PRIMME

large-scale eigenvalue and singular value solver

Documentation

Release 2.0

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CHAPTER

ONE

PRIMME: PRECONDITIONED ITERATIVE MULTIMETHOD EIGENSOLVER

PRIMME, pronounced as *prime*, finds a number of eigenvalues and their corresponding eigenvectors of a real symmetric, or Hermitian matrix. Also singular values and vectors can be computed. Largest, smallest and interior eigenvalues and singular values are supported. Preconditioning can be used to accelerate convergence. PRIMME is written in C99, but complete interfaces are provided for Fortran 77, MATLAB and Python.

1.1 Incompatibilities

From PRIMME 1.x to 2.0:

- Prototype of callbacks has changed: *matrixMatvec*, *applyPreconditioner*, *massMatrixMatvec* and *globalSumReal*.
- The next parameters are *PRIMME_INT*: *n*, *nLocal*, *maxMatvecs*, *iseed*, *numOuterIterations*, *numRestarts*, *numMatvecs* and *numMatvecs*; use the macro `PRIMME_INT_P` to print the values.
- Rename the values of the enum *primme_preset_method*.
- Rename `primme_Free` to *primme_free()*.
- Integer parameters in Fortran functions are of the same size as *PRIMME_INT*, which is `integer*8` by default.
- Extra parameter in many Fortran functions to return the error code.
- Removed `primme_display_stats_f77`.

1.2 Changelog

Changes in PRIMME 2.0 (released on September 19, 2016):

- Changed license to BSD 3-clause.
- New support for singular value problems; see *dprimme_svds()*.
- New support for `float` and `complex float` arithmetic.
- Support for problem dimensions larger than 2^31, without requiring BLAS and LAPACK compiled with 64-bits integers.
- Improve robustness and performance for interior problems; implemented advanced refined and harmonic-Ritz extractions.
- Python interface compatible with NumPy and SciPy Library.

- Added parameter to indicate the leading dimension of the input/output matrices and to return an error code in callbacks *matrixMatvec*, *applyPreconditioner*, *massMatrixMatvec* and *globalSumReal*.
- Changed to type *PRIMME_INT* the options *n*, *nLocal*, *maxMatvecs* and *iseed*, and the stats counters *numOuterIterations*, *numRestarts*, *numMatvecs*, *numPreconds*. Also changed *realWorkSize* to `size_t`. Fortran interface functions will expect an `interger` of size compatible with *PRIMME_INT* for all parameters with integer type: `int`, *PRIMME_INT* and `size_t`; see also parameter `value` in functions `primmetop_set_member_f77()`, *primmetop_get_member_f77()*, *primme_set_member_f77()* and *primme_get_member_f77()*.
- Added parameter to return an error code in Fortran interface functions: `primmetop_set_member_f77()`, *primmetop_get_member_f77()*, *primme_set_member_f77()* and *primme_get_member_f77()*.
- Added leading dimension for `evecs` *ldevecs* and preferred leading dimension for the operators *ldOPs*, such as *matrixMatvec*.
- Optional user-defined convergence function, *convTestFun*.
- Prefixed methods with `PRIMME_`. Rename Fortran constants from `PRIMMEF77_` to `PRIMME_`.
- Removed `primme_display_stats_f77`.

Changes in PRIMME 1.2.2 (released on October 13, 2015):

- Fixed wrong symbols in `libdprimme.a` and `libzprimme.a`.
- *primme_set_method()* sets *PRIMME_JDQMR* instead of *PRIMME_JDQMR_ETol* for preset methods *PRIMME_DEFAULT_MIN_TIME* and *PRIMME_DYNAMIC* when seeking interior values.
- Fixed compilation of driver with a PETSc installation without HYPRE.
- Included the content of the environment variable `INCLUDE` for compiling the driver.

Changes in PRIMME 1.2.1 (released on September 7, 2015):

- Added MATLAB interface to full PRIMME functionality.
- Support for BLAS/LAPACK with 64bits integers (`-DPRIMME_BLASINT_SIZE=64`).
- Simplified configuration of Make_flags and Make_links (removed `TOP` variable and replaced defines `NUM_SUM` and `NUM_IBM` by `F77UNDERSCORE`).
- Replaced directories `DTEST` and `ZTEST` by `TEST`, that has:
  - `driver.c`: read matrices in MatrixMarket format and PETSc binary and call PRIMME with the parameters specified in a file; support complex arithmetic and MPI and can use PETSc preconditioners.
  - `ex*.c` and `ex*.f`: small, didactic examples of usage in C and Fortran and in parallel (with PETSc).
- Fixed a few minor bugs and improved documentation (especially the F77 interface).
- Using Sphinx to manage documentation.

Changes in PRIMME 1.2 (released on December 21, 2014):

- A Fortran compiler is no longer required for building the PRIMME library. Fortran programs can still be linked to PRIMME's F77 interface.
- Fixed some uncommon issues with the F77 interface.
- PRIMME can be called now multiple times from the same program.
- Performance improvements in the QMR inner solver, especially for complex arithmetic.
- Fixed a couple of bugs with the locking functionality.

  - In certain extreme cases where all eigenvalues of a matrix were needed.
  - The order of selecting interior eigenvalues.

  The above fixes have improved robustness and performance.
- PRIMME now assigns unique random seeds per parallel process for up to 4096^3 (140 trillion) processes.
- For the *PRIMME_DYNAMIC* method, fixed issues with initialization and synchronization decisions across multiple processes.
- Fixed uncommon library interface bugs, coordinated better setting the method and the user setting of parameters, and improved the interface in the sample programs and makefiles.
- Other performance and documentation improvements.

1.3 License Information

PRIMME is licensed under the 3-clause license BSD. Python and Matlab interfaces have BSD-compatible licenses. Source code under file:*tests* is compatible with LGPLv3. Details can be taken from COPYING.txt.

1.4 Citing the code

Please cite *[r1]* and *[r6]*.

More information on the algorithms and research that led to this software can be found in the rest of the papers *[r2]*, *[r3]*, *[r4]*, *[r5]*, *[r7]*. The work has been supported by a number of grants from the National Science Foundation.

1.5 Contact Information

For reporting bugs or questions about functionality contact Andreas Stathopoulos by email, *andreas* at *cs.wm.edu*. See further information in the webpage http://www.cs.wm.edu/~andreas/software and on github.

1.6 Directory Structure

The next directories and files should be available:

- `COPYING.txt`, license;
- `Make_flags`, flags to be used by makefiles to compile library and tests;
- `Link_flags`, flags needed in making and linking the test programs;
- `include/`, directory with headers files;
- `src/`, directory with the source code for `libprimme`:
  - `include/`, common headers;
  - `eigs/`, eigenvalue interface and implementation;
  - `svds/`, singular value interface and implementation;
  - `tools/`, tools used to generated some headers;
- `Matlab/`, Matlab interface;

- PYTHON/, Python interface;
- examples/, sample programs in C, C++ and F77, both sequential and parallel;
- tests/, drivers for testing purpose and test cases;
- lib/libprimme.a, the PRIMME library (to be made);
- makefile main make file;
- readme.txt text version of the documentation;
- doc/ directory with the HTML and PDF versions of the documentation.

1.7 Making and Linking

Make_flags has the flags and compilers used to make libprimme.a:

- *CC*, compiler program such as gcc, clang or icc.
- ***CFLAGS*, compiler options such as -g or -O3 and macro definitions** like the ones described next.

Compiler flags for the BLAS and LAPACK libraries:

- -DF77UNDERSCORE, if Fortran appends an underscore to function names (usually it does).
- -DPRIMME_BLASINT_SIZE=64, if the library integers are 64-bit integer (kind=8) type, aka ILP64 interface; usually integers are 32-bits even in 64-bit architectures (aka LP64 interface).

By default PRIMME sets the integer type for matrix dimensions and counters (*PRIMME_INT*) to 64 bits integer int64_t. This can be changed by setting the macro PRIMME_INT_SIZE to one of the following values:

- 0: use the regular int of your compiler.
- 32: use C99 int32_t.
- 64: use C99 int64_t.

Note: When -DPRIMME_BLASINT_SIZE=64 is set the code uses the type int64_t supported by the C99 standard. In case the compiler doesn't honor the standard, you can set the corresponding type name supported, for instance -DPRIMME_BLASINT_SIZE=__int64.

After customizing Make_flags, type this to generate libprimme.a:

```
make lib
```

Making can be also done at the command line:

```
make lib CC=clang CFLAGS='-O3'
```

Link_flags has the flags for linking with external libraries and making the executables located in examples and tests:

- *LDFLAGS*, linker flags such as -framework Accelerate.
- *LIBS*, flags to link with libraries (BLAS and LAPACK are required), such as -lprimme -llapack -lblas -lgfortran -lm.

After that, type this to compile and execute a simple test:

```
$ make test
...
Test passed!
...
Test passed!
```

In case of linking problems check flags in *LDFLAGS* and *LIBS* and consider to add/remove `-DF77UNDERSCORE` from *CFLAGS*. If the execution fails consider to add/remove `-DPRIMME_BLASINT_SIZE=64` from *CFLAGS*.

Full description of actions that *make* can take:

- *make lib*, builds the static library `libprimme.a`.
- *make solib*, builds the shared library `libprimme.so`.
- *make test*, build and execute simple examples.
- *make clean*, removes all `*.o`, `a.out`, and core files from `src`.

1.7.1 Considerations using an IDE

PRIMME can be built in other environments such as Anjuta, Eclipse, KDevelop, Qt Creator, Visual Studio and XCode. To build the PRIMME library do the following:

1. Create a new project and include the source files under the directory `src`.
2. Add the directories `include` and `src/include` as include directories.

To build an example code using PRIMME make sure:

- to add a reference for PRIMME, BLAS and LAPACK libraries;
- to add the directory `include` as an include directory.

1.8 Tested Systems

PRIMME is primary developed with GNU gcc, g++ and gfortran (versions 4.8 and later). Many users have reported builds on several other platforms/compilers:

- SUSE 13.1 & 13.2
- CentOS 6.6
- Ubuntu 14.04
- MacOS X 10.9 & 10.10
- Cygwin & MinGW
- Cray XC30
- SunOS 5.9, quad processor Sun-Fire-280R, and several other UltraSparcs
- AIX 5.2 IBM SP POWER 3+, 16-way SMP, 375 MHz nodes (seaborg at nersc.gov)

1.9 Main Contributors

- James R. McCombs

- Eloy Romero Alcalde
- Andreas Stathopoulos
- Lingfei Wu

CHAPTER

TWO

EIGENVALUE PROBLEMS

2.1 C Library Interface

The PRIMME interface is composed of the following functions. To solve real symmetric and Hermitian standard eigenproblems call respectively:

```
int  sprimme (float *evals, float *evecs, float *resNorms,
                        primme_params *primme)
int  cprimme (float *evals, PRIMME_COMPLEX_FLOAT *evecs,
                   float *resNorms, primme_params *primme)
int  dprimme (double *evals, double *evecs, double *resNorms,
                        primme_params *primme)
int  zprimme (double *evals, PRIMME_COMPLEX_DOUBLE *evecs,
                   double *resNorms, primme_params *primme)
```

Other useful functions:

```
void  primme_initialize (primme_params *primme)
int  primme_set_method (primme_preset_method method,
                                                    primme_params *params)
void  primme_display_params (primme_params primme)
void  primme_free
 (primme_params *primme)
```

PRIMME stores its data on the structure *primme_params*. See Parameters Guide for an introduction about its fields.

2.1.1 Running

To use PRIMME, follow these basic steps.

1. Include:

   ```
   #include "primme.h"   /* header file is required to run primme */
   ```

2. Initialize a PRIMME parameters structure for default settings:

   ```
   primme_params primme;
   primme_initialize (&primme);
   ```

3. Set problem parameters (see also Parameters Guide), and, optionally, set one of the *preset methods*:

   ```
   primme. matrixMatvec = LaplacianMatrixMatvec; /* MV product */
   primme. n = 100;                    /* set problem dimension */
   primme. numEvals = 10;       /* Number of wanted eigenpairs */
   ```

```
ret =  primme_set_method (method, &primme);
...
```

4. Then to solve real symmetric standard eigenproblems call:

   ```
   ret =  dprimme (evals, evecs, resNorms, &primme);
   ```

   The previous is the double precision call. There is available calls for complex double, single and complex single; check it out *zprimme()*, *sprimme()* and *cprimme()*.

   The call arguments are:

   - *evals*, array to return the found eigenvalues;
   - *evecs*, array to return the found eigenvectors;
   - *resNorms*, array to return the residual norms of the found eigenpairs; and
   - *ret*, returned error code.

5. To free the work arrays in PRIMME:

   ```
   primme_free
   (&primme);
   ```

2.1.2 Parameters Guide

PRIMME stores the data on the structure *primme_params*, which has the next fields:

Basic
`PRIMME_INT` *n*, matrix dimension.
`void (*` *matrixMatvec* `)(...)`, matrix-vector product.
`int` *numEvals*, how many eigenpairs to find.
`primme_target` *target*, which eigenvalues to find.
`int` *numTargetShifts*, for targeting interior eigenpairs.
`double *` *targetShifts*
`double` *eps*, tolerance of the residual norm of converged eigenpairs.

For parallel programs
`int` *numProcs*, number of processes
`int` *procID*, rank of this process
`PRIMME_INT` *nLocal*, number of rows stored in this process
`void (*` *globalSumReal* `)(...)`, sum reduction among processes

Accelerate the convergence
`void (*` *applyPreconditioner* `)(...)`, preconditioner-vector product.
`int` *initSize*, initial vectors as approximate solutions.
`int` *maxBasisSize*
`int` *minRestartSize*
`int` *maxBlockSize*

User data
`void *` *commInfo*

void * *matrix*
void * *preconditioner*

Advanced options
PRIMME_INT *ldevecs*, leading dimension of the evecs.
int *numOrthoConst*, orthogonal constrains to the eigenvectors.
int *dynamicMethodSwitch*
int *locking*
PRIMME_INT *maxMatvecs*
PRIMME_INT *maxOuterIterations*
int *intWorkSize*
size_t *realWorkSize*
PRIMME_INT *iseed* [4]
int * *intWork*
void * *realWork*
double *aNorm*
int *printLevel*
FILE * *outputFile*
double * *ShiftsForPreconditioner*
primme_init *initBasisMode*
struct projection_params *projectionParams*
struct restarting_params *restartingParams*
struct correction_params *correctionParams*
struct primme_stats *stats*
void (* *convTestFun*)(...)
PRIMME_INT *ldOPs*, leading dimension to use in *matrixMatvec*...

PRIMME requires the user to set at least the dimension of the matrix (*n*) and the matrix-vector product (*matrixMatvec*), as they define the problem to be solved. For parallel programs, *nLocal*, *procID* and *globalSumReal* are also required.

In addition, most users would want to specify how many eigenpairs to find, and provide a preconditioner (if available).

It is useful to have set all these before calling *primme_set_method()*. Also, if users have a preference on *maxBasisSize*, *maxBlockSize*, etc, they should also provide them into *primme_params* prior to the *primme_set_method()* call. This helps *primme_set_method()* make the right choice on other parameters. It is sometimes useful to check the actual parameters that PRIMME is going to use (before calling it) or used (on return) by printing them with *primme_display_params()*.

2.1.3 Interface Description

The next enumerations and functions are declared in `primme.h`.

sprimme

int **sprimme**(float **evals*, float **evecs*, float **resNorms*, *primme_params* **primme*)
Solve a real symmetric standard eigenproblem.

