FASP User Guide

FASP Developers

Version 2.0.5

Contents

Chapter 1

Introduction

1.1 General description

The Fast Auxiliary Space Preconditioning (FASP) package provides C source files[1] to build a library of iterative solvers and preconditioners for the solution of large-scale linear systems of equations. The components of the FASP basic library include several ready-to-use, modern, and efficient iterative solvers used in applications ranging from simple examples of discretized scalar partial differential equations (PDEs) to numerical simulations of complex, multicomponent physical systems via the Auxiliary Space Preconditioning framework [**?**].

The main components of the FASP basic library include:

- Basic linear iterative methods;
- Standard Krylov subspace methods;
- Geometric and Algebraic Multigrid (G/AMG) methods;
- Incomplete factorization methods.

Source files in the package are organized in various abstract levels as follows:

- Level 0 (Aux*.c): Auxiliary functions (timing, memory, threading, ...)
- Level 1 (Bla*.c): Basic linear algebra subroutines (SpMV, RAP, ILU, SWZ, ...)
- Level 2 (Itr*.c): Iterative methods and smoothers (Jacobi, GS, SOR, Poly, ...)
- Level 3 (Kry*.c): Krylov iterative methods (CG, BiCGstab, MinRes, GMRES, ...)
- Level 4 (Pre*.c): Preconditioners (GMG, AMG, FAMG, ...)
- Level 5 (Sol*.c): User interface for FASP solvers (Solvers, wrappers, ...)
- Level x (Xtr*.c): Interface to external packages (Mumps, Umfpack, ...)

[1] The code is in the C99 (ISO/IEC 9899:1999) compatible.

The FASP distribution also includes several examples for solving simple benchmark problems. The basic (kernel) FASP distribution is open-source and is licensed under GNU Lesser General Public License or LGPL. Other distributions may have different licensing (contact the developer team for details on this).

1.2 Roadmap: from basics to complex applications

A distinct feature of the FASP software project is that it is an open ended project. It contains a basic kernel of sources and is maintained by a team of developers with the expertise to build efficient solvers for a wide range of complex numerical models.

As typical for an open-source software, the further development of FASP project will also be based on the involvement of the community. While we have our own plans for expanding FASP's capabilities, we also count on the users' input in providing requests for, as well as, contributions to, the expansion of FASP in different application areas. Our team is ready to provide (or help with) the design and the implementation of efficient solvers based on the FASP kernel to best meet the goals and the requirements of our users.

The FASP software has been successfully used to build efficient solvers for several discretized PDEs and systems of PDEs: general scalar elliptic equations; linear elasticity; Brinkman equation; bi-harmonic equation; Stokes and Navier-Stokes equations; $H(\mathrm{curl})/H(\mathrm{div})$ systems; Maxwell's system. The resulting solvers have been applied in simulations from fluid dynamics, underground water simulation, fluid-structure interactions, Oldryod-B and Johnson-Segalman models, black-oil model, and magnetohydrodynamics (MHD).

Several of these benchmark problems are included as examples in the open-source distribution, others are under development or have more restrictive licensing.

1.3 How to use this guide

This user's guide describes how to use the existing solvers in FASP via a couple of simple tutorial problems. The user's guide is a self-contained document but does *not* provide any details about the algorithms or their implementation. Along with this guide, we provide a reference manual[2] for

[2] Available online at http://fasp.sourceforge.net. It is also available in "faspsolver/doc/doc.zip".

technical details on the implementation which includes references. We recommend that the users read these references to better understanding of the code. Furthermore, since FASP is under heavy development, please use this guide with caution because the code might have been changed before this document is updated.

1.4 How to obtain FASP

There are several ways to download the FASP source files. We recommend users download the most updated version from the FASP page on SourceForge.

Downloading from SourceForge

The most updated version of FASP can be downloaded directly from

http://fasp.sf.net/download/faspsolver.zip

Downloading from BitBucket

FASP is also hosted on *BitBucket.org*[3] using Mercurial (Hg)[4]. A Hg client for GNU Linux, Mac OS X, or Windows can be downloaded from

http://mercurial.selenic.com/downloads/

There are also many other third-party clients which provides Hg services, for example: EasyMercurial[5] (cross platform) and SourceTree[6] (for Mac OS X only).

As a DVCS (Distributed Version Control System) source-control software, Hg is relatively new. But compared with other tools like Git, Hg is considered *friendlier* with a lower learning curve. This is despite the fact that Hg uses two distinct sets of commands and two distinct vocabularies for operations depending upon whether the repository is local or remote. Documentation for Hg is substantially better, including a book[7]. They've also had the advantage of trying the documentation on a fairly savvy group of developers (Mozilla) who gave them lots of feedback that helped polish the rough edges.

Linux or Mac OS X

First, you need to obtain a free copy of FASP kernel functions from our public Hg repository. If you are downloading FASP for the first time, you can clone the repository to your local machine:

[3] Official website: https://bitbucket.org/
[4] Official website: http://mercurial.selenic.com/
[5] Official website: http://easyhg.org
[6] Official website: http://www.sourcetreeapp.com
[7] The hgbook, http://hgbook.red-bean.com/

```
"Download FASP kernel subroutines via HTTPS"

$ hg clone https://faspusers@bitbucket.org/fasp/faspsolver
```

If you have any problems when clone this repository, please send us an email to faspdev@gmail.com.

