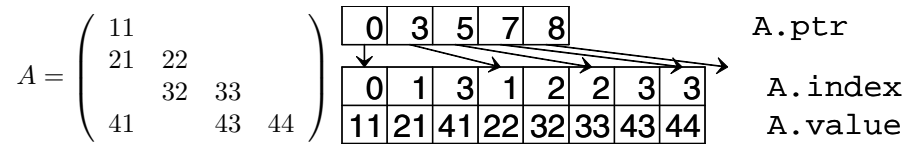


Figure 4: The data structure of the CCS format (for the serial and multithreaded environments).

for the serial and multithreaded environments

```

1: int      n,nnz;
2: int      *ptr,*index;
3: LIS_SCALAR *value;
4: LIS_MATRIX A;
5: n = 4; nnz = 8;
6: ptr = (int *)malloc( (n+1)*sizeof(int) );
7: index = (int *)malloc( nnz*sizeof(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 the 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:

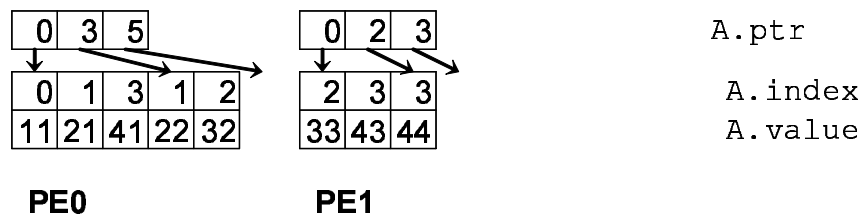


Figure 5: The data structure of the CCS format (for the multiprocessing environment).

for the multiprocessing environment

```

1: int          i,k,n,nnz,my_rank;
2: 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  = (int *)malloc( (n+1)*sizeof(int) );
9: index = (int *)malloc( nnz*sizeof(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 `int lis_matrix_set_ccs(int nnz, int row[], int index[], LIS_SCALAR value[],`
- Fortran subroutine `lis_matrix_set_ccs(integer nnz, integer row(), integer index(),`
`LIS_SCALAR value(), LIS_MATRIX A, 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 the 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:

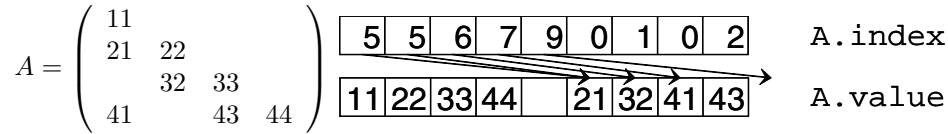


Figure 6: The data structure of the MSR format (for the serial and multithreaded environments).

for the serial and multithreaded environments

```

1: int      n,nnz,ndz;
2: int      *index;
3: LIS_SCALAR *value;
4: LIS_MATRIX A;
5: n = 4; nnz = 8; ndz = 0;
6: index = (int *)malloc( (nnz+ndz+1)*sizeof(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 the 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:

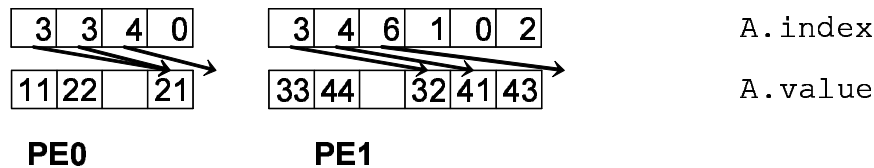


Figure 7: The data structure of the MSR format (for the multiprocessing environment).

for the multiprocessing environment

```

1: int      i,k,n,nnz,ndz,my_rank;
2: 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 = (int *)malloc( (nnz+ndz+1)*sizeof(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 `int lis_matrix_set_msr(int nnz, int ndz, int index[], LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_msr(integer nnz, integer ndz, integer index(), LIS_SCALAR value(), LIS_MATRIX A, 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 the 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:

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

Figure 8: The data structure of the DIA format (for the serial environment).

for the serial environment

```

1: int      n,nnd;
2: int      *index;
3: LIS_SCALAR *value;
4: LIS_MATRIX A;
5: n = 4; nnd = 3;
6: index = (int *)malloc( nnd*sizeof(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:

Figure 9: The data structure of the DIA format (for the multithreaded environment).

```

1: int          n,maxnnd,nprocs;
2: int          *index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: n = 4; maxnnd = 3; nprocs = 2;
6: index = (int *)malloc( maxnnd*sizeof(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 the 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: The data structure of the DIA format (for the multiprocessing environment).

for the multiprocessing environment

```

1: int          i,n,nnd,my_rank;
2: 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 = (int *)malloc( nnd*sizeof(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 `int lis_matrix_set_dia(int nnd, int index[], LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_dia(integer nnd, integer index(), LIS_SCALAR value(), LIS_MATRIX A, 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 $\text{maxnzc} \times n$, 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 $\text{maxnzc} \times n$, 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 the 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: The data structure of the ELL format (for the serial and multithreaded environments).

for the serial and multithreaded environments

```

1: int          n,maxnzc;
2: int          *index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: n = 4; maxnzc = 3;
6: index = (int *)malloc( n*maxnzc*sizeof(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 the 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:

0	0	0	1	1	0	2	2	2	3	A.index
11	21	0	22	32	41	33	43	0	44	A.value
PE0				PE1						

Figure 12: The data structure of the ELL format (for the multiprocessing environment).

for the multiprocessing environment

```

1: int          i,n,maxnzs,my_rank;
2: 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 = (int *)malloc( n*maxnzs*sizeof(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 `int lis_matrix_set_ell(int maxnzs, int index[], LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_ell(integer maxnzs, integer index(), LIS_SCALAR value(), LIS_MATRIX A, 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 the 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:

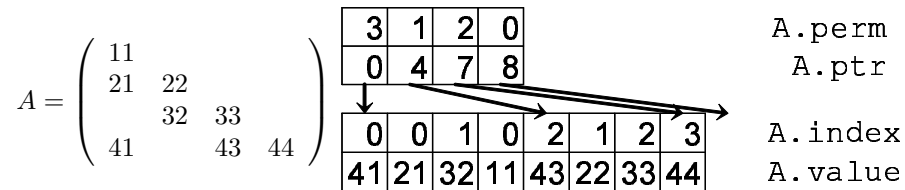


Figure 13: The data structure of the JDS format (for the serial environment).

for the serial environment