Parameters

- **evals** – array at least of size *numEvals* to store the computed eigenvalues; all processes in a parallel run return this local array with the same values.
- **resNorms** – array at least of size *numEvals* to store the residual norms of the computed eigenpairs; all processes in parallel run return this local array with the same values.
- **evecs** – array at least of size *nLocal* times *numEvals* to store columnwise the (local part of the) computed eigenvectors.
- **primme** – parameters structure.

Returns error indicator; see Error Codes.

dprimme

int **dprimme**(double **evals*, double **evecs*, double **resNorms*, *primme_params* **primme*)

Solve a real symmetric standard eigenproblem.

Parameters

- **evals** – array at least of size *numEvals* to store the computed eigenvalues; all processes in a parallel run return this local array with the same values.
- **resNorms** – array at least of size *numEvals* to store the residual norms of the computed eigenpairs; all processes in parallel run return this local array with the same values.
- **evecs** – array at least of size *nLocal* times *numEvals* to store columnwise the (local part of the) computed eigenvectors.
- **primme** – parameters structure.

Returns error indicator; see Error Codes.

cprimme

int **cprimme**(float **evals*, *PRIMME_COMPLEX_FLOAT* **evecs*, float **resNorms*, *primme_params* **primme*)

Solve a Hermitian standard eigenproblem; see function *sprimme()*.

zprimme

int **zprimme**(double **evals*, *PRIMME_COMPLEX_DOUBLE* **evecs*, double **resNorms*, *primme_params* **primme*)

Solve a Hermitian standard eigenproblem; see function *dprimme()*.

primme_initialize

void **primme_initialize**(*primme_params* **primme*)

Set PRIMME parameters structure to the default values.

Parameters

- **primme** – parameters structure.

primme_set_method

int **primme_set_method**(*primme_preset_method method*, *primme_params *primme*)

Set PRIMME parameters to one of the preset configurations.

Parameters

- **method** – preset configuration; one of

  PRIMME_DYNAMIC
  PRIMME_DEFAULT_MIN_TIME
  PRIMME_DEFAULT_MIN_MATVECS
  PRIMME_Arnoldi
  PRIMME_GD
  PRIMME_GD_plusK
  PRIMME_GD_Olsen_plusK
  PRIMME_JD_Olsen_plusK
  PRIMME_RQI
  PRIMME_JDQR
  PRIMME_JDQMR
  PRIMME_JDQMR_ETol
  PRIMME_SUBSPACE_ITERATION
  PRIMME_LOBPCG_OrthoBasis
  PRIMME_LOBPCG_OrthoBasis_Window

- **primme** – parameters structure.

See also Preset Methods.

primme_display_params

void **primme_display_params**(*primme_params primme*)

Display all printable settings of `primme` into the file descriptor *outputFile*.

Parameters

- **primme** – parameters structure.

primme_free

void **primme_free**(*primme_params *primme*)

Free memory allocated by PRIMME.

Parameters

- **primme** – parameters structure.

2.2 FORTRAN Library Interface

The next enumerations and functions are declared in `primme_f77.h`.

ptr
Fortran datatype with the same size as a pointer. Use `integer*4` when compiling in 32 bits and `integer*8` in 64 bits.

2.2.1 primme_initialize_f77

primme_initialize_f77 (primme)
Set PRIMME parameters structure to the default values.

Parameters

- **primme** (*ptr*) – (output) parameters structure.

2.2.2 primme_set_method_f77

primme_set_method_f77 (method, primme, ierr)
Set PRIMME parameters to one of the preset configurations.

Parameters

- **method** (*integer*) – (input) preset configuration. One of:

```
PRIMME_DYNAMIC
PRIMME_DEFAULT_MIN_TIME
PRIMME_DEFAULT_MIN_MATVECS
PRIMME_Arnoldi
PRIMME_GD
PRIMME_GD_plusK
PRIMME_GD_Olsen_plusK
PRIMME_JD_Olsen_plusK
PRIMME_RQI
PRIMME_JDQR
PRIMME_JDQMR
PRIMME_JDQMR_ETol
PRIMME_SUBSPACE_ITERATION
PRIMME_LOBPCG_OrthoBasis
PRIMME_LOBPCG_OrthoBasis_Window
```

  See *primme_preset_method*.

- **primme** (*ptr*) – (input) parameters structure.
- **ierr** (*integer*) – (output) if 0, successful; if negative, something went wrong.

2.2.3 primme_free_f77

primme_free_f77 (primme)
Free memory allocated by PRIMME and delete all values set.

Parameters

- **primme** (*ptr*) – (input/output) parameters structure.

2.2.4 sprimme_f77

sprimme_f77 (evals, evecs, resNorms, primme, ierr)
Solve a real symmetric standard eigenproblem using single precision.

Parameters

- **evals(*)** (*real*) – (output) array at least of size *numEvals* to store the computed eigenvalues; all parallel calls return the same value in this array.
- **resNorms(*)** (*real*) – (output) array at least of size *numEvals* to store the residual norms of the computed eigenpairs; all parallel calls return the same value in this array.
- **evecs(*)** (*real*) – (input/output) array at least of size *nLocal* times *numEvals* to store columnwise the (local part of the) computed eigenvectors.
- **primme** (*ptr*) – parameters structure.
- **ierr** (*integer*) – (output) error indicator; see Error Codes.

2.2.5 cprimme_f77

cprimme_f77 (evals, evecs, resNorms, primme, ierr)
Solve a Hermitian standard eigenproblem. The arguments have the same meaning as in function *sprimme_f77()*.

Parameters

- **evals(*)** (*real*) – (output)
- **resNorms(*)** (*real*) – (output)
- **evecs(*)** (*complex real*) – (input/output)
- **primme** (*ptr*) – (input) parameters structure.
- **ierr** (*integer*) – (output) error indicator; see Error Codes.

2.2.6 dprimme_f77

dprimme_f77 (evals, evecs, resNorms, primme, ierr)
Solve a real symmetric standard eigenproblem using double precision.

Parameters

- **evals(*)** (*double precision*) – (output) array at least of size *numEvals* to store the computed eigenvalues; all parallel calls return the same value in this array.
- **resNorms(*)** (*double precision*) – (output) array at least of size *numEvals* to store the residual norms of the computed eigenpairs; all parallel calls return the same value in this array.

- **evecs(*)** (*double precision*) – (input/output) array at least of size *nLocal* times *numEvals* to store columnwise the (local part of the) computed eigenvectors.
- **primme** (ptr) – parameters structure.
- **ierr** (*integer*) – (output) error indicator; see Error Codes.

2.2.7 zprimme_f77

zprimme_f77(evals, evecs, resNorms, primme, ierr)

Solve a Hermitian standard eigenproblem. The arguments have the same meaning as in function *dprimme_f77()*.

Parameters

- **evals(*)** (*double precision*) – (output)
- **resNorms(*)** (*double precision*) – (output)
- **evecs(*)** (*complex double precision*) – (input/output)
- **primme** (ptr) – (input) parameters structure.
- **ierr** (*integer*) – (output) error indicator; see Error Codes.

2.2.8 primme_set_member_f77

primme_set_member_f77(primme, label, value)

Set a value in some field of the parameter structure.

Parameters

- **primme** (ptr) – (input) parameters structure.
- **label** (*integer*) – field where to set value. One of:

PRIMME_n
PRIMME_matrixMatvec
PRIMME_applyPreconditioner
PRIMME_numProcs
PRIMME_procID
PRIMME_commInfo
PRIMME_nLocal
PRIMME_globalSumReal
PRIMME_numEvals
PRIMME_target
PRIMME_numTargetShifts
PRIMME_targetShifts
PRIMME_locking
PRIMME_initSize
PRIMME_numOrthoConst
PRIMME_maxBasisSize
PRIMME_minRestartSize
PRIMME_maxBlockSize

PRIMME_maxMatvecs
PRIMME_maxOuterIterations
PRIMME_intWorkSize
PRIMME_realWorkSize
PRIMME_iseed
PRIMME_intWork
PRIMME_realWork
PRIMME_aNorm
PRIMME_eps
PRIMME_printLevel
PRIMME_outputFile
PRIMME_matrix
PRIMME_preconditioner
PRIMME_restartingParams_scheme.
PRIMME_restartingParams_maxPrevRetain
PRIMME_correctionParams_precondition
PRIMME_correctionParams_robustShifts
PRIMME_correctionParams_maxInnerIterations
PRIMME_correctionParams_projectors_LeftQ
PRIMME_correctionParams_projectors_LeftX
PRIMME_correctionParams_projectors_RightQ
PRIMME_correctionParams_projectors_RightX
PRIMME_correctionParams_projectors_SkewQ
PRIMME_correctionParams_projectors_SkewX
PRIMME_correctionParams_convTest
PRIMME_correctionParams_relTolBase
PRIMME_stats_numOuterIterations
PRIMME_stats_numRestarts
PRIMME_stats_numMatvecs
PRIMME_stats_numPreconds
PRIMME_stats_elapsedTime
PRIMME_dynamicMethodSwitch
PRIMME_massMatrixMatvec

- **value** – (input) value to set.

  If the type of the option is integer (`int`, *PRIMME_INT*, `size_t`), the type of `value` should be as long as *PRIMME_INT*, which is `integer*8` by default.

Note: **Don't use** this function inside PRIMME's callback functions, e.g., *matrixMatvec* or *applyPreconditioner*, or in functions called by these functions.

2.2.9 primmetop_get_member_f77

primmetop_get_member_f77 (primme, label, value)
Get the value in some field of the parameter structure.

Parameters

- **primme** (ptr) – (input) parameters structure.
- **label** (*integer*) – (input) field where to get value. One of the detailed in function primmetop_set_member_f77().
- **value** – (output) value of the field.

  If the type of the option is integer (int, *PRIMME_INT*, size_t), the type of value should be as long as *PRIMME_INT*, which is integer*8 by default.

Note: **Don't use** this function inside PRIMME's callback functions, e.g., *matrixMatvec* or *applyPreconditioner*, or in functions called by these functions. In those cases use *primme_get_member_f77()*.

Note: When label is one of PRIMME_matrixMatvec, PRIMME_applyPreconditioner, PRIMME_commInfo, PRIMME_intWork, PRIMME_realWork, PRIMME_matrix and PRIMME_preconditioner, the returned value is a C pointer (void*). Use Fortran pointer or other extensions to deal with it. For instance:

```
use iso_c_binding
MPI_Comm comm

comm = MPI_COMM_WORLD
call primme_set_member_f77(primme, PRIMME_commInfo, comm)
...
subroutine par_GlobalSumDouble(x,y,k,primme)
use iso_c_binding
implicit none
...
MPI_Comm, pointer :: comm
type(c_ptr) :: pcomm

call primme_get_member_f77(primme, PRIMME_commInfo, pcomm)
call c_f_pointer(pcomm, comm)
call MPI_Allreduce(x,y,k,MPI_DOUBLE,MPI_SUM,comm,ierr)
```

Most users would not need to retrieve these pointers in their programs.

2.2.10 primmetop_get_prec_shift_f77

primmetop_get_prec_shift_f77(primme, index, value)

Get the value in some position of the array *ShiftsForPreconditioner*.

Parameters

- **primme** (ptr) – (input) parameters structure.
- **index** (*integer*) – (input) position of the array; the first position is 1.
- **value** – (output) value of the array at that position.

2.2.11 primme_get_member_f77

primme_get_member_f77(primme, label, value)
Get the value in some field of the parameter structure.

Parameters

- **primme** (*ptr*) – (input) parameters structure.
- **label** (*integer*) – (input) field where to get value. One of the detailed in function `primmetop_set_member_f77()`.
- **value** – (output) value of the field.

  If the type of the option is integer (`int`, *PRIMME_INT*, `size_t`), the type of `value` should be as long as *PRIMME_INT*, which is `integer*8` by default.

Note: Use this function exclusively inside PRIMME's callback functions, e.g., *matrixMatvec* or *applyPreconditioner*, or in functions called by these functions. Otherwise, e.g., from the main program, use the function *primmetop_get_member_f77()*.

Note: When `label` is one of `PRIMME_matrixMatvec`, `PRIMME_applyPreconditioner`, `PRIMME_commInfo`, `PRIMME_intWork`, `PRIMME_realWork`, `PRIMME_matrix` and `PRIMME_preconditioner`, the returned `value` is a C pointer (`void*`). Use Fortran pointer or other extensions to deal with it. For instance:

```
use iso_c_binding
MPI_Comm comm

comm = MPI_COMM_WORLD
call primme_set_member_f77(primme, PRIMME_commInfo, comm)
...
subroutine par_GlobalSumDouble(x,y,k,primme)
use iso_c_binding
implicit none
...
MPI_Comm, pointer :: comm
type(c_ptr) :: pcomm

call primme_get_member_f77(primme, PRIMME_commInfo, pcomm)
call c_f_pointer(pcomm, comm)
call MPI_Allreduce(x,y,k,MPI_DOUBLE,MPI_SUM,comm,ierr)
```

Most users would not need to retrieve these pointers in their programs.

2.2.12 primme_get_prec_shift_f77

primme_get_prec_shift_f77(primme, index, value)
Get the value in some position of the array *ShiftsForPreconditioner*.

Parameters

- **primme** (*ptr*) – (input) parameters structure.
- **index** (*integer*) – (input) position of the array; the first position is 1.

- **value** – (output) value of the array at that position.

Note: Use this function exclusively inside the function *matrixMatvec*, *massMatrixMatvec*, or *applyPreconditioner*. Otherwise use the function *primmetop_get_prec_shift_f77()*.

2.3 Python Interface

Primme.**eigsh**(*A*, *k=6*, *M=None*, *sigma=None*, *which='LM'*, *v0=None*, *ncv=None*, *maxiter=None*, *tol=0*, *return_eigenvectors=True*, *Minv=None*, *OPinv=None*, *mode='normal'*, *lock=None*, *return_stats=False*, *maxBlockSize=0*, *minRestartSize=0*, *maxPrevRetain=0*, *method=None*)

Find k eigenvalues and eigenvectors of the real symmetric square matrix or complex Hermitian matrix A.

Solves `A * x[i] = w[i] * x[i]`, the standard eigenvalue problem for w[i] eigenvalues with corresponding eigenvectors x[i].

If M is specified, solves `A * x[i] = w[i] * M * x[i]`, the generalized eigenvalue problem for w[i] eigenvalues with corresponding eigenvectors x[i]

Parameters

- **A** (*An N x N matrix, array, sparse matrix, or LinearOperator*) – the operation A * x, where A is a real symmetric matrix or complex Hermitian.
- **k** (*int, optional*) – The number of eigenvalues and eigenvectors desired.
- **M** (*An N x N matrix, array, sparse matrix, or LinearOperator*) – (not supported yet) the operation M * x for the generalized eigenvalue problem

  A * x = w * M * x.