After a long pause[8], you should have obtained "*faspsolver*" in your current directory successfully. If you have already cloned the repository before, you can just pull a new version and update your local version with it: Go to your local "*faspsolver*" directory and then

```
"Pull a new version from BitBucket"
$ hg pull

"Update you local version to the new version"
$ hg update
```

Windows OS

If you are using Windows, you may want to install TortoiseHg[9]. After installing it, the TortoiseHg menu has been merged into the right-click menu of Windows Explore. You could download FASP copy from BitBucket.org. Choose "TortoiseHg" `-->` "Clone" in the pop-up menu, the source address is

https://faspusers@bitbucket.org/fasp/faspsovler

Then press "Clone" and you will obtain "faspsolver" in the directory you set.

1.5 Building and installing the FASP library and examples

FASP has been tested using the compilers and built-in libraries of several Linux distributions (`Cent OS`, `Debian`, `Fedora`, `RedHat`, `Ubuntu`) Mac OS X 10.6 and later (Leopard, Snow Leopard, Lion, Mavericks, Yosemite, El Capitan), and Windows (XP, Win 7) with several compliers, including `gcc`, `g++`, `clang`, `icc`, `VC++`. FASP also easily links to applications written in Fortran and this has been tested with `gfortran`, `g95`, `ifort` Fortran compilers.

[8] In fact, a very long pause. This is because the initial clone with copy all the history data which is about 400MB in total. Depending on the speed of your network, it could take 15 minutes to one hour.

[9] Official website: http://tortoisehg.bitbucket.org/

FASP on Linux or Mac OS X

To build the FASP library for these operating systems. Open a terminal window, where you can issue commands from the command line and do the following: (1) go to the main FASP directory (we will refer to it as `$(faspsolver)` from now on); (2) modify the "*FASP.mk.example*" file to math your system and save it as "FASP.mk"; (3) then execute:

```
$ make config
$ make install
```

These two commands build the FASP library/header files. It installs the library in `$(faspsolver)/lib` and the header files in `$(faspsolver)/include`. It also creates a file `$(faspsolver)/Config.mk` which contains few of the configuration variables and can be loaded by external project Makefiles (see §1.6 for details on `$(faspsolver)Config.mk`).

If you do not have "FASP.mk" present in the current directory, default settings will be used for building and installation FASP.

Next, if you would like to try some of the examples that come with FASP, you can build the "test" and "tutorial" targets as follows:

```
$ make test
$ make tutorial
```

Equivalently, you may also build the test suite and the tutorial examples by using the "local" Makefile(s) in `$(faspsolver)/test` and `$(faspsolver)/tutorial`.

```
$ make -C test
$ make -C tutorial
```

Note: While these two approaches to build the FASP test suite and the FASP examples produce equivalent result in most cases, we note an important difference. The former approach uses a `CMake` installation process. The latter works without invoking `Cmake` and represents an example of how one may link an external project with the FASP library. We refer to §1.6 below for more details.

If everything went all right, you can go to the "`faspsolver/test`" directory and try to run a test problem:

```
$ ./test.ex
```

If you need help with the available options, type

```
$ make help
```

and you will get the following screen

```
=============================================================
||   Fast Auxiliary Space Preconditioners (FASP)    ||
=============================================================

Quick start:

To tune compiling options for FASP, copy "FASP.mk.example" to "FASP.mk" and put
user-defined setting there and then type "make config; make install".

More options:
=============================================================================
$ make config              # Configure the building environment
$ make config CC=gcc       # Configure with a specific C compiler
$ make config shared=yes   # Configure to build shared library instead of static
$ make config debug=yes    # Configure with compiler debug options ON
$ make config debug=all    # Configure with FASP internal debug options ON
$ make config openmp=yes   # Configure with OpenMP support
$ make config prefix=dir   # Configure installation directory
=============================================================================
$ make                     # Compile the library (after "make config")
$ make install             # Install FASP library and header files
$ make uninstall           # Remove the files installed by "make install"
$ make test                # Install FASP test examples
$ make tutorial            # Install FASP tutorial examples
$ make headers             # Generate function declarations automatically
$ make version             # Show version information
$ make docs                # Generate the FASP documentation with Doxygen
$ make clean               # Remove obj files but retain configuration options
$ make distclean           # Remove build directory and cleans test & tutorial
$ make help                # Show this screen
=============================================================================
```

Many options can be changed in "FASP.mk", as well as from the command line. For example,

```
$ make config CC=gcc49 prefix=/usr/local
$ sudo make install
```

will install in the FASP library in `/usr/local/lib` and the include files in `/usr/local/include` so that they may be accessed by multiple users.

The example given above in most cases will require administrative privileges from the user, i.e. using `sudo` or other equivalent mechanism, to install in a system directory (such as `/usr/local` in our example). We do not recommend such way of installing FASP, although it will work in most cases if the user has administrative privileges. We recommend installation of FASP library/headers locally and then, if needed, copying them to a different location.