```

1: int          n,nnz,maxnzs;
2: int          *perm,*ptr,*index;
3: LIS_SCALAR   *value;
4: LIS_MATRIX   A;
5: n = 4; nnz = 8; maxnzs = 3;
6: perm = (int *)malloc( n*sizeof(int) );
7: ptr = (int *)malloc( (maxnzs+1)*sizeof(int) );
8: index = (int *)malloc( nnz*sizeof(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 the 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:

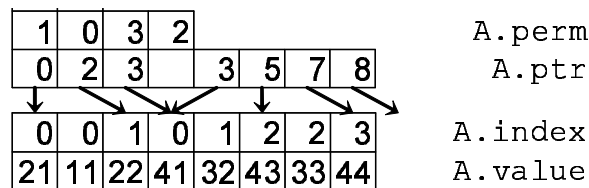


Figure 14: The data structure of the JDS format (for the multithreaded environment).

```

for the multithreaded environment
1: int      n, nnz, maxmaxnzs, nprocs;
2: int      *perm, *ptr, *index;
3: LIS_SCALAR *value;
4: LIS_MATRIX A;
5: n = 4; nnz = 8; maxmaxnzs = 3; nprocs = 2;
6: perm = (int *)malloc( n*sizeof(int) );
7: ptr = (int *)malloc( nprocs*(maxmaxnzs+1)*sizeof(int) );
8: index = (int *)malloc( nnz*sizeof(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 the 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:

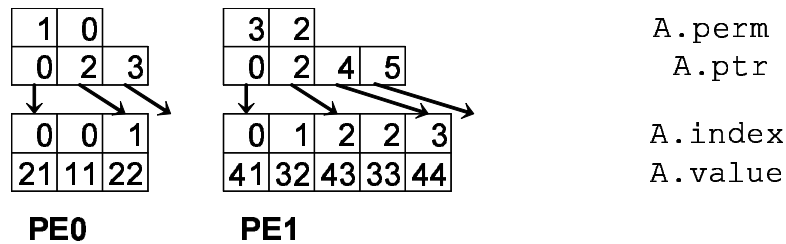


Figure 15: The data structure of the JDS format (for the multiprocessing environment).

for the multiprocessing environment

```

1: int      i,n,nnz,maxnzs,my_rank;
2: 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 = (int *)malloc( n*sizeof(int) );
9: ptr = (int *)malloc( (maxnzs+1)*sizeof(int) );
10: index = (int *)malloc( nnz*sizeof(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 int lis_matrix_set_jds(int nnz, int maxnzs, int perm[], int ptr[],
 int index[], LIS_SCALAR value[], LIS_MATRIX A)
- Fortran subroutine lis_matrix_set_jds(integer nnz, integer maxnzs, integer ptr(),
 integer index(), LIS_SCALAR value(), LIS_MATRIX A, 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 the 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:

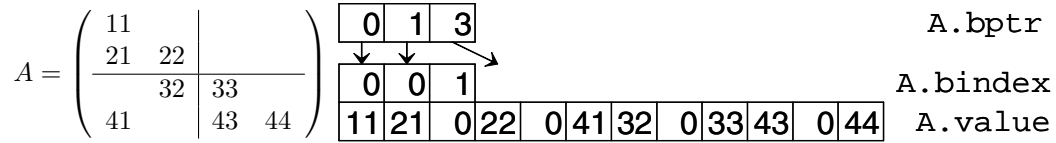


Figure 16: The data structure of the BSR format (for the serial and multithreaded environments).

for the serial and multithreaded environments

```

1: int      n, bnr, bnc, nr, nc, bnnz;
2: int      *bptr, *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 = (int *)malloc( (nr+1)*sizeof(int) );
7: bindex = (int *)malloc( bnnz*sizeof(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 the 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:

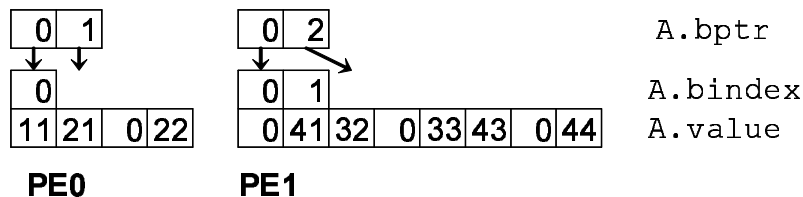


Figure 17: The data structure of the BSR format (for the multiprocessing environment).

for the multiprocessing environment

```

1: int      n, bnr, bnc, nr, nc, bnnz, my_rank;
2: 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  = (int *)malloc( (nr+1)*sizeof(int) );
9: bindex = (int *)malloc( bnnz*sizeof(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 `int lis_matrix_set_bsr(int bnr, int bnc, int bnnz, int bptr[], int bindex[], LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_bsr(integer bnr, integer bnc, integer bnnz, integer bptr(), integer bindex(), LIS_SCALAR value(), LIS_MATRIX A, integer ierr)`

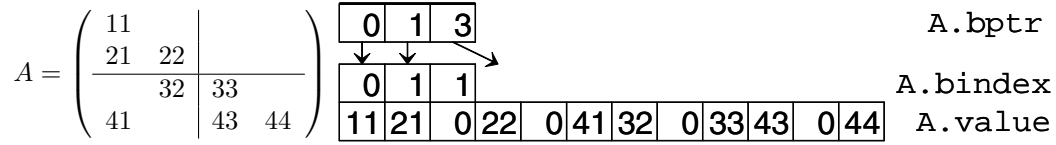
5.8 Block Sparse Column (BSC)

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 **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 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 the 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:



for the serial and multithreaded environments

```

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

5.8.2 Creating Matrices (for the 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:

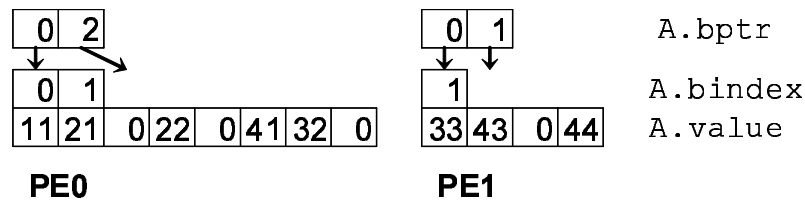


Figure 19: The data structure of the BSC format (for the multiprocessing environment).

for the multiprocessing environment