  M must represent a real, symmetric matrix if A is real, and must represent a complex, hermitian matrix if A is complex. For best results, the data type of M should be the same as that of A.
- **sigma** (*real, optional*) – Find eigenvalues near sigma.
- **v0** (*N x i, ndarray, optional*) – Starting vectors for iteration.
- **ncv** (*int, optional*) – The maximum size of the basis
- **which** (*str ['LM' | 'SM' | 'LA' | 'SA' | 'BE']*) – If A is a complex hermitian matrix, 'BE' is invalid. Which *k* eigenvectors and eigenvalues to find:

  'LM' : Largest (in magnitude) eigenvalues

  'SM' : Smallest (in magnitude) eigenvalues

  'LA' : Largest (algebraic) eigenvalues

  'SA' : Smallest (algebraic) eigenvalues

  'BE' : Half (k/2) from each end of the spectrum (not supported)

  When sigma != None, 'which' refers to the shifted eigenvalues `w'[i]`
- **maxiter** (*int, optional*) – Maximum number of iterations.
- **tol** (*float*) – Accuracy for eigenvalues (stopping criterion). The default value is sqrt of machine precision.
- **Minv** (*(not supported)*) –

- **OPinv** (*N x N matrix, array, sparse matrix, or LinearOperator*) – Preconditioner to accelerate the convergence. Usually it is an approximation of the inverse of (A - sigma*M).
- **return_eigenvectors** (*bool*) – Return eigenvectors (True) in addition to eigenvalues
- **mode** (*string ['normal' | 'buckling' | 'cayley']*) – Only 'normal' mode is supported.
- **lock** (*N x i, ndarray, optional*) – Seek the eigenvectors orthogonal to these ones. The provided vectors *should* be orthonormal. Useful to not converge some already computed solutions.
- **maxBlockSize** (*int, optional*) – Maximum number of vectors added at every iteration.
- **minRestartSize** (*int, optional*) – Number of approximate eigenvectors kept from last iteration in restart.
- **maxPrevRetain** (*int, optional*) – Number of approximate eigenvectors kept from previous iteration in restart. Also referred as +k vectors in GD+k.
- **method** (*int, optional*) – Preset method, one of:
  - DEFAULT_MIN_TIME : a variant of JDQMR,
  - DEFAULT_MIN_MATVECS : GD+k
  - DYNAMIC : choose dynamically between both previous methods.

  See a detailed description of the methods and other possible values in [2].
- **report_stats** (*bool, optional*) – If True, it is also returned extra information from PRIMME.

Returns

- **w** (*array*) – Array of k eigenvalues
- **v** (*array*) – An array representing the *k* eigenvectors. The column `v[:,i]` is the eigenvector corresponding to the eigenvalue `w[i]`.
- **stats** (*dict, optional (if return_stats)*) – Extra information reported by PRIMME:
  - "numOuterIterations": number of outer iterations
  - "numRestarts": number of restarts
  - "numMatvecs": number of A*v
  - "numPreconds": number of OPinv*v
  - "elapsedTime": time that took
  - "estimateMinEVal": the leftmost Ritz value seen
  - "estimateMaxEVal": the rightmost Ritz value seen
  - "estimateLargestSVal": the largest singular value seen

Raises `PrimmeError` – When the requested convergence is not obtained.

The PRIMME error code can be found as `err` attribute of the exception object.

See also:

[2] Preset Methods, http://www.cs.wm.edu/~andreas/software/doc/readme.html#preset-methods

scipy.sparse.linalg.eigs() eigenvalues and eigenvectors for a general (nonsymmetric) matrix A

Primme.svds() singular value decomposition for a matrix A

Notes

This function is a wrapper to PRIMME functions to find the eigenvalues and eigenvectors [1].

References

Examples

```
>>> import Primme, scipy.sparse
>>> A = scipy.sparse.spdiags(range(100), [0], 100, 100) # sparse diag. matrix
>>> evals, evecs = Primme.eigsh(A, 3, tol=1e-6, which='LA')
>>> evals # the three largest eigenvalues of A
array([ 99.,  98.,  97.])
>>> evals, evecs = Primme.eigsh(A, 3, tol=1e-6, which='LA', lock=evecs)
>>> evals # the next three largest eigenvalues
array([ 96.,  95.,  94.])
```

2.4 MATLAB Interface

function [varargout] = primme_eigs(varargin)

`primme_eigs()` finds a few eigenvalues and eigenvectors of a real symmetric or Hermitian matrix, A, by calling the function `PRIMME_mex` (flag,dim,...). This in turn calls PRIMME. Full PRIMME functionality is supported.

Input: [A, numEvals, target, opts, eigsMethod, P]

Output: [evals, evecs, norms, primmeout]

We provide different levels of function calls, similarly to MATLAB eigs():

```
primme_eigs(A)
primme_eigs(A, numEvals)
primme_eigs(A, numEvals, target)
primme_eigs(A, numEvals, target, opts)
primme_eigs(A, numEvals, target, opts, eigsMethod)
primme_eigs(A, numEvals, target, opts, eigsMethod, P)
primme_eigs(A, numEvals, target, opts, eigsMethod, P1,P2)
primme_eigs(A, numEvals, target, opts, eigsMethod, Pfun)
primme_eigs(Afun, dim,...)
```

`primme_eigs(A)` returns a vector of A's 6 largest algebraic eigenvalues. A must be real symmetric or complex Hermitian and should be large and sparse.

`primme_eigs(Afun,dim)` accepts a function AFUN instead of a matrix. AFUN is a function handle and `y = Afun(x)` returns the matrix-vector product A*x. `primme_eigs(A,...)` could be replaced by primme_eigs(Afun, dim,...) in any of above levels of function calls. Examples are given in PRIMME_MEX_Readme.txt in the root directory of PRIMME_MEX folder.

[1] PRIMME Software, https://github.com/primme/primme

`[V,D] = primme_eigs(A)` returns a diagonal matrix D, of A's 6 largest algebraic eigenvalues and a matrix V whose columns are the corresponding eigenvectors.

`[V,D,norms,primmeout] = primme_eigs(A)` also returns an array of the residual norms of the computed eigenpairs, and a struct to report statistical information about *numOuterIterations*, *numRestarts*, *numMatvecs* and *numPreconds*.

`primme_eigs(A,numEvals)` finds the *numEvals* largest algebraic eigenvalues. numEvals must be less than the dimension of the matrix A.

`primme_eigs(A,numEvals,target)` returns numEvals target eigenvalues. `target` could be a string like below:

- 'LA' : *primme_largest* (default)
- 'SA' : *primme_smallest*
- 'CGT': *primme_closest_geq*
- 'CLT': *primme_closest_leq*
- 'CT' : *primme_closest_abs*

`primme_eigs(A,numEvals,target,opts,eigsMethod)` specifies any of a set of possible options as explained below in the opts structure.

`eigsMethod` is an integer specifying one of the preset methods in PRIMME:

- 0: *PRIMME_DYNAMIC*, (default) Switches dynamically to the best method
- 1: *PRIMME_DEFAULT_MIN_TIME*, Currently set at JDQMR_ETol
- 2: *PRIMME_DEFAULT_MIN_MATVECS*, Currently set at GD+block
- 3: *PRIMME_Arnoldi*, obviously not an efficient choice
- 4: *PRIMME_GD*, classical block Generalized Davidson
- 5: *PRIMME_GD_plusK*, GD+k block GD with recurrence restarting
- 6: *PRIMME_GD_Olsen_plusK*, GD+k with approximate Olsen precond.
- 7: *PRIMME_JD_Olsen_plusK*, GD+k, exact Olsen (two precond per step)
- 8: *PRIMME_RQI*, Rayleigh Quotient Iteration. Also INVIT, but for INVIT provide targetShifts
- 9: *PRIMME_JDQR*, Original block, Jacobi Davidson
- 10: *PRIMME_JDQMR*, Our block JDQMR method (similar to JDCG)
- 11: *PRIMME_JDQMR_ETol*, Slight, but efficient JDQMR modification
- 12: *PRIMME_SUBSPACE_ITERATION*, equiv. to GD(block,2*block)
- 13: *PRIMME_LOBPCG_OrthoBasis*, equiv. to GD(nev,3*nev)+nev
- 14: *PRIMME_LOBPCG_OrthoBasis_Window* equiv. to GD(block,3*block)+block nev>block

`primme_eigs(A,numEvals,target,opts,eigsMethod,P)`

`primme_eigs(A,numEvals,target,opts,eigsMethod,P1,P2)` uses preconditioner P or P = P1*P2 to accelerate convergence of the methods. If P is [] then a preconditioner is not applied. P may be a function handle Pfun such that Pfun(x) returns Px.

`opts` is an option structure which contain following parameters:

- *aNorm*: the estimate norm value of matrix A [{0.0}|scaler]
- *eps*: desired computing accuracy [{1e-12}|scaler]

- *maxBlockSize*: maximum block size the PRIMME uses [{1}|scaler]
- *printLevel*: different level reporting(0-5) [{1}|scaler]
- *outputFile*: output file name where user wants to save results
- *precondition*: set to 1 if use preconditioner [{0}|1]
- isreal: the complexity of A represented by AFUN [{ture}|false]
- *numTargetShifts*: number of shifts for interior eigenvalues [{0}|scaler]
- *targetShifts*: shifts for interior eigenvalues [{}|vector]
- *initSize*: On INPUT, the number of initial guesses provided in evecs array. ON OUTPUT, the number of converged eigenpairs [{0}|scaler]
- *numOrthoConst*: Number of external orthogonalization constraints provided in the first numOrthoConst vectors of evecs [{0}|scaler]
- locking: If set to 1, hard locking will be used, otherwise the code will try to use soft locking [{0}|1]
- *maxBasisSize*: maximum basis size allowed in the main iteration
- *minRestartSize*: minimum Ritz vectors to restart
- *maxMatvecs*: maximum number of matrix vector multiplications [{INT_MAX}|scaler]
- *maxOuterIterations*: maximum number of outer iterations [{INT_MAX}|scaler]
- restartingParams. *scheme*: the restart scheme [{primme_thick}| primme_dtr]
- restartingParams. *maxPrevRetain*: number of approximations from previous iteration to be retained after restart [{1}|scaler]
- *robustShifts*: set to 1 if use robustShifting to help avoid stagnation and misconverge [{0}|1]
- *maxInnerIterations*: number of inner QMR iterations [{0}|scaler]
- *LeftQ*: a projector with Q must be applied on the left [{0}|1]
- *LeftX*: a projector with X must be applied on the left [{0}|1]
- *RightQ*: a projector with Q must be applied on the right [{0}|1]
- *RightX*: a projector with X must be applied on the right [{0}|1]
- *SkewQ*: the Q right projector must be skew [{0}|1]
- *SkewX*: the X right projector must be skew [{0}|1]
- *relTolBase*: a legacy from calssical JDQR (recommend not use)
- *convTest*: how to stop the inner QMR Method
- *iseed*: set iseed value for initialization
- *intWorkSize*: memory size for integer workspace
- *realWorkSize*: memory size for real or complex workspace

See also `Matlab/readme.txt`.

2.5 Appendix

2.5.1 Types

The following data types are macros used in PRIMME as followed.

PRIMME_INT
Integer type used in matrix dimensions (such as *n* and *nLocal*) and counters (such as *numMatvecs*).

The integer size is controlled by the compilation flag `PRIMME_INT_SIZE`, see Making and Linking.

PRIMME_COMPLEX_FLOAT
Macro that is `complex float` in C and `std::complex<float>` in C++.

PRIMME_COMPLEX_DOUBLE
Macro that is `complex double` in C and `std::complex<double>` in C++.

2.5.2 primme_params

primme_params
Structure to set the problem matrices and eigensolver options.

PRIMME_INT **n**
Dimension of the matrix.

Input/output:

primme_initialize() sets this field to 0;
this field is read by *dprimme()*.

void **(*matrixMatvec)** (void **x*, *PRIMME_INT* **ldx*, void **y*, *PRIMME_INT* **ldy*, int **blockSize*, *primme_params* **primme*, int **ierr*)
Block matrix-multivector multiplication, $y = Ax$ in solving $Ax = \lambda x$ or $Ax = \lambda Bx$.

Parameters

- **x** – matrix of size *nLocal* x `blockSize` in column-major order with leading dimension `ldx`.
- **ldx** – the leading dimension of the array `x`.
- **y** – matrix of size *nLocal* x `blockSize` in column-major order with leading dimension `ldy`.
- **ldy** – the leading dimension of the array `y`.
- **blockSize** – number of columns in `x` and `y`.
- **primme** – parameters structure.
- **ierr** – output error code; if it is set to non-zero, the current call to PRIMME will stop.

The actual type of `x` and `y` depends on which function is being calling. For *dprimme()*, it is `double`, for *zprimme()* it is *PRIMME_COMPLEX_DOUBLE*, for *sprimme()* it is `float` and for *cprimme()* it is *PRIMME_COMPLEX_FLOAT*.

Input/output:

primme_initialize() sets this field to NULL;
this field is read by *dprimme()*.

Note: If you have performance issues with leading dimension different from `nLocal`, set `ldOPs` to `nLocal`.

void **(*applyPreconditioner)**(void **x*, *PRIMME_INT* **ldx*, void **y*, *PRIMME_INT* **ldy*, int **blockSize*, *primme_params* **primme*, int **ierr*)

Block preconditioner-multivector application, $y = M^{-1}x$ where M is usually an approximation of $A-\sigma I$ or $A - \sigma B$ for finding eigenvalues close to σ. The function follows the convention of `matrixMatvec`.

Input/output:

`primme_initialize()` sets this field to NULL;
this field is read by `dprimme()`.

void **(*massMatrixMatvec)**(void **x*, *PRIMME_INT* **ldx*, void **y*, *PRIMME_INT* **ldy*, int **blockSize*, *primme_params* **primme*, int **ierr*)

Block matrix-multivector multiplication, $y = Bx$ in solving $Ax = \lambda Bx$. The function follows the convention of `matrixMatvec`.

Input/output:

`primme_initialize()` sets this field to NULL;
this field is read by `dprimme()`.

Warning: Generalized eigenproblems not implemented in current version. This member is included for future compatibility.

int **numProcs**

Number of processes calling `dprimme()` or `zprimme()` in parallel.

Input/output:

`primme_initialize()` sets this field to 1;
this field is read by `dprimme()`.

int **procID**

The identity of the local process within a parallel execution calling `dprimme()` or `zprimme()`. Only the process with id 0 prints information.

Input/output:

`primme_initialize()` sets this field to 0;
`dprimme()` sets this field to 0 if `numProcs` is 1;
this field is read by `dprimme()`.

int **nLocal**

Number of local rows on this process.

Input/output:

`primme_initialize()` sets this field to 0;
`dprimme()` sets this field to `n` if `numProcs` is 1;
this field is read by `dprimme()`.

void ***commInfo**

A pointer to whatever parallel environment structures needed. For example, with MPI, it could be a pointer to the MPI communicator. PRIMME does not use this. It is available for possible use in user functions defined in `matrixMatvec`, `applyPreconditioner`, `massMatrixMatvec` and `globalSumReal`.

Input/output:

primme_initialize() sets this field to NULL;

void **(*globalSumReal)**(void **sendBuf*, void **recvBuf*, int **count*, *primme_params* **primme*, int **ierr*)

Global sum reduction function. No need to set for sequential programs.

Parameters

- **sendBuf** – array of size `count` with the local input values.
- **recvBuf** – array of size `count` with the global output values so that the i-th element of recvBuf is the sum over all processes of the i-th element of `sendBuf`.
- **count** – array size of `sendBuf` and `recvBuf`.
- **primme** – parameters structure.
- **ierr** – output error code; if it is set to non-zero, the current call to PRIMME will stop.

The actual type of `sendBuf` and `recvBuf` depends on which function is being calling. For *dprimme()* and *zprimme()* it is `double`, and for *sprimme()* and *cprimme()* it is `float`. Note that `count` is the number of values of the actual type.

Input/output:

primme_initialize() sets this field to an internal function;
dprimme() sets this field to an internal function if *numProcs* is 1 and *globalSumReal* is NULL;
this field is read by *dprimme()*.

When MPI is used, this can be a simply wrapper to MPI_Allreduce() as shown below:

```
void par_GlobalSumForDouble(void *sendBuf, void *recvBuf, int *count,
                            primme_params *primme, int *ierr) {
   MPI_Comm communicator = *(MPI_Comm *) primme->commInfo;
   if(MPI_Allreduce(sendBuf, recvBuf, *count, MPI_DOUBLE, MPI_SUM,
                    communicator) == MPI_SUCCESS) {
      *ierr = 0;
   } else {
      *ierr = 1;
   }
}
```

}

When calling *sprimme()* and *cprimme()* replace `MPI_DOUBLE` by `MPI_FLOAT.

int **numEvals**

Number of eigenvalues wanted.