```

1: int      n, bnr, bnc, nr, nc, bnnz, my_rank;
2: 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  = (int *)malloc( (nr+1)*sizeof(int) );
9: bindex = (int *)malloc( bnnz*sizeof(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 `int lis_matrix_set_bsc(int bnr, int bnc, int bnnz, int bptr[], int bindex[], LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_bsc(integer bnr, integer bnc, integer bnnz, integer bptr(), integer bindex(), LIS_SCALAR value(), LIS_MATRIX A, 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 the 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:

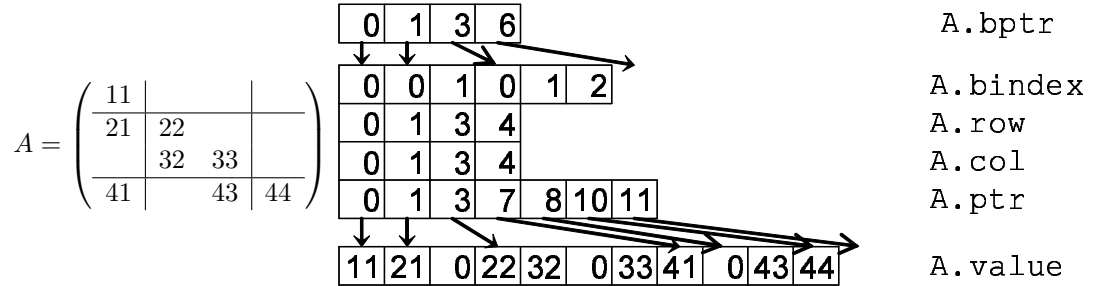


Figure 20: The data structure of the VBR format (for the serial and multithreaded environments).

for the serial and multithreaded environments

```

1: int      n,nnz,nr,nc,bnnz;
2: 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 = (int *)malloc( (nr+1)*sizeof(int) );
7: row = (int *)malloc( (nr+1)*sizeof(int) );
8: col = (int *)malloc( (nc+1)*sizeof(int) );
9: ptr = (int *)malloc( (bnnz+1)*sizeof(int) );
10: bindex = (int *)malloc( bnnz*sizeof(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 the 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:

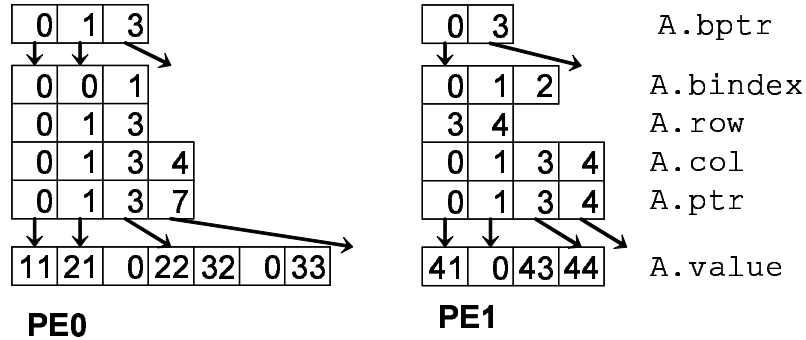


Figure 21: The data structure of the VBR format (for the multiprocessing environment).

for the multiprocessing environment

```

1: int          n,nnz,nr,nc,bnnz,my_rank;
2: 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  = (int *)malloc( (nr+1)*sizeof(int) );
9: row   = (int *)malloc( (nr+1)*sizeof(int) );
10: col   = (int *)malloc( (nc+1)*sizeof(int) );
11: ptr   = (int *)malloc( (bnnz+1)*sizeof(int) );
12: bindex = (int *)malloc( bnnz*sizeof(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 `int lis_matrix_set_vbr(int nnz, int nr, int nc, int bnnz, int row[], int col[], int ptr[], int bptr[], int bindex[], LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_vbr(integer nnz, integer nr, integer nc, integer bnnz, integer row(), integer col(), integer ptr(), integer bptr(), integer bindex(), LIS_SCALAR value(), LIS_MATRIX A, 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 the 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:

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

Figure 22: The data structure of the COO format (for the serial and multithreaded environments).

for the serial and multithreaded environments

```

1: int      n,nnz;
2: int      *row,*col;
3: LIS_SCALAR *value;
4: LIS_MATRIX A;
5: n = 4; nnz = 8;
6: row = (int *)malloc( nnz*sizeof(int) );
7: col = (int *)malloc( nnz*sizeof(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 the 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:

0	1	1																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
---	---	---	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Figure 23: The data structure of the COO format (for the multiprocessing environment).

for the multiprocessing environment

```

1: int      n,nnz,my_rank;
2: 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  = (int *)malloc( nnz*sizeof(int) );
9: col  = (int *)malloc( nnz*sizeof(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 `int lis_matrix_set_coo(int nnz, int row[], int col[], LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_coo(integer nnz, integer row(), integer col(), LIS_SCALAR value(), LIS_MATRIX A, 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 the 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: The data structure of the DNS format (for the serial and multithreaded environments).

for the serial and multithreaded environments

```

1: 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 the 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	
PE0				PE1				

Figure 25: The data structure of the DNS format (for the multiprocessing environment).

for the multiprocessing environment

```

1: 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 `int lis_matrix_set_dns(LIS_SCALAR value[], LIS_MATRIX A)`
- Fortran subroutine `lis_matrix_set_dns(LIS_SCALAR value(), LIS_MATRIX A, integer ierr)`

6 Functions

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

Return Values

<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      int lis_vector_create(LIS_Comm comm, LIS_VECTOR *v)
Fortran subroutine lis_vector_create(LIS_Comm comm, LIS_VECTOR v, 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      int lis_vector_destroy(LIS_VECTOR v)
Fortran subroutine lis_vector_destroy(LIS_VECTOR v, integer ierr)
```

Description

Destroy the vector v

Input

v	The vector to be destroyed
-----	----------------------------

Output

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

6.1.3 lis_vector_duplicate