Input/output:

primme_initialize() sets this field to 1;
this field is read by *primme_set_method()* (see Preset Methods) and *dprimme()*.

primme_target **target**

Which eigenpairs to find:

primme_smallest Smallest algebraic eigenvalues; *targetShifts* is ignored.

primme_largest Largest algebraic eigenvalues; *targetShifts* is ignored.

primme_closest_geq Closest to, but greater or equal than the shifts in *targetShifts*.

primme_closest_leq Closest to, but less or equal than the shifts in *targetShifts*.

primme_closest_abs Closest in absolute value to the shifts in *targetShifts*.

primme_largest_abs Furthest in absolute value to the shifts in *targetShifts*.

Input/output:

primme_initialize() sets this field to *primme_smallest*;
this field is read by *dprimme()*.

int **numTargetShifts**
Size of the array *targetShifts*. Used only when *target* is *primme_closest_geq*, *primme_closest_leq*, *primme_closest_abs* or *primme_largest_abs*. The default values is 0.

Input/output:

primme_initialize() sets this field to 0;
this field is read by *dprimme()*.

double ***targetShifts**
Array of shifts, at least of size *numTargetShifts*. Used only when *target* is *primme_closest_geq*, *primme_closest_leq*, *primme_closest_abs* or *primme_largest_abs*.

Eigenvalues are computed in order so that the i-th eigenvalue is the closest (or closest but left or closest but right, see *target*) to the i-th shift. If *numTargetShifts* < *numEvals*, the last shift given is used for all the remaining i's.

Input/output:

primme_initialize() sets this field to NULL;
this field is read by *dprimme()*.

Note: Considerations for interior problems:

- PRIMME will try to compute the eigenvalues in the order given in the *targetShifts*. However, for code efficiency and robustness, the shifts should be ordered. Order them in ascending (descending) order for shifts closer to the lower (higher) end of the spectrum.
- If some shift is close to the lower (higher) end of the spectrum, use either *primme_closest_geq* (*primme_closest_leq*) or *primme_closest_abs*.
- *primme_closest_leq* and *primme_closest_geq* are more efficient than *primme_closest_abs*.
- For interior eigenvalues larger *maxBasisSize* is usually more robust.
- To find the largest magnitude eigenvalues set *target* to *primme_largest_abs*, *numTargetShifts* to 1 and *targetShifts* to an array with a zero value.

---

int **printLevel**
The level of message reporting from the code. All output is writen in *outputFile*.

One of:

- 0: silent.
- 1: print some error messages when these occur.
- 2: as 1, and info about targeted eigenpairs when they are marked as converged:

```
#Converged $1 eval[ $2 ]= $3 norm $4 Mvecs $5 Time $7
```

or locked:

```
#Lock epair[ $1 ]= $3 norm $4 Mvecs $5 Time $7
```

•3: as 2, and info about targeted eigenpairs every outer iteration:

```
OUT $6 conv $1 blk $8 MV $5 Sec $7 EV $3 |r| $4
```

Also, if it is used the dynamic method, show JDQMR/GDk performance ratio and the current method in use.

•4: as 3, and info about targeted eigenpairs every inner iteration:

```
INN MV $5 Sec $7 Eval $3 Lin|r| $9 EV|r| $4
```

•5: as 4, and verbose info about certain choices of the algorithm.

Output key:

$1: Number of converged pairs up to now.
$2: The index of the pair currently converged.
$3: The eigenvalue.
$4: Its residual norm.
$5: The current number of matrix-vector products.
$6: The current number of outer iterations.
$7: The current elapsed time.
$8: Index within the block of the targeted pair .
$9: QMR norm of the linear system residual.

In parallel programs, output is produced in call with *procID* 0 when *printLevel* is from 0 to 4. If *printLevel* is 5 output can be produced in any of the parallel calls.

Input/output:

primme_initialize() sets this field to 1;
this field is read by *dprimme()*.

Note: Convergence history for plotting may be produced simply by:

```
grep OUT outpufile | awk '{print $8" "$14}' > out
grep INN outpufile | awk '{print $3" "$11}' > inn
```

Then in Matlab:

```
plot(out(:,1),out(:,2),'bo');hold; plot(inn(:,1),inn(:,2),'r');
```

Or in gnuplot:

```
plot 'out' w lp, 'inn' w lp
```

---

double **aNorm**
An estimate of the norm of A, which is used in the default convergence criterion (see *eps*).

If *aNorm* is less than or equal to 0, the code uses the largest absolute Ritz value seen. On return, *aNorm* is then replaced with that value.

Input/output:

primme_initialize() sets this field to 0.0;
this field is read and written by *dprimme()*.

double **eps**
If *convTestFun* is NULL, an eigenpairs is marked as converged when the 2-norm of the residual vector is less than *eps* * *aNorm*. The residual vector is $Ax - \lambda x$ or $Ax - \lambda Bx$.

Input/output:

primme_initialize() sets this field to 10^{-12};
this field is read by *dprimme()*.

FILE ***outputFile**
Opened file to write down the output.

Input/output:

primme_initialize() sets this field to the standard output;
this field is read by *dprimme()* and *primme_display_params()*.

int **dynamicMethodSwitch**
If this value is 1, it alternates dynamically between *PRIMME_DEFAULT_MIN_TIME* and *PRIMME_DEFAULT_MIN_MATVECS*, trying to identify the fastest method.

On exit, it holds a recommended method for future runs on this problem:

-1: use *PRIMME_DEFAULT_MIN_MATVECS* next time.
-2: use *PRIMME_DEFAULT_MIN_TIME* next time.
-3: close call, use *PRIMME_DYNAMIC* next time again.

Input/output:

primme_initialize() sets this field to 0;
written by *primme_set_method()* (see Preset Methods);
this field is read by *dprimme()*.

Note: Even for expert users we do not recommend setting *dynamicMethodSwitch* directly, but through *primme_set_method()*.

Note: The code obtains timings by the `gettimeofday` Unix utility. If a cheaper, more accurate timer is available, modify the `PRIMMESRC/COMMONSRC/wtime.c`

---

int **locking**
If set to 1, hard locking will be used (locking converged eigenvectors out of the search basis). If set to 0, the code will try to use soft locking (à la ARPACK), when large enough *minRestartSize* is available.

Input/output:

primme_initialize() sets this field to -1;
written by *primme_set_method()* (see Preset Methods);

this field is read by *dprimme()*.

int **initSize**

On input, the number of initial vector guesses provided in `evecs` argument in *dprimme()* or *zprimme()*.

On output, *initSize* holds the number of converged eigenpairs. Without *locking* all *numEvals* approximations are in `evecs` but only the *initSize* ones are converged.

During execution, it holds the current number of converged eigenpairs. In addition, if locking is used, these are accessible in `evals` and `evecs`.

Input/output:

primme_initialize() sets this field to 0;
this field is read and written by *dprimme()*.

PRIMME_INT **ldevecs**

The leading dimension of `evecs`. The default is *nLocal*.

Input/output:

primme_initialize() sets this field to 0;
this field is read by *dprimme()*.

int **numOrthoConst**

Number of vectors to be used as external orthogonalization constraints. These vectors are provided in the first *numOrthoConst* positions of the `evecs` argument in *dprimme()* or *zprimme()* and must be orthonormal.

PRIMME finds new eigenvectors orthogonal to these constraints (equivalent to solving the problem with $(I - YY^*)A(I - YY^*)$ and $(I - YY^*)B(I - YY^*)$ matrices where Y are the given constraint vectors). This is a handy feature if some eigenvectors are already known, or for finding more eigenvalues after a call to *dprimme()* or *zprimme()*, possibly with different parameters (see an example in `TEST/ex_zseq.c`).

Input/output:

primme_initialize() sets this field to 0;
this field is read by *dprimme()*.

int **maxBasisSize**

The maximum basis size allowed in the main iteration. This has memory implications.

Input/output:

primme_initialize() sets this field to 0;
this field is read and written by *primme_set_method()* (see Preset Methods);
this field is read by *dprimme()*.

int **minRestartSize**

Maximum Ritz vectors kept after restarting the basis.

Input/output:

primme_initialize() sets this field to 0;
this field is read and written by *primme_set_method()* (see Preset Methods);
this field is read by *dprimme()*.

int **maxBlockSize**

The maximum block size the code will try to use.

The user should set this based on the architecture specifics of the target computer, as well as any a priori knowledge of multiplicities. The code does *not* require that *maxBlockSize* > 1 to find multiple eigenvalues. For some methods, keeping to 1 yields the best overall performance.

Input/output:

primme_initialize() sets this field to 1;
this field is read and written by *primme_set_method()* (see Preset Methods);
this field is read by *dprimme()*.

Note: Inner iterations of QMR are not performed in a block fashion. Every correction equation from a block is solved independently.

PRIMME_INT **maxMatvecs**
Maximum number of matrix vector multiplications (approximately equal to the number of preconditioning operations) that the code is allowed to perform before it exits.

Input/output:

primme_initialize() sets this field to INT_MAX;
this field is read by *dprimme()*.

PRIMME_INT **maxOuterIterations**
Maximum number of outer iterations that the code is allowed to perform before it exits.

Input/output:

primme_initialize() sets this field to INT_MAX;
this field is read by *dprimme()*.

int **intWorkSize**
If *dprimme()* or *zprimme()* is called with all arguments as NULL except for *primme_params* then PRIMME returns immediately with *intWorkSize* containing the size *in bytes* of the integer workspace that will be required by the parameters set in PRIMME.

Otherwise if *intWorkSize* is not 0, it should be the size of the integer work array *in bytes* that the user provides in *intWork*. If *intWorkSize* is 0, the code will allocate the required space, which can be freed later by calling *primme_free()*.

Input/output:

primme_initialize() sets this field to 0;
this field is read and written by *dprimme()*.

size_t **realWorkSize**
If *dprimme()* or *zprimme()* is called with all arguments as NULL except for *primme_params* then PRIMME returns immediately with *realWorkSize* containing the size *in bytes* of the real workspace that will be required by the parameters set in PRIMME.

Otherwise if *realWorkSize* is not 0, it should be the size of the real work array *in bytes* that the user provides in *realWork*. If *realWorkSize* is 0, the code will allocate the required space, which can be freed later by calling *primme_free()*.

Input/output:

primme_initialize() sets this field to 0;
this field is read and written by *dprimme()*.

int ***intWork**
Integer work array.

If NULL, the code will allocate its own workspace. If the provided space is not enough, the code will return the error code `-37`.

On exit, the first element shows if a locking problem has occurred. Using locking for large *numEvals* may, in some rare cases, cause some pairs to be practically converged, in the sense that their components are in the basis of `evecs`. If this is the case, a Rayleigh Ritz on returned `evecs` would provide the accurate eigenvectors (see *[r4]*).

Input/output:

primme_initialize() sets this field to NULL;
this field is read and written by *dprimme()*.

void ***realWork**
Real work array.

If NULL, the code will allocate its own workspace. If the provided space is not enough, the code will return the error code `-36`.

Input/output:

primme_initialize() sets this field to NULL;
this field is read and written by *dprimme()*.

PRIMME_INT **iseed**
The `PRIMME_INT iseed[4]` is an array with the seeds needed by the LAPACK dlarnv and zlarnv.

The default value is an array with values -1, -1, -1 and -1. In that case, `iseed` is set based on the value of *procID* to avoid every parallel process generating the same sequence of pseudorandom numbers.

Input/output:

primme_initialize() sets this field to `[-1,-1,-1,-1]`;
this field is read and written by *dprimme()*.

void ***matrix**
This field may be used to pass any required information in the matrix-vector product *matrixMatvec*.

Input/output:

primme_initialize() sets this field to NULL;

void ***preconditioner**
This field may be used to pass any required information in the preconditioner function *applyPreconditioner*.

Input/output:

primme_initialize() sets this field to NULL;

double ***ShiftsForPreconditioner**
Array of size `blockSize` provided during execution of *dprimme()* and *zprimme()* holding the shifts to be used (if needed) in the preconditioning operation.

For example if the block size is 3, there will be an array of three shifts in *ShiftsForPreconditioner*. Then the user can invert a shifted preconditioner for each of the block vectors $(M - ShiftsForPreconditioner_i)^{-1}x_i$. Classical Davidson (diagonal) preconditioning is an example of this.

this field is read and written by *dprimme()*.

primme_init **initBasisMode**
Select how the search subspace basis is initialized up to *minRestartSize* vectors if not enough initial vectors are provided (see *initSize*):

- `primme_init_krylov`, with a block Krylov subspace generated by the matrix problem and the last initial vectors if given or a random vector otherwise; the size of the block is *maxBlockSize*.
- `primme_init_random`, with random vectors.
- `primme_init_user`, the initial basis will have only initial vectors if given, or a single random vector.

Input/output:

primme_initialize() sets this field to *primme_init_krylov*;
this field is read by *dprimme()*.

primme_projection **projectionParams.projection**
Select the extraction technique, i.e., how the approximate eigenvectors x_i and eigenvalues λ_i are computed from the search subspace $\mathcal{V}$:

- `primme_proj_RR`, Rayleigh-Ritz, $Ax_i - Bx_i\lambda_i \perp \mathcal{V}$.
- `primme_proj_Harm`, Harmonic Rayleigh-Ritz, $Ax_i - Bx_i\lambda_i \perp (A-\tau B)\mathcal{V}$, where τ is the current target shift (see *targetShifts*).
- `primme_proj_ref`, refined extraction, compute $||x_i|| = 1$ so that minimizes $||(A - \tau B)x_i||$; the eigenvalues are computed as the Rayleigh quotients, $\lambda_i = \frac{x_i^* A x_i}{x_i^* B x_i}$.

Input/output:

primme_initialize() sets this field to *primme_proj_default*;
primme_set_method() and *dprimme()* sets it to *primme_proj_RR* if it is *primme_proj_default*.

primme_restartscheme **restartingParams.scheme**
Select a restarting strategy:

- `primme_thick`, Thick restarting. This is the most efficient and robust in the general case.
- `primme_dtr`, Dynamic thick restarting. Helpful without preconditioning but it is expensive to implement.

Input/output:

primme_initialize() sets this field to *primme_thick*;
written by *primme_set_method()* (see Preset Methods);
this field is read by *dprimme()*.

int **restartingParams.maxPrevRetain**
Number of approximations from previous iteration to be retained after restart (this is the locally optimal restarting, see *[r2]*). The restart size is *minRestartSize* plus *maxPrevRetain*.

Input/output:

primme_initialize() sets this field to 0;
this field is read and written by *primme_set_method()* (see Preset Methods);
this field is read by *dprimme()*.

int **correctionParams.precondition**
Set to 1 to use preconditioning. Make sure *applyPreconditioner* is not NULL then!

Input/output:

primme_initialize() sets this field to 0;
this field is read and written by *primme_set_method()* (see Preset Methods);
this field is read by *dprimme()*.

int **correctionParams.robustShifts**
Set to 1 to use robust shifting. It tries to avoid stagnation and misconvergence by providing as shifts in *ShiftsForPreconditioner* the Ritz values displaced by an approximation of the eigenvalue error.

Input/output:

primme_initialize() sets this field to 0;
written by *primme_set_method()* (see Preset Methods);
this field is read by *dprimme()*.

int **correctionParams.maxInnerIterations**
Control the maximum number of inner QMR iterations:

- 0: no inner iterations;
- >0: perform at most that number of inner iterations per outer step;
- <0: perform at most the rest of the remaining matrix-vector products up to reach *maxMatvecs*.