```
C      int lis_vector_duplicate(void *vin, LIS_VECTOR *vout)
Fortran subroutine lis_vector_duplicate(LIS_VECTOR vin, LIS_VECTOR vout,
      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      int lis_vector_set_size(LIS_VECTOR v, int local_n, int global_n)
Fortran subroutine lis_vector_set_size(LIS_VECTOR v, integer local_n,
      integer global_n, integer ierr)
```

Description

Assign the size of the vector v

Input

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

Output

<code>ierr</code>	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.

6.1.5 lis_vector_get_size

```
C      int lis_vector_get_size(LIS_VECTOR v, int *local_n, int *global_n)
Fortran subroutine lis_vector_get_size(LIS_VECTOR v, integer local_n,
      integer global_n, integer ierr)
```

Description

Get the size of the vector v

Input

<code>v</code>	The vector
----------------	------------

Output

<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

Note

In the case of the serial and multithreaded environments, *local_n* is equal to *global_n*.

6.1.6 lis_vector_get_range

```
C      int lis_vector_get_range(LIS_VECTOR v, int *is, int *ie)
Fortran subroutine lis_vector_get_range(LIS_VECTOR v, integer is, integer ie,
      integer ierr)
```

Description

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

Input

v The partial vector

Output

is The location where the partial vector v starts in the global vector

ie The next location where the partial vector v ends in the global vector

$ierr$ The return code

Note

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      int lis_vector_set_value(int flag, int i, LIS_SCALAR value, LIS_VECTOR v)
Fortran subroutine lis_vector_set_value(integer flag, integer i, LIS_SCALAR value,
      LIS_VECTOR v, 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 $value$ assigned to the 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      int lis_vector_get_value(LIS_VECTOR v, int i, LIS_SCALAR *value)
Fortran subroutine lis_vector_get_value(LIS_VECTOR v, integer i, LIS_SCALAR value,
      integer ierr)
```

Description

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

Input

<code>i</code>	The location where the value is assigned
<code>v</code>	The destination vector

Output

<code>value</code>	The value of the i -th row
<code>ierr</code>	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      int lis_vector_set_values(int flag, int count, int index[],
      LIS_SCALAR value[], LIS_VECTOR v)
Fortran subroutine lis_vector_set_values(integer flag, integer count,
      integer index(), LIS_SCALAR value(), LIS_VECTOR v, 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      int lis_vector_get_values(LIS_VECTOR v, int start, int count,  
                                LIS_SCALAR value[])  
Fortran subroutine lis_vector_get_values(LIS_VECTOR v, integer start,  
                                         integer count, LIS_SCALAR value(), 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      int lis_vector_scatter(LIS_SCALAR value[], LIS_VECTOR v)
Fortran subroutine lis_vector_scatter(LIS_SCALAR value(), LIS_VECTOR v, 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

value	The array which stores the scalar values to be assigned
-------	---

Output

v	The destination vector
ierr	The return code

Note

6.1.12 lis_vector_gather

```
C      int lis_vector_gather(LIS_VECTOR v, LIS_SCALAR value[])
Fortran subroutine lis_vector_gather(LIS_VECTOR v, LIS_SCALAR value(), integer ierr)
```

Description

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

Input

v	The source vector
---	-------------------

Output

value	The vector to store the scalar values
ierr	The return code

Note

6.1.13 lis_vector_copy

```
C      int lis_vector_copy(LIS_VECTOR x, LIS_VECTOR y)
Fortran subroutine lis_vector_copy(LIS_VECTOR x, LIS_VECTOR y, integer ierr)
```

Description

Copy the values of the vector elements

Input

x	The source vector
---	-------------------

Output

y	The destination vector
ierr	The return code

6.1.14 lis_vector_set_all

```
C      int lis_vector_set_all(LIS_SCALAR value, LIS_VECTOR x)
Fortran subroutine lis_vector_set_all(LIS_SCALAR value, LIS_VECTOR x, integer ierr)
```

Description

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

Input

value	The scalar value to be assigned
v	The destination vector

Output

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          int lis_matrix_create(LIS_Comm comm, LIS_MATRIX *A)
Fortran subroutine lis_matrix_create(LIS_Comm comm, LIS_MATRIX A, 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          int lis_matrix_destroy(LIS_MATRIX A)
Fortran subroutine lis_matrix_destroy(LIS_MATRIX A, 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      int lis_matrix_duplicate(LIS_MATRIX Ain, LIS_MATRIX *Aout)
Fortran subroutine lis_matrix_duplicate(LIS_MATRIX Ain, LIS_MATRIX Aout,
      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      int lis_matrix_malloc(LIS_MATRIX A, int nnz_row, int nnz[])
Fortran subroutine lis_matrix_malloc(LIS_MATRIX A, integer nnz_row, integer nnz[],
      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      int lis_matrix_set_value(int flag, int i, int j, LIS_SCALAR value,  
                               LIS_MATRIX A)  
Fortran subroutine lis_matrix_set_value(integer flag, integer i, integer j,  
                                         LIS_SCALAR value, LIS_MATRIX A, 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, when `lis_matrix_set_value` is used, the function `lis_matrix_assemble` must be called.

6.2.6 lis_matrix_assemble

```
C      int lis_matrix_assemble(LIS_MATRIX A)  
Fortran subroutine lis_matrix_assemble(LIS_MATRIX A, 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

```
int lis_matrix_set_size(LIS_MATRIX A, int local_n, int global_n)
Fortran subroutine lis_matrix_set_size(LIS_MATRIX A, integer local_n,
integer global_n, 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      int lis_matrix_get_size(LIS_MATRIX A, int *local_n, int *global_n)
Fortran subroutine lis_matrix_get_size(LIS_MATRIX A, integer local_n,
integer global_n, 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      int lis_matrix_get_range(LIS_MATRIX A, int *is, int *ie)
Fortran subroutine lis_matrix_get_range(LIS_MATRIX A, integer is, integer ie,
      integer ierr)
```

Description

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

Input

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

Output

is	The location where the partial matrix A starts in the global matrix
ie	The next location where the partial matrix A ends in the global matrix
ierr	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      int lis_matrix_set_type(LIS_MATRIX A, int matrix_type)
Fortran subroutine lis_matrix_set_type(LIS_MATRIX A, int matrix_type, 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
Compressed Column Storage	(CCS)	LIS_MATRIX_CCS
Modified Compressed Sparse Row	(MSR)	LIS_MATRIX_MSR
Diagonal	(DIA)	LIS_MATRIX_DIA
Ellpack-Itpack Generalized Diagonal	(ELL)	LIS_MATRIX_ELL
Jagged Diagonal	(JDS)	LIS_MATRIX_JDS
Block Sparse Row	(BSR)	LIS_MATRIX_BSR
Block Sparse Column	(BSC)	LIS_MATRIX_BSC
Variable Block Row	(VBR)	LIS_MATRIX_VBR
Dense	(DNS)	LIS_MATRIX_DNS
Coordinate	(COO)	LIS_MATRIX_COO

6.2.11 lis_matrix_get_type

```
C      int lis_matrix_get_type(LIS_MATRIX A, int *matrix_type)
Fortran subroutine lis_matrix_get_type(LIS_MATRIX A, integer matrix_type,
      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      int lis_matrix_set_blocksize(LIS_MATRIX A, int bnr, int bnc, int row[],
                                   int col[])
Fortran subroutine lis_matrix_set_blocksize(LIS_MATRIX A, integer bnr, integer bnc,
                                           integer row[], integer col[], 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      int lis_matrix_convert(LIS_MATRIX Ain, LIS_MATRIX Aout)
Fortran subroutine lis_matrix_convert(LIS_MATRIX Ain, LIS_MATRIX Aout, 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      int lis_matrix_copy(LIS_MATRIX Ain, LIS_MATRIX Aout)
Fortran subroutine lis_matrix_copy(LIS_MATRIX Ain, LIS_MATRIX Aout, 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      int lis_matrix_get_diagonal(LIS_MATRIX A, LIS_VECTOR d)
Fortran subroutine lis_matrix_get_diagonal(LIS_MATRIX A, LIS_VECTOR d, 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      int lis_matrix_set_crs(int nnz, int ptr[], int index[], LIS_SCALAR value[],
                             LIS_MATRIX A)
Fortran subroutine lis_matrix_set_crs(integer nnz, integer row(), integer index(),
                                     LIS_SCALAR value(), LIS_MATRIX A, 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 used, the function `lis_matrix_assemble` must be called.

6.2.17 lis_matrix_set_ccs

```
C      int lis_matrix_set_ccs(int nnz, int ptr[], int index[], LIS_SCALAR value[],
                             LIS_MATRIX A)
Fortran subroutine lis_matrix_set_ccs(integer nnz, integer row(), integer index(),
                                     LIS_SCALAR value(), LIS_MATRIX A, 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 used, the function `lis_matrix_assemble` must be called.

6.2.18 lis_matrix_set_msr

```
C      int lis_matrix_set_msr(int nnz, int ndz, int index[], LIS_SCALAR value[],
                             LIS_MATRIX A)
Fortran subroutine lis_matrix_set_msr(integer nnz, integer ndz, integer index(),
                                     LIS_SCALAR value(), LIS_MATRIX A, 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 used, the function `lis_matrix_assemble` must be called.

6.2.19 lis_matrix_set_dia

```
C      int lis_matrix_set_dia(int nnd, int index[], LIS_SCALAR value[],
                             LIS_MATRIX A)
Fortran subroutine lis_matrix_set_dia(integer nnd, integer index(),
                                     LIS_SCALAR value(), LIS_MATRIX A, 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 used, the function `lis_matrix_assemble` must be called.

6.2.20 lis_matrix_set_ell

```
C      int lis_matrix_set_ell(int maxnzs, int index[], LIS_SCALAR value[],
                             LIS_MATRIX A)
Fortran subroutine lis_matrix_set_ell(integer maxnzs, integer index(),
                                     LIS_SCALAR value(), LIS_MATRIX A, 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 used, the function `lis_matrix_assemble` must be called.

6.2.21 lis_matrix_set_jds

```
C      int lis_matrix_set_jds(int nnz, int maxnzs, int perm[], int ptr[],
                             int index[], LIS_SCALAR value[], LIS_MATRIX A)
Fortran subroutine lis_matrix_set_jds(integer nnz, integer maxnzs, integer ptr(),
                                     integer index(), LIS_SCALAR value(), LIS_MATRIX A, 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 used, the function `lis_matrix_assemble` must be called.

6.2.22 lis_matrix_set_bsr

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

Description

Associate the arrays in the BSR format with the matrix A

Input

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

Output

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

Note

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

6.2.23 lis_matrix_set_bsc

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

Description

Associate the arrays in the BSC format with the matrix A

Input

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

Output

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

Note

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

6.2.24 lis_matrix_set_vbr

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

Description

Associate the arrays in the VBR format with the matrix A

Input

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

Output

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

Note

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

6.2.25 lis_matrix_set_coo

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

Description

Associate the arrays in the COO format with the matrix A

Input

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

Output

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

Note

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

6.2.26 lis_matrix_set_dns

```
C      int lis_matrix_set_dns(LIS_SCALAR value[], LIS_MATRIX A)
Fortran subroutine lis_matrix_set_dns(LIS_SCALAR value(), LIS_MATRIX A, 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 used, the function `lis_matrix_assemble` must be called.

6.3 Operating Vectors and Matrices

6.3.1 lis_vector_scale

```
C      int lis_vector_scale(LIS_SCALAR alpha, LIS_VECTOR x)
Fortran subroutine lis_vector_scale(LIS_SCALAR alpha, LIS_VECTOR x, integer ierr)
```

Description

Multiply the vector x by the scalar α

Input

alpha	The scalar value α
x	The vector to be multiplied

Output

x	The vector multiplied by α
ierr	The return code

6.3.2 lis_vector_dot

```
C      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,
                                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      int lis_vector_nrm1(LIS_VECTOR x, LIS_SCALAR *val)
Fortran subroutine lis_vector_nrm1(LIS_VECTOR x, LIS_SCALAR val, integer ierr)
```