Input/output:

primme_initialize() sets this field to 0;
this field is read and written by *primme_set_method()* (see Preset Methods);
this field is read by *dprimme()*.

See also *convTest*.

double **correctionParams.relTolBase**
Parameter used when *convTest* is *primme_decreasing_LTolerance*.

Input/output:

primme_initialize() sets this field to 0;
written by *primme_set_method()* (see Preset Methods);
this field is read by *dprimme()*.

primme_convergencetest **correctionParams.convTest**
Set how to stop the inner QMR method:

- `primme_full_LTolerance`: stop by iterations only;
- `primme_decreasing_LTolerance`, stop when relTolBase$^{-\text{outIts}}$ where outIts is the number of outer iterations and retTolBase is set in *relTolBase*; This is a legacy option from classical JDQR and we recommend **strongly** against its use.
- `primme_adaptive`, stop when the estimated eigenvalue residual has reached the required tolerance (based on Notay's JDCG).
- `primme_adaptive_ETolerance`, as *primme_adaptive* but also stopping when the estimated eigenvalue residual has reduced 10 times.

Input/output:

primme_initialize() sets this field to `primme_adaptive_ETolerance`;
written by *primme_set_method()* (see Preset Methods);
this field is read by *dprimme()*.

Note: Avoid to set *maxInnerIterations* to -1 and *convTest* to *primme_full_LTolerance*.

See also *maxInnerIterations*.

int **correctionParams.projectors.LeftQ**

int **correctionParams.projectors.LeftX**

int **correctionParams.projectors.RightQ**

int **correctionParams.projectors.RightX**

int **correctionParams.projectors.SkewQ**

int **correctionParams.projectors.SkewX**

Control the projectors involved in the computation of the correction appended to the basis every (outer) iteration.

Consider the current selected Ritz value Λ and vectors X, the residual associated vectors $R = AX - X\Lambda$, the previous locked vectors Q, and the preconditioner M^{-1}.

When *maxInnerIterations* is 0, the correction D appended to the basis in GD is:

RightX	SkewX	D
0	0	$M^{-1}R$ (Classic GD)
1	0	$M^{-1}(R - \Delta X)$ (cheap Olsen's Method)
1	1	$(I - M^{-1}X(X^*M^{-1}X)^{-1}X^*)M^{-1}R$ (Olsen's Method)
0	1	error

Where Δ is a diagonal matrix that $\Delta_{i,i}$ holds an estimation of the error of the approximate eigenvalue $\Lambda_{i,i}$.

The values of `RightQ`, `SkewQ`, `LeftX` and `LeftQ` are ignored.

When *maxInnerIterations* is not 0, the correction D in Jacobi-Davidson results from solving:

$$P_Q^l P_X^l (A - \sigma I) P_X^r P_Q^r M^{-1} D' = -R, \quad D = P_X^r P_Q^l M^{-1} D'.$$

For `LeftQ`:

0: $P_Q^l = I$;
1: $P_Q^l = I - QQ^*$.

For `LeftX`:

0: $P_X^l = I$;
1: $P_X^l = I - XX^*$.

For `RightQ` and `SkewQ`:

RightQ	SkewQ	P_Q^r
0	0	I
1	0	$I - QQ^*$
1	1	$I - KQ(Q^*KQ)^{-1}Q^*$
0	1	error

For `RightX` and `SkewX`:

RightX	SkewX	P_X^r
0	0	I
1	0	$I - XX^*$
1	1	$I - KX(X^*KX)^{-1}X^*$
0	1	error

Input/output:

primme_initialize() sets all of them to 0;
this field is written by *primme_set_method()* (see Preset Methods);
this field is read by *dprimme()*.

See *[r3]* for a study about different projector configurations in JD.

PRIMME_INT **ldOPs**
Recommended leading dimension to be used in *matrixMatvec*, *applyPreconditioner* and *massMatrixMatvec*. The default value is zero, which means no user recommendation. In that case, PRIMME computes ldOPs internally to get better memory performance.

Input/output:

primme_initialize() sets this field to 0;
this field is read by *dprimme()*.

PRIMME_INT **stats.numOuterIterations**
Hold the number of outer iterations. The value is available during execution and at the end.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

PRIMME_INT **stats.numRestarts**
Hold the number of restarts during execution and at the end.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

PRIMME_INT **stats.numMatvecs**
Hold how many vectors the operator in *matrixMatvec* has been applied on. The value is available during execution and at the end.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

PRIMME_INT **stats.numPreconds**
Hold how many vectors the operator in *applyPreconditioner* has been applied on. The value is available during execution and at the end.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

PRIMME_INT **stats.numGlobalSum**
Hold how many times *globalSumReal* has been called. The value is available during execution and at the end.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

double **stats.volumeGlobalSum**
Hold how many REAL have been reduced by *globalSumReal*. The value is available during execution and at the end.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

double **stats.elapsedTime**
Hold the wall clock time spent by the call to *dprimme()* or *zprimme()*. The value is available at the end of the execution.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

double **stats.timeMatvec**
Hold the wall clock time spent by *matrixMatvec*. The value is available at the end of the execution.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

double **stats.timePrecond**
Hold the wall clock time spent by *applyPreconditioner*. The value is available at the end of the execution.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

double **stats.timeOrtho**
Hold the wall clock time spent by orthogonalization. The value is available at the end of the execution.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

double **stats.timeGlobalSum**
Hold the wall clock time spent by *globalSumReal*. The value is available at the end of the execution.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

double **stats.estimateMinEVal**
Hold the estimation of the smallest eigenvalue for the current eigenproblem. The value is available during execution and at the end.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

double **stats.estimateMaxEVal**
Hold the estimation of the largest eigenvalue for the current eigenproblem. The value is available during execution and at the end.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

double **stats.estimateLargestSVal**
Hold the estimation of the largest singular value (i.e., the absolute value of the eigenvalue with largest absolute value) for the current eigenproblem. The value is available during execution and at the end.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

double **stats.maxConvTol**
Hold the maximum residual norm of the converged eigenvectors. The value is available during execution and at the end.

Input/output:

primme_initialize() sets this field to 0;
written by *dprimme()*.

void **(*convTestFun)**(double **eval*, void **evecs*, double **resNorm*, int **isconv*, *primme_params* **primme*, int **ierr*)
Function that evaluates if the approximate eigenpair has converged. If NULL, it is used the default convergence criteria (see *eps*).

Parameters

- **eval** – the approximate value to evaluate.
- **x** – one dimensional array of size *nLocal* containing the approximate vector; it can be NULL. The actual type depends on which function is being calling. For *dprimme()*, it is `double`, for *zprimme()* it is *PRIMME_COMPLEX_DOUBLE*, for *sprimme()* it is `float` and for for *cprimme()* it is *PRIMME_COMPLEX_FLOAT*.
- **resNorm** – the norm of residual vector.
- **isconv** – (output) the function sets zero if the pair is not converged and non zero otherwise.
- **primme** – parameters structure.
- **ierr** – output error code; if it is set to non-zero, the current call to PRIMME will stop.

Input/output:

primme_initialize() sets this field to NULL;
this field is read by *dprimme()*.

2.5.3 Error Codes

The functions *dprimme()* and *zprimme()* return one of the next values:

- 0: success.
- 1: reported only amount of required memory.
- -1: failed in allocating int or real workspace.
- -2: malloc failed in allocating a permutation integer array.

- -3: main_iter() encountered problem; the calling stack of the functions where the error occurred was printed in `stderr`.
- -4: if argument `primme` is NULL.
- -5: if *n* <= 0 or *nLocal* <= 0.
- -6: if *numProcs* < 1.
- -7: if *matrixMatvec* is NULL.
- -8: if *applyPreconditioner* is NULL and *precondition* > 0.
- -10: if *numEvals* > *n*.
- -11: if *numEvals* < 0.
- -12: if *eps* > 0 and *eps* < machine precision.
- -13: if *target* is not properly defined.
- -14: if *target* is one of *primme_closest_geq*, *primme_closest_leq*, *primme_closest_abs* or *primme_largest_abs* but *numTargetShifts* <= 0 (no shifts).
- -15: if *target* is one of *primme_closest_geq*, *primme_closest_leq*, *primme_closest_abs* or *primme_largest_abs* but *targetShifts* is NULL (no shifts array).
- -16: if *numOrthoConst* < 0 or *numOrthoConst* >= *n*. (no free dimensions left).
- -17: if *maxBasisSize* < 2.
- -18: if *minRestartSize* <= 0.
- -19: if *maxBlockSize* <= 0.
- -20: if *maxPrevRetain* < 0.
- -21: if *scheme* is not one of *primme_thick* or *primme_dtr*.
- -22: if *initSize* < 0.
- -23: if *locking* == 0 and *initSize* > *maxBasisSize*.
- -24: if *locking* and *initSize* > *numEvals*.
- -25: if *maxPrevRetain* + *minRestartSize* >= *maxBasisSize*.
- -26: if *minRestartSize* >= *n*.
- -27: if *printLevel* < 0 or *printLevel* > 5.
- -28: if *convTest* is not one of *primme_full_LTolerance*, *primme_decreasing_LTolerance*, *primme_adaptive_ETolerance* or *primme_adaptive*.
- -29: if *convTest* == *primme_decreasing_LTolerance* and *relTolBase* <= 1.
- -30: if `evals` is NULL, but not `evecs` and `resNorms`.
- -31: if `evecs` is NULL, but not `evals` and `resNorms`.
- -32: if `resNorms` is NULL, but not `evecs` and `evals`.
- -33: if *locking* == 0 and *minRestartSize* < *numEvals*.
- -34: if *ldevecs* < *nLocal*
- -35: if *ldOPs* is not zero and less than *nLocal*
- -36: not enough memory for *realWork*

- -37: not enough memory for *intWork*

2.5.4 Preset Methods

primme_preset_method

PRIMME_DEFAULT_MIN_TIME
Set as *PRIMME_JDQMR_ETol* when *target* is either primme_smallest or primme_largest, and as *PRIMME_JDQMR* otherwise. This method is usually the fastest if the cost of the matrix vector product is inexpensive.

PRIMME_DEFAULT_MIN_MATVECS
Currently set as *PRIMME_GD_Olsen_plusK*; this method usually performs fewer matrix vector products than other methods, so it's a good choice when this operation is expensive.

PRIMME_DYNAMIC
Switches to the best method dynamically; currently, between methods *PRIMME_DEFAULT_MIN_TIME* and *PRIMME_DEFAULT_MIN_MATVECS*.

With *PRIMME_DYNAMIC* *primme_set_method()* sets *dynamicMethodSwitch* = 1 and makes the same changes as for method *PRIMME_DEFAULT_MIN_TIME*.

PRIMME_Arnoldi
Arnoldi implemented à la Generalized Davidson.

With *PRIMME_Arnoldi* *primme_set_method()* sets:

- *locking* = 0;
- *maxPrevRetain* = 0;
- *precondition* = 0;
- *maxInnerIterations* = 0.

PRIMME_GD
Generalized Davidson.

With *PRIMME_GD* *primme_set_method()* sets:

- *locking* = 0;
- *maxPrevRetain* = 0;
- *robustShifts* = 1;
- *maxInnerIterations* = 0;
- *RightX* = 0;
- *SkewX* = 0.

PRIMME_GD_plusK
GD with locally optimal restarting.

With *PRIMME_GD_plusK* *primme_set_method()* sets *maxPrevRetain* = 2 if *maxBlockSize* is 1 and *numEvals* > 1; otherwise it sets *maxPrevRetain* to *maxBlockSize*. Also:

- *locking* = 0;
- *maxInnerIterations* = 0;
- *RightX* = 0;
- *SkewX* = 0.

PRIMME_GD_Olsen_plusK
GD+k and the cheap Olsen's Method.

With *PRIMME_GD_Olsen_plusK* *primme_set_method()* makes the same changes as for method *PRIMME_GD_plusK* and sets *RightX* = 1.

PRIMME_JD_Olsen_plusK
GD+k and Olsen's Method.

With *PRIMME_JD_Olsen_plusK* *primme_set_method()* makes the same changes as for method *PRIMME_GD_plusK* and also sets *robustShifts* = 1, *RightX* to 1, and *SkewX* to 1.

PRIMME_RQI
(Accelerated) Rayleigh Quotient Iteration.

With *PRIMME_RQI* *primme_set_method()* sets:

- *locking* = 1;
- *maxPrevRetain* = 0;
- *robustShifts* = 1;
- *maxInnerIterations* = -1;
- *LeftQ* = 1;
- *LeftX* = 1;
- *RightQ* = 0;
- *RightX* = 1;
- *SkewQ* = 0;
- *SkewX* = 0;
- *convTest* = *primme_full_LTolerance*.

Note: If *numTargetShifts* > 0 and *targetShifts* are provided, the interior problem solved uses these shifts in the correction equation. Therefore RQI becomes INVIT (inverse iteration) in that case.

PRIMME_JDQR
Jacobi-Davidson with fixed number of inner steps.

With *PRIMME_JDQR* *primme_set_method()* sets:

- *locking* = 1;
- *maxPrevRetain* = 1;
- *robustShifts* = 0;
- *maxInnerIterations* = 10 if it is 0;
- *LeftQ* = 0;
- *LeftX* = 1;
- *RightQ* = 1;
- *RightX* = 1;
- *SkewQ* = 1;
- *SkewX* = 1;
- *relTolBase* = 1.5;
- *convTest* = *primme_full_LTolerance*.

PRIMME_JDQMR
Jacobi-Davidson with adaptive stopping criterion for inner Quasi Minimum Residual (QMR).

With *PRIMME_JDQMR* *primme_set_method()* sets:

- *locking* = 0;
- *maxPrevRetain* = 1 if it is 0
- *maxInnerIterations* = -1;
- *LeftQ* = *precondition*;
- *LeftX* = 1;
- *RightQ* = 0;
- *RightX* = 0;
- *SkewQ* = 0;

- *SkewX* = 1;
- *convTest* = *primme_adaptive*.

PRIMME_JDQMR_ETol
JDQMR but QMR stops after residual norm reduces by a 0.1 factor.

With *PRIMME_JDQMR_ETol* *primme_set_method()* makes the same changes as for the method *PRIMME_JDQMR* and sets *convTest* = *primme_adaptive_ETolerance*.

PRIMME_SUBSPACE_ITERATION
Subspace iteration.

With *PRIMME_SUBSPACE_ITERATION* *primme_set_method()* sets:

- *locking* = 1;
- *maxBasisSize* = *numEvals* * 2;
- *minRestartSize* = *numEvals*;
- *maxBlockSize* = *numEvals*;
- *scheme* = *primme_thick*;
- *maxPrevRetain* = 0;
- *robustShifts* = 0;
- *maxInnerIterations* = 0;
- *RightX* = 1;
- *SkewX* = 0.

PRIMME_LOBPCG_OrthoBasis
LOBPCG with orthogonal basis.

With *PRIMME_LOBPCG_OrthoBasis* *primme_set_method()* sets:

- *locking* = 0;
- *maxBasisSize* = *numEvals* * 3;
- *minRestartSize* = *numEvals*;
- *maxBlockSize* = *numEvals*;
- *scheme* = *primme_thick*;
- *maxPrevRetain* = *numEvals*;
- *robustShifts* = 0;
- *maxInnerIterations* = 0;
- *RightX* = 1;
- *SkewX* = 0.

PRIMME_LOBPCG_OrthoBasis_Window
LOBPCG with sliding window of *maxBlockSize* < 3 * *numEvals*.