Description

Calculate the 1-norm of 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      int lis_vector_nrm2(LIS_VECTOR x, LIS_SCALAR *val)
Fortran subroutine lis_vector_nrm2(LIS_VECTOR x, LIS_SCALAR val, 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      int lis_vector_nrmi(LIS_VECTOR x, LIS_SCALAR *val)
Fortran subroutine lis_vector_nrmi(LIS_VECTOR x, LIS_SCALAR val, 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      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,
                                   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      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,
                                   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      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, 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      int lis_matrix_scaling(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR d, int action)
Fortran subroutine lis_matrix_scaling(LIS_MATRIX A, LIS_VECTOR b,
                                  LIS_VECTOR d, integer action, integer ierr)
```

Description

Scale the matrix A

Input

A	The matrix
b	The vector
action	LIS_SCALE_JACOBI : Jacobi scaling $D^{-1}Ax = D^{-1}b$, where D represents the diagonal of $A = (a_{ij})$ LIS_SCALE_SYMM_DIAG : 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      void lis_matvec(LIS_MATRIX A, LIS_VECTOR x, LIS_VECTOR y)
Fortran subroutine lis_matvec(LIS_MATRIX A, LIS_VECTOR x, LIS_VECTOR y)
```

Description

Calculate the matrix vector product $y = Ax$

Input

A	The matrix
x	The vector

Output

y	Ax
---	------

6.3.11 lis_matvect

```
C      void lis_matvect(LIS_MATRIX A, LIS_VECTOR x, LIS_VECTOR y)
Fortran subroutine lis_matvect(LIS_MATRIX A, LIS_VECTOR x, LIS_VECTOR y)
```

Description

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

Input

A	The matrix
x	The vector

Output

y	$A^T x$
---	---------

6.4 Solving Linear Equations

6.4.1 lis_solver_create

```
C      int lis_solver_create(LIS_SOLVER *solver)
Fortran subroutine lis_solver_create(LIS_SOLVER solver, 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      int lis_solver_destroy(LIS_SOLVER solver)
Fortran subroutine lis_solver_destroy(LIS_SOLVER solver, integer ierr)
```

Description

Destroy the solver

Input

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

Output

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

6.4.3 lis_solver_set_option

```
C      int lis_solver_set_option(char *text, LIS_SOLVER solver)
Fortran subroutine lis_solver_set_option(character text, LIS_SOLVER solver,
      integer ierr)
```

Description

Set the options for the solver

Input

text The command line options

Output

solver The solver

ierr The return code

Note

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.

Specifying Linear Solvers (Default: **-i bicg**)

Method	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 ω ($0 < \omega < 2$)
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}		

Specifying Preconditioners (Default: `-p none`)

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

Precision (Default: `-f double`)

Precision	Option	Auxiliary Options
DOUBLE	<code>-f {double 0}</code>	
QUAD	<code>-f {quad 1}</code>	

6.4.4 lis_solver_set_optionC

```
C      int lis_solver_set_optionC(LIS_SOLVER solver)
Fortran subroutine lis_solver_set_optionC(LIS_SOLVER solver, 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      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, integer ierr)
```

Description

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

Input

A	The coefficient matrix
b	The right hand side vector
x	The initial vector
solver	The solver

Output

x	The solution
solver	The number of iterations, execution time, etc.
ierr	The return code (0)

6.4.6 lis_solve_kernel

```
C      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, integer ierr)
```

Description

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

Input

A	The coefficient matrix
b	The right hand side vector
x	The initial vector
solver	The solver
precon	The preconditioner

Output

x	The solution
solver	The number of the iterations, the execution time, etc.
ierr	The return code (0)

6.4.7 lis_solver_get_status

```
C      int lis_solver_get_status(LIS_SOLVER solver, int *status)
Fortran subroutine lis_solver_get_status(LIS_SOLVER solver, integer status,
                                         integer ierr)
```

Description

Get the status from the solver

Input

solver	The solver
--------	------------

Output

status	The number of iterations
ierr	The return code

6.4.8 lis_solver_get_iters

```
C      int lis_solver_get_iters(LIS_SOLVER solver, int *iters)
Fortran subroutine lis_solver_get_iters(LIS_SOLVER solver, integer iters,
                                         integer ierr)
```

Description

Get the number of iterations from the solver

Input

solver	The solver
--------	------------

Output

iters	The number of iterations
ierr	The return code

6.4.9 lis_solver_get_itersex

```
C      int lis_solver_get_itersex(LIS_SOLVER solver, int *iters, int *iters_double,  
                                int *iters_quad)  
Fortran subroutine lis_solver_get_itersex(LIS_SOLVER solver, integer iters,  
                                integer iters_double, integer iters_quad, 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      int lis_solver_get_time(LIS_SOLVER solver, double *times)  
Fortran subroutine lis_solver_get_time(LIS_SOLVER solver, real*8 times,  
                                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

6.4.11 lis_solver_get_timeex

```
C      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,
      integer ierr)
```

Description

Get the execution time from the solver

Input

solver	The solver
--------	------------

Output

<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

6.4.12 lis_solver_get_residualnorm

```
C      int lis_solver_get_residualnorm(LIS_SOLVER solver, LIS_REAL *residual)
Fortran subroutine lis_solver_get_residualnorm(LIS_SOLVER solver, LIS_REAL residual,
      integer ierr)
```

Description

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

Input

solver	The solver
--------	------------

Output

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

6.4.13 lis_solver_get_rhistory

```
C      int lis_solver_get_rhistory(VECTOR v)
Fortran subroutine lis_solver_get_rhistory(LIS_VECTOR v, 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      int lis_solver_get_solver(LIS_SOLVER solver, int *nsol)
Fortran subroutine lis_solver_get_solver(LIS_SOLVER solver, integer nsol,
      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_get_solvername

```
C      int lis_get_solvername(int nsol, char *name)
Fortran subroutine lis_get_solvername(integer nsol, character name, 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

6.5 Solving Eigenvalue Problems

6.5.1 lis_esolver_create

```
C      int lis_esolver_create(LIS_ESOLVER *esolver)
Fortran subroutine lis_esolver_create(LIS_ESOLVER esolver, 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      int lis_esolver_destroy(LIS_ESOLVER esolver)
Fortran subroutine lis_esolver_destroy(LIS_ESOLVER esolver, 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      int lis_esolver_set_option(char *text, LIS_ESOLVER esolver)
Fortran subroutine lis_esolver_set_option(character text, LIS_ESOLVER esolver,
      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.

Specifying Eigensolvers (Default: **-e pi**)

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

Specifying 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 ω ($0 < \omega < 2$)
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 ω 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 α 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	
-emaxiter [1000]	The maximum number of the iterations
-etol [1.0e-12]	The convergence criterion
-eprint [0]	The display of the residual
	-eprint {none 0} None
	-eprint {mem 1} Saves the residual history
	-eprint {out 2} Displays the residual history
	-eprint {all 3} Saves the residual history and displays it on the screen
-ie [ii]	The inner eigensolver used in the Lanczos iteration and the subspace iteration
	-ie {pi 1} The power iteration (Subspace Iteration only)
	-ie {ii 2} The inverse iteration
	-ie {aii 3} The approximate inverse iteration
	-ie {rqi 4} The Rayleigh quotient iteration
-shift [0.0]	The amount of the shift
-initx_ones [true]	The behavior of the initial vector x_0
	-initx_ones {false 0} Given values
	-initx_ones {true 1} All values are set to 1
-omp_num_threads [t]	The number of the threads (t represents the maximum number of the threads)
-estorage [0]	The matrix storage format
-estorage_block [2]	The block size of the BSR and BSC

Precision (Default: <code>-ef double</code>)		
Precision	Option	Auxiliary Options
DOUBLE	<code>-ef {double 0}</code>	
QUAD	<code>-ef {quad 1}</code>	

6.5.4 lis_esolver_set_optionC

```
C      int lis_esolver_set_optionC(LIS_ESOLVER esolver)
Fortran subroutine lis_esolver_set_optionC(LIS_ESOLVER esolver, integer ierr)
```

Description

Set the options for the eigensolver on the command line

Input

None

Output

esolver	The eigensolver
ierr	The return code

6.5.5 lis_solve

```
C      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, integer ierr)
```

Description

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

Input

A	The matrix
x	The initial vector
esolver	The eigensolver

Output

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

6.5.6 lis_esolver_get_status

```
C      int lis_esolver_get_status(LIS_ESOLVER esolver, int *status)
Fortran subroutine lis_esolver_get_status(LIS_ESOLVER esolver, integer status,
      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      int lis_esolver_get_iters(LIS_ESOLVER esolver, int *iters)
Fortran subroutine lis_esolver_get_iters(LIS_ESOLVER esolver, integer iters,
      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      int lis_esolver_get_itersex(LIS_ESOLVER esolver, int *iters,  
                                int *iters_double, int *iters_quad)  
Fortran subroutine lis_esolver_get_itersex(LIS_ESOLVER esolver, integer iters,  
                                integer iters_double, integer iters_quad, 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      int lis_esolver_get_time(LIS_ESOLVER esolver, double *times)  
Fortran subroutine lis_esolver_get_time(LIS_ESOLVER esolver, real*8 times,  
                                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      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,
                                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      int lis_esolver_get_residualnorm(LIS_ESOLVER esolver, LIS_REAL *residual)
Fortran subroutine lis_esolver_get_residualnorm(LIS_ESOLVER esolver,
                                LIS_REAL residual, 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      int lis_esolver_get_rhistory(VECTOR v)
Fortran subroutine lis_esolver_get_rhistory(LIS_VECTOR v, 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      int lis_esolver_get_evalues(LIS_ESOLVER esolver, LIS_VECTOR v)
Fortran subroutine lis_esolver_get_evalues(LIS_ESOLVER esolver,
      LIS_VECTOR v, 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_evectors

```
C      int lis_esolver_get_evectors(LIS_ESOLVER esolver, LIS_MATRIX A)
Fortran subroutine lis_esolver_get_evectors(LIS_ESOLVER esolver,
      LIS_MATRIX A, 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      int lis_esolver_get_esolver(LIS_ESOLVER esolver, int *nesol)
Fortran subroutine lis_esolver_get_esolver(LIS_ESOLVER esolver, integer nesol,
      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:

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

6.5.16 lis_get_esolvername

```
C      int lis_get_esolvername(int nesol, char *ename)
Fortran subroutine lis_get_esolvername(integer nesol, character ename, 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      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, 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      int lis_input_vector(LIS_VECTOR v, char *filename)
Fortran subroutine lis_input_vector(LIS_VECTOR v, character filename, 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      int lis_input_matrix(LIS_MATRIX A, char *filename)
Fortran subroutine lis_input_matrix(LIS_MATRIX A, LIS_VECTOR x,
      character filename, integer ierr)
```

Description

Read the matrix data from the external file

Input

filename	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      int lis_output(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR x, int format,
      char *filename)
Fortran subroutine lis_output(LIS_MATRIX A, LIS_VECTOR b, LIS_VECTOR x,
      integer format, character path, integer ierr)
```

Description

Write the matrix and vector data into the external file

Input

A	The Matrix
b	The right hand side vector (If no vector is written to the external file, then NULL must be input.)
x	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      int lis_output_vector(LIS_VECTOR v, int format, char *filename)
Fortran subroutine lis_output_vector(LIS_VECTOR v, integer format,
      character filename, 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      int lis_output_matrix(LIS_MATRIX A, int format, char *filename)
Fortran subroutine lis_output_matrix(LIS_MATRIX A, integer format, character path,
      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      int lis_initialize(int* argc, char** argv[])
Fortran subroutine lis_initialize(integer ierr)
```

Description

Initialize the execution environment

Input

<code>argc</code>	The number of the command line arguments
<code>argv</code>	The command line argument

Output

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

6.7.2 lis_finalize

```
C      void lis_finalize()
Fortran subroutine lis_finalize(integer ierr)
```

Description

Finalize the execution environment

Input

None

Output

<code>ierr</code>	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.