With *PRIMME_LOBPCG_OrthoBasis_Window* *primme_set_method()* sets:

- *locking* = 0;
- *maxBasisSize* = *maxBlockSize* * 3;
- *minRestartSize* = *maxBlockSize*;
- *maxBlockSize* = *numEvals*;
- *scheme* = *primme_thick*;
- *maxPrevRetain* = *maxBlockSize*;
- *robustShifts* = 0;
- *maxInnerIterations* = 0;
- *RightX* = 1;
- *SkewX* = 0.

CHAPTER

THREE

SINGULAR VALUE PROBLEMS

3.1 C Library Interface

The PRIMME SVDS interface is composed of the following functions. To solve real and complex singular value problems call respectively:

```
int  sprimme_svds (float *svals, float *svecs, float *resNorms,
                           primme_svds_params *primme_svds)
int  cprimme_svds (float *svals,  PRIMME_COMPLEX_FLOAT *svecs,
                  float *resNorms, primme_svds_params *primme_svds)
int  dprimme_svds (double *svals, double *svecs, double *resNorms,
                        primme_svds_params *primme_svds)
int  zprimme_svds (double *svals,  PRIMME_COMPLEX_DOUBLE *svecs,
                  double *resNorms, primme_svds_params *primme_svds)
```

Other useful functions:

```
void  primme_svds_initialize (primme_svds_params *primme_svds)
int  primme_svds_set_method (primme_svds_preset_method method,
   primme_preset_method methodStage1,
   primme_preset_method methodStage2, primme_svds_params *primme_svds)
void  primme_svds_display_params (primme_svds_params primme_svds)
void  primme_svds_free
 (primme_svds_params *primme_svds)
```

PRIMME SVDS stores its data on the structure *primme_svds_params*. See Parameters Guide for an introduction about its fields.

3.1.1 Running

To use PRIMME SVDS, follow these basic steps.

1. Include:

   ```
   #include "primme.h"   /* header file is required to run primme */
   ```

2. Initialize a PRIMME SVDS parameters structure for default settings:

   ```
   primme_svds_params primme_svds;
   primme_svds_initialize (&primme_svds);
   ```

3. Set problem parameters (see also Parameters Guide), and, optionally, set one of the *preset methods*:

```
primme_svds. matrixMatvec = matrixMatvec; /* MV product */
primme_svds. m = 1000;     /* set the matrix dimensions */
primme_svds. n = 100;
primme_svds. numSvals = 10; /* Number of singular values */
 primmesvds_set_method (primme_svds_hybrid, PRIMME_DEFAULT_METHOD,
                        PRIMME_DEFAULT_METHOD, &primme_svds);
...
```

4. Then to solve a real singular value problem call:

   ```
   ret =  dprimme_svds (svals, svecs, resNorms, &primme_svds);
   ```

   The previous is the double precision call. There is available calls for complex double, single and complex single; check it out *zprimme_svds()*, *sprimme_svds()* and *cprimme_svds()*.

   To solve complex singular value problems call:

   ```
   ret =  zprimme_svds (svals, svecs, resNorms, &primme_svds);
   ```

   The call arguments are:

   - *svals*, array to return the found singular values;
   - *svecs*, array to return the found left and right singular vectors;
   - *resNorms*, array to return the residual norms of the found triplets; and
   - *ret*, returned error code.

5. To free the work arrays in PRIMME SVDS:

   ```
   primme_svds_free
   (&primme_svds);
   ```

3.1.2 Parameters Guide

PRIMME SVDS stores the data on the structure *primme_svds_params*, which has the next fields:

Basic
`PRIMME_INT` *m*, number of rows of the matrix.
`PRIMME_INT` *n*, number of columns of the matrix.
`void (*` *matrixMatvec* `)(...)`, matrix-vector product.
`int` *numSvals*, how many singular triplets to find.
`primme_svds_target` *target*, which singular values to find.
`double` *eps*, tolerance of the residual norm of converged triplets.

For parallel programs
`int` *numProcs*, number of processes
`int` *procID*, rank of this process
`PRIMME_INT` *mLocal*, number of rows stored in this process
`PRIMME_INT` *nLocal*, number of columns stored in this process
`void (*` *globalSumReal* `)(...)`, sum reduction among processes

Accelerate the convergence
`void (*` *applyPreconditioner* `)(...)`, preconditioner-vector product.

int *initSize*, initial vectors as approximate solutions.
int *maxBasisSize*
int minRestartSize
int *maxBlockSize*

User data
void * *commInfo*
void * *matrix*
void * *preconditioner*

Advanced options
int *numTargetShifts*, for targeting interior singular values.
double * *targetShifts*
int *numOrthoConst*, orthogonal constrains to the singular vectors.
int *locking*
PRIMME_INT *maxMatvecs*
int *intWorkSize*
size_t *realWorkSize*
PRIMME_INT *iseed* [4]
int * *intWork*
void * *realWork*
double *aNorm*
int *printLevel*
FILE * *outputFile*
primme_svds_operator *method*
primme_svds_operator *methodStage2*
primme_params *primme*
primme_params *primmeStage2*

PRIMME SVDS requires the user to set at least the matrix dimensions (*m* x *n*) and the matrix-vector product (*matrixMatvec*), as they define the problem to be solved. For parallel programs, *mLocal*, *nLocal*, *procID* and *globalSumReal* are also required.

In addition, most users would want to specify how many singular triplets to find, and provide a preconditioner (if available).

It is useful to have set all these before calling *primme_svds_set_method()*. Also, if users have a preference on *maxBasisSize*, *maxBlockSize*, etc, they should also provide them into *primme_svds_params* prior to the *primme_svds_set_method()* call. This helps *primme_svds_set_method()* make the right choice on other parameters. It is sometimes useful to check the actual parameters that PRIMME SVDS is going to use (before calling it) or used (on return) by printing them with *primme_svds_display_params()*.

3.1.3 Interface Description

The next enumerations and functions are declared in `primme.h`.

sprimme_svds

int **sprimme_svds**(float **svals*, float **svecs*, float **resNorms*, *primme_svds_params* **primme_svds*)
Solve a real singular value problem.

Parameters

- **svals** – array at least of size *numSvals* to store the computed singular values; all processes in a parallel run return this local array with the same values.
- **resNorms** – array at least of size *numSvals* to store the residual norms of the computed triplets; all processes in parallel run return this local array with the same values.
- **svecs** – array at least of size (*mLocal* + *nLocal*) times *numSvals* to store columnwise the (local part of the) computed left singular vectors and the right singular vectors.
- **primme_svds** – parameters structure.

Returns error indicator; see Error Codes.

On input, svecs should start with the content of the *numOrthoConst* left vectors, followed by the *initSize* left vectors, followed by the *numOrthoConst* right vectors and followed by the *initSize* right vectors. The i-th left vector starts at svecs[i* *mLocal*]. The i-th right vector starts at svecs[(*numOrthoConst* + *initSize*)* *mLocal* + i* *nLocal*].

On return, the i-th left singular vector starts at svecs[(*numOrthoConst* +i)* *mLocal*]. The i-th right singular vector starts at svecs[(*numOrthoConst* + *initSize*)* *mLocal* + (*numOrthoConst* +i)* *nLocal*]. The first vector has i=0.

dprimme_svds

int **dprimme_svds**(double **svals*, double **svecs*, double **resNorms*, *primme_svds_params* **primme_svds*)
Solve a real singular value problem.

Parameters

- **svals** – array at least of size *numSvals* to store the computed singular values; all processes in a parallel run return this local array with the same values.
- **resNorms** – array at least of size *numSvals* to store the residual norms of the computed triplets; all processes in parallel run return this local array with the same values.
- **svecs** – array at least of size (*mLocal* + *nLocal*) times *numSvals* to store columnwise the (local part of the) computed left singular vectors and the right singular vectors.
- **primme_svds** – parameters structure.

Returns error indicator; see Error Codes.

On input, svecs should start with the content of the *numOrthoConst* left vectors, followed by the *initSize* left vectors, followed by the *numOrthoConst* right vectors and followed by the *initSize* right vectors. The i-th left vector starts at svecs[i* *mLocal*]. The i-th right vector starts at svecs[(*numOrthoConst* + *initSize*)* *mLocal* + i* *nLocal*].

On return, the i-th left singular vector starts at svecs[(*numOrthoConst* +i)* *mLocal*]. The i-th right singular vector starts at svecs[(*numOrthoConst* + *initSize*)* *mLocal* + (*numOrthoConst* +i)* *nLocal*]. The first vector has i=0.

cprimme_svds

int **cprimme_svds**(float **svals*, *PRIMME_COMPLEX_FLOAT* **svecs*, float **resNorms*, *primme_svds_params* **primme_svds*)

Solve a complex singular value problem; see function *dprimme_svds()*.

zprimme_svds

int **zprimme_svds**(double **svals*, *PRIMME_COMPLEX_DOUBLE* **svecs*, double **resNorms*, *primme_svds_params* **primme_svds*)

Solve a complex singular value problem; see function *dprimme_svds()*.

primme_svds_initialize

void **primme_svds_initialize**(*primme_svds_params* **primme_svds*)

Set PRIMME SVDS parameters structure to the default values.

Parameters

- **primme_svds** – parameters structure.

primme_svds_set_method

int **primme_svds_set_method**(*primme_svds_preset_method* *method*, *primme_preset_method* *methodStage1*, *primme_preset_method* *methodStage2*, *primme_svds_params* **primme_svds*)

Set PRIMME SVDS parameters to one of the preset configurations.

Parameters

- **method** – preset method to compute the singular triplets; one of
  - *primme_svds_default*, currently set as *primme_svds_hybrid*.
  - *primme_svds_normalequations*, compute the eigenvectors of A^*A or AA^*.
  - *primme_svds_augmented*, compute the eigenvectors of the augmented matrix, $\begin{pmatrix} 0 & A^* \\ A & 0 \end{pmatrix}$.
  - *primme_svds_hybrid*, start with *primme_svds_normalequations*; use the resulting approximate singular vectors as initial vectors for *primme_svds_augmented* if the required accuracy was not achieved.
- **methodStage1** – preset method to compute the eigenpairs at the first stage; see available values at *primme_set_method()*.
- **methodStage2** – preset method to compute the eigenpairs with the second stage of primme_svds_hybrid; see available values at *primme_set_method()*.
- **primme_svds** – parameters structure.

See also Preset Methods.

primme_svds_display_params

void **primme_svds_display_params**(*primme_svds_params primme_svds*)

Display all printable settings of `primme_svds` into the file descriptor *outputFile*.

Parameters

- **primme_svds** – parameters structure.

primme_svds_free

void **primme_svds_free**(*primme_svds_params *primme_svds*)

Free memory allocated by PRIMME SVDS.

Parameters

- **primme_svds** – parameters structure.

3.2 FORTRAN Library Interface

The next enumerations and functions are declared in `primme_svds_f77.h`.

3.2.1 sprimme_svds_f77

sprimme_svds_f77(svals, svecs, resNorms, primme_svds)

Solve a real singular value problem using single precision.

Parameters

- **svals(*)** (*real*) – (output) array at least of size *numSvals* to store the computed singular values; all processes in a parallel run return this local array with the same values.
- **resNorms(*)** (*real*) – array at least of size *numSvals* to store the residual norms of the computed triplets; all processes in parallel run return this local array with the same values.
- **svecs(*)** (*real*) – array at least of size (*mLocal* + *nLocal*) times *numSvals* to store columnwise the (local part of the) computed left singular vectors and the right singular vectors.
- **primme_svds** (`ptr`) – parameters structure.

Returns error indicator; see Error Codes.

3.2.2 cprimme_svds_f77

cprimme_svds_f77(svals, svecs, resNorms, primme_svds)

Solve a complex singular value problem using single precision.

Parameters

- **svals(*)** (*real*) – (output) array at least of size *numSvals* to store the computed singular values; all processes in a parallel run return this local array with the same values.

- **resNorms(*)** (*real*) – array at least of size *numSvals* to store the residual norms of the computed triplets; all processes in parallel run return this local array with the same values.
- **svecs(*)** (*complex*) – array at least of size (*mLocal* + *nLocal*) times *numSvals* to store columnwise the (local part of the) computed left singular vectors and the right singular vectors.
- **primme_svds** (ptr) – parameters structure.

Returns error indicator; see Error Codes.

3.2.3 dprimme_svds_f77

dprimme_svds_f77(svals, svecs, resNorms, primme_svds)
Solve a real singular value problem using double precision.

Parameters

- **svals(*)** (*double precision*) – (output) array at least of size *numSvals* to store the computed singular values; all processes in a parallel run return this local array with the same values.
- **resNorms(*)** (*double precision*) – array at least of size *numSvals* to store the residual norms of the computed triplets; all processes in parallel run return this local array with the same values.
- **svecs(*)** (*double precision*) – array at least of size (*mLocal* + *nLocal*) times *numSvals* to store columnwise the (local part of the) computed left singular vectors and the right singular vectors.
- **primme_svds** (ptr) – parameters structure.

Returns error indicator; see Error Codes.

3.2.4 zprimme_svds_f77

zprimme_svds_f77(svals, svecs, resNorms, primme_svds)
Solve a complex singular value problem using double precision.

Parameters

- **svals(*)** (*double precision*) – (output) array at least of size *numSvals* to store the computed singular values; all processes in a parallel run return this local array with the same values.
- **resNorms(*)** (*double precision*) – array at least of size *numSvals* to store the residual norms of the computed triplets; all processes in parallel run return this local array with the same values.
- **svecs(*)** (*complex*16*) – array at least of size (*mLocal* + *nLocal*) times *numSvals* to store columnwise the (local part of the) computed left singular vectors and the right singular vectors.
- **primme_svds** (ptr) – parameters structure.

Returns error indicator; see Error Codes.

3.2.5 primme_svds_initialize_f77

primme_svds_initialize_f77 (primme_svds)
Set PRIMME SVDS parameters structure to the default values.

Parameters

- **primme_svds** (ptr) – (output) parameters structure.

3.2.6 primme_svds_set_method_f77

primme_svds_set_method_f77 (method, methodStage1, methodStage2, primme_svds, ierr)
Set PRIMME SVDS parameters to one of the preset configurations.

Parameters

- **method** (*integer*) – (input) preset configuration to compute the singular triplets; one of
  - *PRIMME_SVDS_default*, currently set as *PRIMME_SVDS_hybrid*.
  - *PRIMME_SVDS_normalequations*, compute the eigenvectors of A^*A or AA^*.
  - *PRIMME_SVDS_augmented*, compute the eigenvectors of the augmented matrix, $\begin{pmatrix} 0 & A^* \\ A & 0 \end{pmatrix}$.
  - *PRIMME_SVDS_hybrid*, start with *PRIMME_SVDS_normalequations*; use the resulting approximate singular vectors as initial vectors for *PRIMME_SVDS_augmented* if the required accuracy was not achieved.
- **methodStage1** (primme_preset_method) – (input) preset method to compute the eigenpairs at the first stage; see available values at *primme_set_method_f77()*.
- **methodStage2** (primme_preset_method) – (input) preset method to compute the eigenpairs with the second stage of *PRIMME_SVDS_hybrid*; see available values at *primme_set_method_f77()*.
- **primme_svds** (ptr) – (input/output) parameters structure.
- **ierr** (*integer*) – (output) if 0, successful; if negative, something went wrong.

3.2.7 primme_svds_display_params_f77

primme_svds_display_params_f77 (primme_svds)
Display all printable settings of primme_svds into the file descriptor *outputFile*.

Parameters

- **primme_svds** (ptr) – (input) parameters structure.

3.2.8 primme_svds_free_f77

primme_svds_free_f77 (primme_svds)
Free memory allocated by PRIMME SVDS and delete all values set.

Parameters

- **primme_svds** (ptr) – (input/output) parameters structure.

3.2.9 primme_svds_set_member_f77

primme_svds_set_member_f77 (primme_svds, label, value)
Set a value in some field of the parameter structure.

Parameters

- **primme_svds** (ptr) – (input) parameters structure.
- **label** (*integer*) – field where to set value. One of:

PRIMME_SVDS_primme
PRIMME_SVDS_primmeStage2
PRIMME_SVDS_m
PRIMME_SVDS_n
PRIMME_SVDS_matrixMatvec
PRIMME_SVDS_applyPreconditioner
PRIMME_SVDS_numProcs
PRIMME_SVDS_procID
PRIMME_SVDS_mLocal
PRIMME_SVDS_nLocal
PRIMME_SVDS_commInfo
PRIMME_SVDS_globalSumReal
PRIMME_SVDS_numSvals
PRIMME_SVDS_target
PRIMME_SVDS_numTargetShifts
PRIMME_SVDS_targetShifts
PRIMME_SVDS_method
PRIMME_SVDS_methodStage2
PRIMME_SVDS_intWorkSize
PRIMME_SVDS_realWorkSize
PRIMME_SVDS_intWork
PRIMME_SVDS_realWork
PRIMME_SVDS_matrix
PRIMME_SVDS_preconditioner
PRIMME_SVDS_locking
PRIMME_SVDS_numOrthoConst
PRIMME_SVDS_aNorm
PRIMME_SVDS_eps
PRIMME_SVDS_precondition
PRIMME_SVDS_initSize
PRIMME_SVDS_maxBasisSize
PRIMME_SVDS_maxBlockSize
PRIMME_SVDS_maxMatvecs
PRIMME_SVDS_iseed
PRIMME_SVDS_printLevel
PRIMME_SVDS_outputFile
PRIMME_SVDS_stats_numOuterIterations
PRIMME_SVDS_stats_numRestarts

PRIMME_SVDS_stats_numMatvecs
PRIMME_SVDS_stats_numPreconds
PRIMME_SVDS_stats_elapsedTime

- **value** – (input) value to set.

Note: **Don't use** this function inside PRIMME SVDS's callback functions, e.g., *matrixMatvec* or *applyPreconditioner*, or in functions called by these functions.

3.2.10 primme_svdstop_get_member_f77

primme_svdstop_get_member_f77 (primme_svds, label, value)

Get the value in some field of the parameter structure.

Parameters

- **primme_svds** (ptr) – (input) parameters structure.
- **label** (*integer*) – (input) field where to get value. One of the detailed in function primmesvds_top_set_member_f77().
- **value** – (output) value of the field.

Note: **Don't use** this function inside PRIMME SVDS's callback functions, e.g., *matrixMatvec* or *applyPreconditioner*, or in functions called by these functions. In those cases use *primme_svds_get_member_f77()*.

Note: When label is one of PRIMME_SVDS_matrixMatvec, PRIMME_SVDS_applyPreconditioner, PRIMME_SVDS_commInfo, PRIMME_SVDS_intWork, PRIMME_SVDS_realWork, PRIMME_SVDS_matrix and PRIMME_SVDS_preconditioner, the returned value is a C pointer (void*). Use Fortran pointer or other extensions to deal with it. For instance:

```
use iso_c_binding
MPI_Comm comm

comm = MPI_COMM_WORLD
call primme_svds_set_member_f77(primme_svds, PRIMME_SVDS_commInfo, comm)
...
subroutine par_GlobalSumDouble(x,y,k,primme_svds)
use iso_c_binding
implicit none
...
MPI_Comm, pointer :: comm
type(c_ptr) :: pcomm

call primme_svds_get_member_f77(primme_svds, PRIMME_SVDS_commInfo, pcomm)
call c_f_pointer(pcomm, comm)
call MPI_Allreduce(x,y,k,MPI_DOUBLE,MPI_SUM,comm,ierr)
```

Most users would not need to retrieve these pointers in their programs.

3.2.11 primme_svds_get_member_f77

primme_svds_get_member_f77(primme_svds, label, value)
Get the value in some field of the parameter structure.

Parameters

- **primme_svds** (ptr) – (input) parameters structure.
- **label** (*integer*) – (input) field where to get value. One of the detailed in function primme_svdstop_set_member_f77().
- **value** – (output) value of the field.

Note: Use this function exclusively inside PRIMME SVDS's callback functions, e.g., *matrixMatvec* or *applyPreconditioner*, or in functions called by these functions. Otherwise, e.g., from the main program, use the function *primme_svdstop_get_member_f77()*.

Note: When label is one of PRIMME_SVDS_matrixMatvec, PRIMME_SVDS_applyPreconditioner, PRIMME_SVDS_commInfo, PRIMME_SVDS_intWork, PRIMME_SVDS_realWork, PRIMME_SVDS_matrix and PRIMME_SVDS_preconditioner, the returned value is a C pointer (void*). Use Fortran pointer or other extensions to deal with it. For instance:

```
use iso_c_binding
MPI_Comm comm

comm = MPI_COMM_WORLD
call primme_svds_set_member_f77(primme_svds, PRIMME_SVDS_commInfo, comm)
...
subroutine par_GlobalSumDouble(x,y,k,primme_svds)
use iso_c_binding
implicit none
...
MPI_Comm, pointer :: comm
type(c_ptr) :: pcomm

call primme_svds_get_member_f77(primme_svds, PRIMME_SVDS_commInfo, pcomm)
call c_f_pointer(pcomm, comm)
call MPI_Allreduce(x,y,k,MPI_DOUBLE,MPI_SUM,comm,ierr)
```

Most users would not need to retrieve these pointers in their programs.

3.3 Python Interface

Primme.**svds**(*A*, *k=6*, *ncv=None*, *tol=0*, *which='LM'*, *v0=None*, *maxiter=None*, *return_singular_vectors=True*, *precAHA=None*, *precAAH=None*, *precAug=None*, *u0=None*, *locku0=None*, *lockv0=None*, *return_stats=False*, *maxBlockSize=0*)
Compute k singular values and vectors for a sparse matrix.

Parameters

- **A** (*{sparse matrix, LinearOperator}*) – Array to compute the SVD on, of shape (M, N)

- **k** (*int, optional*) – Number of singular values and vectors to compute. Must be 1 <= k < min(A.shape).
- **ncv** (*int, optional*) – The maximum size of the basis
- **tol** (*float, optional*) – Tolerance for singular values. Zero (default) means machine precision.
- **which** (*str ['LM' | 'SM'] or number, optional*) – Which *k* singular values to find:
  - 'LM' : largest singular values
  - 'SM' : smallest singular values
  - number : closest singular values to (referred as sigma later)
- **u0** (*ndarray, optional*) – Left starting vectors for the iterations.

  Should be approximate left singular vectors. If only u0 or v0 is provided, the other is computed.
- **v0** (*ndarray, optional*) – Right starting vectors for the iterations.
- **maxiter** (*int, optional*) – Maximum number of iterations.
- **precAHA** (*{N x N matrix, array, sparse matrix, LinearOperator}, optional*) – Approximate inverse of (A.H*A - sigma**2*I). If provided and M>N, it usually accelerates the convergence.
- **precAAH** (*{M x M matrix, array, sparse matrix, LinearOperator}, optional*) – Approximate inverse of (A*A.H - sigma**2*I). If provided and M<N, it usually accelerates the convergence.
- **precAug** (*{(M+N) x (M+N) matrix, array, sparse matrix, LinearOperator}, optional*) – Approximate inverse of ([zeros() A.H; zeros() A] - sigma*I). It usually accelerates the convergence if tol<dtype.eps**.5.
- **locku0** (*ndarray, optional*) – Left orthogonal vector constrain.

  Seek singular triplets orthogonal to locku0 and lockv0. The provided vectors *should* be orthonormal. If only locku0 or lockv0 is provided, the other is computed. Useful to not converge some already computed solutions.
- **lockv0** (*ndarray, optional*) – Right orthogonal vector constrain. See locku0.
- **maxBlockSize** (*int, optional*) – Maximum number of vectors added at every iteration.
- **report_stats** (*bool, optional*) – If True, it is also returned extra information from PRIMME.

Returns

- **u** (*ndarray, shape=(M, k), optional*) – Unitary matrix having left singular vectors as columns. Returned if *return_singular_vectors* is True.
- **s** (*ndarray, shape=(k,)*) – The singular values.
- **vt** (*ndarray, shape=(k, N), optional*) – Unitary matrix having right singular vectors as rows. Returned if *return_singular_vectors* is True.
- **stats** (*dict, optional (if return_stats)*) – Extra information reported by PRIMME:
  - "numOuterIterations": number of outer iterations

- "numRestarts": number of restarts
- "numMatvecs": number of A*v
- "numPreconds": number of OPinv*v
- "elapsedTime": time that took

Returned if *return_stats* is True.

See also:

Primme.eigsh() eigenvalue decomposition for a sparse symmetrix/complex Hermitian matrix A

scipy.sparse.linalg.eigs() eigenvalues and eigenvectors for a general (nonsymmetric) matrix A

Examples

```
>>> import Primme, scipy.sparse
>>> A = scipy.sparse.spdiags(range(1, 11), [0], 100, 10) # sparse diag. rect.␣
↪matrix
>>> svecs_left, svals, svecs_right = Primme.svds(A, 3, tol=1e-6, which='SM')
>>> svals # the three smallest singular values of A
array([ 1.,  2.,  3.])
```

```
>>> import Primme, scipy.sparse
>>> A = scipy.sparse.rand(10000, 100, random_state=10)
>>> prec = scipy.sparse.spdiags(np.reciprocal(A.multiply(A).sum(axis=0)),
...            [0], 100, 100) # square diag. preconditioner
>>> svecs_left, svals, svecs_right = Primme.svds(A, 3, which=6.0, tol=1e-6,␣
↪precAHA=prec)
>>> ["%.5f" % x for x in svals.flat] # the three closest singular values of A to␣
↪0.5
['5.99871', '5.99057', '6.01065']
```

3.4 Appendix

3.4.1 primme_svds_params

primme_svds_params

Structure to set the problem matrix and the solver options.

PRIMME_INT **m**

Number of rows of the matrix.

Input/output:
primme_initialize() sets this field to 0;
this field is read by *dprimme()*.

PRIMME_INT **n**

Number of columns of the matrix.

Input/output:
primme_initialize() sets this field to 0;
this field is read by *dprimme()*.

void **(*matrixMatvec)**(void **x*, *PRIMME_INT ldx*, void **y*, *PRIMME_INT ldy*, int **blockSize*, int **transpose*, *primme_svds_params *primme_svds*, int **ierr*)

Block matrix-multivector multiplication, $y = Ax$ if `transpose` is zero, and $y = A^*x$ otherwise.

Parameters

- **x** – input array.
- **ldx** – leading dimension of `x`.
- **y** – output array.
- **ldy** – leading dimension of `y`.
- **blockSize** – number of columns in `x` and `y`.
- **transpose** – if non-zero, the transpose A should be applied.
- **primme_svds** – parameters structure.
- **ierr** – output error code; if it is set to non-zero, the current call to PRIMME will stop.

If `transpose` is zero, then `x` and `y` are arrays of dimensions *nLocal* x `blockSize` and *mLocal* x `blockSize` respectively. Elsewhere they have dimensions *mLocal* x `blockSize` and *nLocal* x `blockSize`. Both arrays are column-major (consecutive rows are consecutive in memory).

The actual type of `x` and `y` depends on which function is being calling. For *dprimme_svds()*, it is `double`, for *zprimme_svds()* it is *PRIMME_COMPLEX_DOUBLE*, for *sprimme_svds()* it is `float` and for *cprimme_svds()* it is *PRIMME_COMPLEX_FLOAT*.

Input/output:

primme_initialize() sets this field to NULL;

this field is read by *dprimme_svds()* and *zprimme_svds()*.

Note: Integer arguments are passed by reference to make easier the interface to other languages (like Fortran).

---

void **(*applyPreconditioner)**(void **x*, *PRIMME_INT ldx*, void **y*, *PRIMME_INT ldy*, int **blockSize*, int **mode*, *primme_svds_params *primme_svds*, int **ierr*)

Block preconditioner-multivector application. Depending on `mode` it is expected an approximation of the inverse of

- `primme_svds_op_AtA`: $y = A^*Ax - \sigma^2 I$,
- `primme_svds_op_AAt`: $y = AA^*x - \sigma^2 I$,
- `primme_svds_op_augmented`: $\begin{pmatrix} 0 & A^* \\ A & 0 \end{pmatrix} - \sigma I$.

Where σ is the current target (see *targetShifts*) (for finding the smallest σ is zero).

Parameters

- **x** – input array.
- **ldx** – leading dimension of `x`.
- **y** – output array.
- **ldy** – leading dimension of `y`.
- **blockSize** – number of columns in `x` and `y`.
- **mode** – one of `primme_svds_op_AtA`, `primme_svds_op_AAt` or `primme_svds_op_augmented`.
- **primme_svds** – parameters structure.
- **ierr** – output error code; if it is set to non-zero, the current call to PRIMME will stop.

If `mode` is `primme_svds_op_AtA`, then `x` and `y` are arrays of dimensions *nLocal* x `blockSize`; if mode is `primme_svds_op_AAt`, they are *mLocal* x `blockSize`; and

otherwise they are (*mLocal* + *nLocal*) x `blockSize`. Both arrays are column-major (consecutive rows are consecutive in memory).

The actual type of `x` and `y` depends on which function is being calling. For *dprimme_svds()*, it is `double`, for *zprimme_svds()* it is *PRIMME_COMPLEX_DOUBLE*, for *sprimme_svds()* it is `float` and for *cprimme_svds()* it is *PRIMME_COMPLEX_FLOAT*.

Input/output:
primme_initialize() sets this field to NULL;
this field is read by *dprimme_svds()* and *zprimme_svds()*.

int **numProcs**
Number of processes calling *dprimme_svds()* or *zprimme_svds()* in parallel.

Input/output:
primme_initialize() sets this field to 1;
this field is read by *dprimme()* and *zprimme_svds()*.

int **procID**
The identity of the local process within a parallel execution calling *dprimme_svds()* or *zprimme_svds()*. Only the process with id 0 prints information.

Input/output:
primme_svds_initialize() sets this field to 0;
dprimme_svds() sets this field to 0 if *numProcs* is 1;
this field is read by *dprimme_svds()* and *zprimme_svds()*.

PRIMME_INT **mLocal**
Number of local rows on this process. The value depends on how the matrix and preconditioner is distributed along the processes.

Input/output:
primme_svds_initialize() sets this field to 0;
dprimme_svds() sets this field to *m* if *numProcs* is 1;
this field is read by *dprimme_svds()* and *zprimme_svds()*.
See also: *matrixMatvec* and *applyPreconditioner*.

PRIMME_INT **nLocal**
Number of local columns on this process. The value depends on how the matrix and preconditioner is distributed along the processes.

Input/output:
primme_svds_initialize() sets this field to 0;
dprimme_svds() sets this field to to *n* if *numProcs* is 1;
this field is read by *dprimme_svds()* and *zprimme_svds()*.

void ***commInfo**
A pointer to whatever parallel environment structures needed. For example, with MPI, it could be a pointer to the MPI communicator. PRIMME does not use this. It is available for possible use in user functions defined in *matrixMatvec*, *applyPreconditioner* and *globalSumReal*.