References

- [1] S. Fujino, M. Fujiwara and M. Yoshida. BiCGSafe method based on minimization of associate residual (in Japanese). Transactions of JSCES, Paper No.20050028, 2005. <http://save.k.u-tokyo.ac.jp/jscs/trans/trans2005/No20050028.pdf>.
- [2] T. Sogabe, M. Sugihara and S. Zhang. An Extension of the Conjugate Residual Method for Solving Nonsymmetric Linear Systems(in Japanese). Transactions of the Japan Society for Industrial and Applied Mathematics, Vol. 15, No. 3, pp. 445–460, 2005.
- [3] K. Abe, T. Sogabe, S. Fujino and S. Zhang. A Product-type Krylov Subspace Method Based on Conjugate Residual Method for Nonsymmetric Coefficient Matrices (in Japanese). IPSJ Transactions on Advanced Computing Systems, Vol. 48, No. SIG8(ACS18), pp. 11–21, 2007.
- [4] S. Fujino and Y. Onoue. Estimation of BiCRSafe method based on residual of BiCR method (in Japanese). IPSJ SIG Technical Report, 2007-HPC-111, pp. 25–30, 2007.
- [5] Y. Saad. A Flexible Inner-outer Preconditioned GMRES Algorithm. SIAM J. Sci. Stat. Comput., Vol. 14, pp. 461–469, 1993.
- [6] Y. Saad. ILUT: a dual threshold incomplete LU factorization. Numerical linear algebra with applications, Vol. 1, No. 4, pp. 387–402, 1994.
- [7] ITSOL: ITERATIVE SOLVERS package
<http://www-users.cs.umn.edu/~saad/software/ITSOL/index.html>.
- [8] N. Li, Y. Saad and E. Chow. Crout version of ILU for general sparse matrices. SIAM J. Sci. Comput., Vol. 25, pp. 716–728, 2003.
- [9] T. Kohno, H. Kotakemori and H. Niki. Improving the Modified Gauss-Seidel Method for Z-matrices. Linear Algebra and its Applications, Vol. 267, pp. 113–123, 1997.
- [10] A. Fujii, A. Nishida, and Y. Oyanagi. Evaluation of Parallel Aggregate Creation Orders : Smoothed Aggregation Algebraic Multigrid Method. High Performance Computational Science And Engineering, pp. 99–122, Springer, 2005.
- [11] K. Abe, S. Zhang, H. Hasegawa and R. Himeno. A SOR-base Variable Preconditioned CGR Method (in Japanese). Trans. JSIAM, Vol. 11, No. 4, pp. 157–170, 2001.
- [12] R. Bridson and W.-P. Tang. Refining an approximate inverse. J. Comput. Appl. Math., Vol. 123, pp. 293–306, 2000.
- [13] P. Sonnerfeld and M. B. van Gijzen. IDR(s): a family of simple and fast algorithms for solving large nonsymmetric systems of linear equations. SIAM J. Sci. Comput., Vol. 31, Issue 2, pp. 1035–1062, 2008.
- [14] A. Greenbaum. Iterative Methods for Solving Linear Systems. SIAM, 1997.
- [15] D. H. Bailey. A fortran-90 double-double library. <http://www.nersc.gov/~dhbailey/mpdist/mpdist.html>.
- [16] Y. Hida, X. S. Li and D. H. Bailey. Algorithms for quad-double precision floating point arithmetic. Proceedings of the 15th Symposium on Computer Arithmetic, pp.155–162, 2001.
- [17] T. Dekker. A floating-point technique for extending the available precision. Numerische Mathematik, vol.18 pp. 224–242, 1971.
- [18] A. V. Knyazev. Toward the Optimal Preconditioned Eigensolver: Locally Optimal Block Preconditioned Conjugate Gradient Method. SIAM J. Sci. Comput., Vol. 23, No. 2, pp. 517–541, 2001.

- [19] A. Nishida. Experience in Developing an Open Source Scalable Software Infrastructure in Japan. Lecture Notes in Computer Science 6017, Springer, pp. 87-98, 2010.
- [20] E. Suetomi and H. Sekimoto. Conjugate gradient like methods and their application to eigenvalue problems for neutron diffusion equation. Annals of Nuclear Energy, Vol. 18, No. 4, pp. 205–227, 1991.
- [21] D. E. Knuth. The Art of Computer Programming: Seminumerical Algorithms, vol.2. Addison-Wesley, 1969.
- [22] D. H. Bailey. High-Precision Floating-Point Arithmetic in Scientific Computation. Computing in Science and Engineering, Volume 7, Issue 3, pp. 54–61, IEEE, 2005.
- [23] Intel Fortran Compiler User’s Guide Vol I.
- [24] H. Kotakemori, A. Fujii, H. Hasegawa and A. Nishida. Implementation of Fast Quad Precision Operation and Acceleration with SSE2 for Iterative Solver Library (in Japanese). IPSJ Transactions on Advanced Computing Systems, Vol. 1, No. 1, pp. 73–84, 2008.
- [25] R. Barrett, et al. Templates for the Solution of Linear Systems: Building Blocks for Iterative Methods. SIAM, 1994.
- [26] Z. Bai, et al. Templates for the Solution of Algebraic Eigenvalue Problems. SIAM, 2000.
- [27] Y. Saad. SPARSKIT: a basic tool kit for sparse matrix computations, version 2, June 1994. <http://www.cs.umn.edu/~saad/software/SPARSKIT/sparskit.html>.
- [28] S. Balay, et al. PETSc users manual. Technical Report ANL-95/11, Argonne National Laboratory, August 2004.
- [29] R. S. Tuminaro, et al. Official Aztec user’s guide, version 2.1. Technical Report SAND99-8801J, Sandia National Laboratories, November 1999.
- [30] R. B. Lehoucq, D. C. Sorensen, and C. Yang. ARPACK Users’ Guide: Solution of Large-scale Eigenvalue Problems with implicitly-restarted Arnoldi Methods. SIAM, 1998.
- [31] R. Bramley and X. Wang. SPLIB: A library of iterative methods for sparse linear system. Technical report, Indiana University–Bloomington, 1995.
- [32] Matrix Market. <http://math.nist.gov/MatrixMarket>.

A File Formats

This section describes the file formats available for the library.

A.1 Extended Matrix Market Format

The Matrix Market format[32] does not support vector data. For this library, it has been extended to handle vector data. Assume that the number of the nonzero elements for 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
2.0000000000000000E+00  1.0000000000000000E+00  1.0000000000000000E+00
2.0000000000000000E+00  1.0000000000000000E+00  1.0000000000000000E+00
2.0000000000000000E+00  1.0000000000000000E+00  1.0000000000000000E+00
2.0000000000000000E+00
0.0000000000000000E+00  1.0000000000000000E+00  2.0000000000000000E+00
3.0000000000000000E+00

```

A.3 Extended Matrix Market Format for Vectors

The Matrix Market format[32] has been extended to store 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
% <--+
% | Comment lines with 0 or more lines
% <--+
N <-- Number of rows
I1 B(I1) <--+
I2 B(I2) | Row number value
. . . | The index is one origin
IN B(IN) <--+
```

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) | Vector value
. . . |
B(N) <--+
```

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
```