Input/output:
primme_svds_initialize() sets this field to NULL;

void **(*globalSumReal)**(double **sendBuf*, double **recvBuf*, int **count*, *primme_svds_params* **primme_svds*, int **ierr*)
Global sum reduction function. No need to set for sequential programs.

Parameters

- **sendBuf** – array of size `count` with the local input values.
- **recvBuf** – array of size `count` with the global output values so that the i-th element of recvBuf is the sum over all processes of the i-th element of `sendBuf`.
- **count** – array size of `sendBuf` and `recvBuf`.
- **primme_svds** – parameters structure.
- **ierr** – output error code; if it is set to non-zero, the current call to PRIMME will stop.

The actual type of `sendBuf` and `recvBuf` depends on which function is being calling. For *dprimme_svds()* and *zprimme_svds()* it is `double`, and for *sprimme_svds()* and *cprimme_svds()* it is `float`. Note that `count` is the number of values of the actual type.

Input/output:

primme_svds_initialize() sets this field to an internal function;

dprimme_svds() sets this field to an internal function if *numProcs* is 1 and *globalSumReal* is NULL;

this field is read by *dprimme_svds()* and *zprimme_svds()*.

When MPI is used, this can be a simply wrapper to MPI_Allreduce() as shown below:

```
void par_GlobalSumForDouble(void *sendBuf, void *recvBuf, int *count,
                            primme_svds_params *primme_svds, int *ierr) {
   MPI_Comm communicator = *(MPI_Comm *) primme_svds->commInfo;
   if (MPI_Allreduce(sendBuf, recvBuf, *count, MPI_DOUBLE, MPI_SUM,
                  communicator) == MPI_SUCCESS) {
      *ierr = 0;
   } else {
      *ierr = 1;
   }
}

When calling :c:func:`sprimme_svds` and :c:func:`cprimme_svds`␣
↪replace ``MPI_DOUBLE`` by ```MPI_FLOAT``.
```

int **numSvals**

Number of singular triplets wanted.

Input/output:

primme_svds_initialize() sets this field to 1;

this field is read by *primme_svds_set_method()* (see Preset Methods) and *dprimme_svds()*.

primme_svds_target **target**

Which singular values to find:

primme_svds_smallest Smallest singular values; *targetShifts* is ignored.
primme_svds_largest Largest singular values; *targetShifts* is ignored.
primme_svds_closest_abs Closest in absolute value to the shifts in *targetShifts*.

Input/output:

primme_svds_initialize() sets this field to *primme_svds_smallest*;

this field is read by *dprimme_svds()* and *zprimme_svds()*.

int **numTargetShifts**

Size of the array *targetShifts*. Used only when *target* is *primme_svds_closest_abs*. The default values is 0.

Input/output:

primme_svds_initialize() sets this field to 0;

this field is read by *dprimme_svds()* and *zprimme_svds()*.

double ***targetShifts***
Array of shifts, at least of size *numTargetShifts*. Used only when *target* is *primme_svds_closest_abs*.

Singular values are computed in order so that the i-th singular value is the closest to the i-th shift. If *numTargetShifts* < *numSvals*, the last shift given is used for all the remaining i's.

Input/output:
primme_svds_initialize() sets this field to NULL;
this field is read by *dprimme_svds()* and *zprimme_svds()*.

Note: Eventually this is used by *dprimme()* and *zprimme()*. Please see considerations of *targetShifts*.

---

int **printLevel**
The level of message reporting from the code. For now it controls the reporting level of the underneath eigensolvers. See *printLevel* in primme_params.

All output is writen in *outputFile*.

Input/output:
primme_svds_initialize() sets this field to 1;
this field is read by *dprimme_svds()* and *zprimme_svds()*.

double **aNorm**
An estimate of the 2-norm of A, which is used in the default convergence criterion (see *eps*).

If *aNorm* is less than or equal to 0, the code uses the largest absolute Ritz value seen. On return, *aNorm* is then replaced with that value.

Input/output:
primme_svds_initialize() sets this field to 0.0;
this field is read and written by *dprimme_svds()* and *zprimme_svds()*.

double **eps**
A triplet is marked as converged when the 2-norm of the residual vectors is less than *eps* * *aNorm*. The residual vectors are $Av - \sigma u$ and $A^*u - \sigma v$ for the triplet (u, σ, v).

Input/output:
primme_svds_initialize() sets this field to 10^{-12};
this field is read by *dprimme_svds()* and *zprimme_svds()*.

FILE ***outputFile**
Opened file to write down the output.

Input/output:
primme_svds_initialize() sets this field to the standard output;
this field is read by *dprimme_svds()*, *zprimme_svds()* and *primme_svds_display_params()*

int **locking**
If set to 1, the underneath eigensolvers will use hard locking. See *locking*.

Input/output:
primme_svds_initialize() sets this field to -1;
written by *primme_svds_set_method()* (see Preset Methods);
this field is read by *dprimme_svds()* and *zprimme_svds()*.

int **initSize**

On input, the number of initial vector guesses provided in `svecs` argument in *dprimme_svds()* and *zprimme_svds()*.

On output, *initSize* holds the number of converged triplets. Without *locking* all *numSvals* approximations are in `svecs` but only the first *initSize* are converged.

During execution, it holds the current number of converged triplets.

Input/output:
primme_svds_initialize() sets this field to 0;
this field is read and written by *dprimme_svds()* and *zprimme_svds()*.

int **numOrthoConst**
Number of vectors to be used as external orthogonalization constraints. The left and the right vector constraints are provided as input of the `svecs` argument in *sprimme_svds()* or other variant, and must be orthonormal.

PRIMME SVDS finds new triplets orthogonal to these constraints (equivalent to solving the problem $(I - UU^*)A(I - VV^*)$ where U and V are the given left and right constraint vectors). This is a handy feature if some singular triplets are already known, or for finding more triplets after a call to *dprimme_svds()* or *zprimme_svds()*, possibly with different parameters (see an example in `TEST/exsvd_zseq.c`).

Input/output:
primme_svds_initialize() sets this field to 0;
this field is read by *dprimme_svds()* and *zprimme_svds()*.

int **maxBasisSize**
The maximum basis size allowed in the main iteration. This has memory implications.

Input/output:
primme_svds_initialize() sets this field to 0;
this field is read and written by *primme_svds_set_method()* (see Preset Methods);
this field is read by *dprimme_svds()* and *zprimme_svds()*.

int **maxBlockSize**
The maximum block size the code will try to use.

The user should set this based on the architecture specifics of the target computer, as well as any a priori knowledge of multiplicities. The code does *not* require that *maxBlockSize* > 1 to find multiple triplets. For some methods, keeping to 1 yields the best overall performance.

Input/output:
primme_svds_initialize() sets this field to 1;
this field is read and written by *primme_svds_set_method()* (see Preset Methods);
this field is read by *dprimme_svds()* and *zprimme_svds()*.

PRIMME_INT **maxMatvecs**
Maximum number of matrix vector multiplications (approximately half the number of preconditioning operations) that the code is allowed to perform before it exits.

Input/output:
primme_svds_initialize() sets this field to `INT_MAX`;
this field is read by *dprimme_svds()* and *zprimme_svds()*.

int **intWorkSize**
If *dprimme_svds()* or *zprimme_svds()* is called with all arguments as NULL except for

primme_svds_params then it returns immediately with *intWorkSize* containing the size *in bytes* of the integer workspace that will be required by the parameters set.

Otherwise if *intWorkSize* is not 0, it should be the size of the integer work array *in bytes* that the user provides in *intWork*. If *intWorkSize* is 0, the code will allocate the required space, which can be freed later by calling *primme_svds_free()*.

Input/output:
primme_svds_initialize() sets this field to 0;
this field is read and written by *dprimme_svds()* and *zprimme_svds()*.

size_t **realWorkSize**
If *dprimme_svds()* or *zprimme_svds()* is called with all arguments as NULL except for *primme_svds_params* then it returns immediately with *realWorkSize* containing the size *in bytes* of the real workspace that will be required by the parameters set.

Otherwise if *realWorkSize* is not 0, it should be the size of the real work array *in bytes* that the user provides in *realWork*. If *realWorkSize* is 0, the code will allocate the required space, which can be freed later by calling *primme_svds_free()*.

Input/output:
primme_svds_initialize() sets this field to 0;
this field is read and written by *dprimme_svds()* and *zprimme_svds()*.

int ***intWork**
Integer work array.

If NULL, the code will allocate its own workspace. If the provided space is not enough, the code will return the error code `-21`.

Input/output:
primme_svds_initialize() sets this field to NULL;
this field is read and written by *dprimme_svds()* and *zprimme_svds()*.

void ***realWork**
Real work array.

If NULL, the code will allocate its own workspace. If the provided space is not enough, the code will return the error code `-20`.

Input/output:
primme_svds_initialize() sets this field to NULL;
this field is read and written by *dprimme_svds()* and *zprimme_svds()*.

PRIMME_INT **iseed**
The `PRIMME_INT iseed[4]` is an array with the seeds needed by the LAPACK dlarnv and zlarnv.

The default value is an array with values -1, -1, -1 and -1. In that case, `iseed` is set based on the value of *procID* to avoid every parallel process generating the same sequence of pseudorandom numbers.

Input/output:
primme_svds_initialize() sets this field to `[-1,-1,-1,-1]`;
this field is read and written by *dprimme_svds()* and *zprimme_svds()*.

void ***matrix**
This field may be used to pass any required information in the matrix-vector product *matrixMatvec*.

Input/output:

primme_svds_initialize() sets this field to NULL;

void ***preconditioner**

This field may be used to pass any required information in the preconditioner function *applyPreconditioner*.

Input/output:

primme_svds_initialize() sets this field to NULL;

int **precondition**

Set to 1 to use preconditioning. Make sure *applyPreconditioner* is not NULL then!

Input/output:

primme_svds_initialize() sets this field to 0;

this field is read and written by *primme_svds_set_method()* (see Preset Methods);

this field is read by *dprimme_svds()* and *zprimme_svds()*.

primme_svds_op_operator **method**

Select the equivalent eigenvalue problem that will be solved:

- `primme_svds_op_AtA`: $A^*Ax = \sigma^2 x$,
- `primme_svds_op_AAt`: $AA^*x = \sigma^2 x$,
- `primme_svds_op_augmented`: $\begin{pmatrix} 0 & A^* \\ A & 0 \end{pmatrix} x = \sigma x$.

The options for this solver are stored in *primme*.

Input/output:

primme_svds_initialize() sets this field to `primme_svds_op_none`;

this field is read and written by *primme_svds_set_method()* (see Preset Methods);

this field is read by *dprimme_svds()* and *zprimme_svds()*.

primme_svds_op_operator **methodStage2**

Select the equivalent eigenvalue problem that will be solved to refine the solution. The allowed options are `primme_svds_op_none` to not refine the solution and `primme_svds_op_augmented` to refine the solution by solving the augmented problem with the current solution as the initial vectors. See *method*.

The options for this solver are stored in *primmeStage2*.

Input/output:

primme_svds_initialize() sets this field to `primme_svds_op_none`;

this field is read and written by *primme_svds_set_method()* (see Preset Methods);

this field is read by *dprimme_svds()* and *zprimme_svds()*.

primme_params **primme**

Parameter structure storing the options for underneath eigensolver that will be called at the first stage. See *method*.

Input/output:

primme_svds_initialize() initialize this structure;

this field is read and written by *primme_svds_set_method()* (see Preset Methods);

this field is read and written by *dprimme_svds()* and *zprimme_svds()*.

primme_params **primmeStage2**

Parameter structure storing the options for underneath eigensolver that will be called at the second stage. See *methodStage2*.

Input/output:
primme_svds_initialize() initialize this structure;
this field is read and written by *primme_svds_set_method()* (see Preset Methods);
this field is read and written by *dprimme_svds()* and *zprimme_svds()*.

PRIMME_INT **stats.numOuterIterations**
Hold the number of outer iterations.

Input/output:
primme_svds_initialize() sets this field to 0;
written by *dprimme_svds()* and *zprimme_svds()*.

PRIMME_INT **stats.numRestarts**
Hold the number of restarts.

Input/output:
primme_svds_initialize() sets this field to 0;
written by *dprimme_svds()* and *zprimme_svds()*.

PRIMME_INT **stats.numMatvecs**
Hold how many vectors the operator in *matrixMatvec* has been applied on.

Input/output:
primme_svds_initialize() sets this field to 0;
written by *dprimme_svds()* and *zprimme_svds()*.

PRIMME_INT **stats.numPreconds**
Hold how many vectors the operator in *applyPreconditioner* has been applied on.

Input/output:
primme_svds_initialize() sets this field to 0;
written by *dprimme_svds()* and *zprimme_svds()*.

double **stats.elapsedTime**
Hold the wall clock time spent by the call to *dprimme_svds()* or *zprimme_svds()*.

Input/output:
primme_svds_initialize() sets this field to 0;
written by *dprimme_svds()* and *zprimme_svds()*.

3.4.2 Error Codes

The functions *dprimme_svds()* and *zprimme_svds()* return one of the next values:

- 0: success,
- 1: reported only amount of required memory,
- -1: failed in allocating int or real workspace,
- -2: malloc failed in allocating a permutation integer array,
- -3: main_iter() encountered problem; the calling stack of the functions where the error occurred was printed in 'stderr',
- -4: `primme_svds` is NULL,
- -5: Wrong value for *m* or *n*,
- -6: Wrong value for *numProcs*,

- -7: *matrixMatvec* is not set,
- -8: *applyPreconditioner* is not set but *precondition* == 1 ,
- -9: *numProcs* >1 but *globalSumReal* is not set,
- -10: Wrong value for *numSvals*, it's larger than min(*m*, *n*),
- -11: Wrong value for *numSvals*, it's smaller than 1,
- -13: Wrong value for *target*,
- -14: Wrong value for *method*,
- -15: Not supported combination of method and *methodStage2*,
- -16: Wrong value for *printLevel*,
- -17: `svals` is not set,
- -18: `svecs` is not set,
- -19: `resNorms` is not set
- -20: not enough memory for *realWork*
- -21: not enough memory for *intWork*
- -100 up to -199: eigensolver error from first stage; see the value plus 100 in Error Codes.
- -200 up to -299: eigensolver error from second stage; see the value plus 200 in Error Codes.

3.4.3 Preset Methods

primme_svds_preset_method

primme_svds_default
Set as `primme_svds_hybrid`.

primme_svds_normalequations
Solve the equivalent eigenvalue problem $A^*AV = \Sigma^2 V$ and computes U by normalizing the vectors AV. If *m* is smaller than *n*, AA^* is solved instead.

With `primme_svds_normalequations` *primme_svds_set_method()* sets *method* to `primme_svds_op_AtA` if *m* is larger or equal than *n*, and to `primme_svds_op_AAt` otherwise; and *methodStage2* is set to `primme_svds_op_none`.

primme_svds_augmented
Solve the equivalent eigenvalue problem $\begin{pmatrix} 0 & A^* \\ A & 0 \end{pmatrix} X = \sigma X$ with $X = \begin{pmatrix} V \\ U \end{pmatrix}$.

With `primme_svds_augmented` *primme_svds_set_method()* sets *method* to `primme_svds_op_augmented` and *methodStage2* to `primme_svds_op_none`.

primme_svds_hybrid
First solve the equivalent normal equations (see `primme_svds_normalequations`) and then refine the solution solving the augmented problem (see `primme_svds_augmented`).

With `primme_svds_normalequations` *primme_svds_set_method()* sets *method* to `primme_svds_op_AtA` if *m* is larger or equal than *n*, and to `primme_svds_op_AAt` otherwise; and *methodStage2* is set to `primme_svds_op_augmented`.

CHAPTER

FOUR

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