To easily uninstall FASP and clean up the working directory, FASP comes with an automatic uninstallation script; you can run

```
$ make uninstall
$ make distclean
```

Windows 7

We provide a Visual Studio 2010 (VS10) distribution and a VS10 distribution of FASP for Windows users. For example, you can just open "`faspsolver/vs10/faspsolver-vs10.sln`" if you are using VS08 as your default developing environment. Then a single-click at the "Build Solution" on the menu or "F7" key will give you all the FASP libraries and the test programs in "`faspsolver/test/`". The way for building in VS10 is similar.

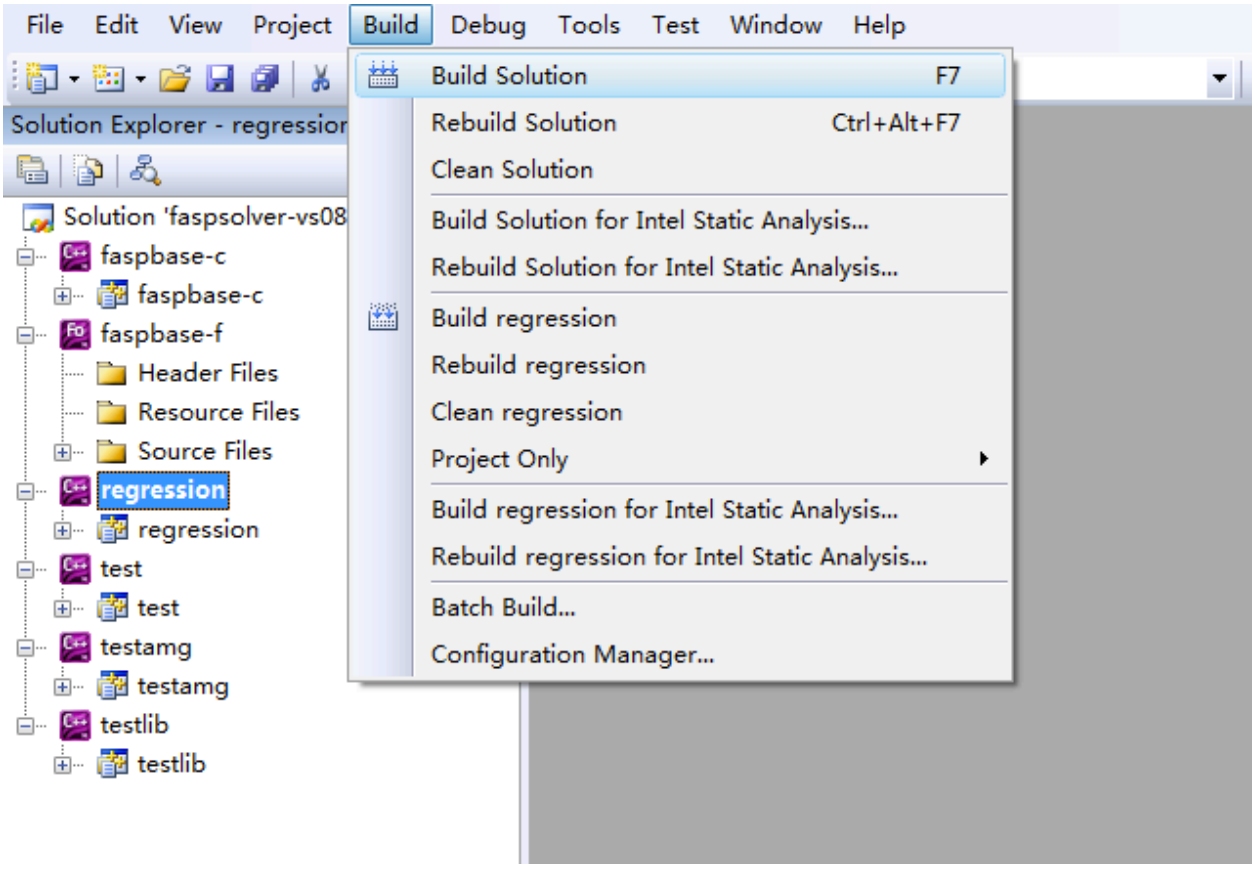

Figure 1.1: Build FASP using Visual Studio 2010.

You need a C/C++ complier and the Visual Studio to build FASP. For example, the build can be accomplished using either Microsoft Visual C++ or Intel C compiler.

If you are using other versions of Visual Studio (like VS05 or VS12), we advise NOT to convert the "VS10" files to your newer VS version automatically because the FASP source files might be removed by the Visual Studio. In such a case, we recommend that you create your own version to build all the libraries and test programs.

If you need to build a VS FASP yourself, you need to create 5 projects:

1. "faspbase-c" contains all the ".c" and ".inl" files in the directory "./base/src/". You should add "./base/include" in Additional Directories. This project contains the core subroutines of faspsolver.
2. "faspbase-f" contains all the ".f" files in "./base/extra/sparsekit".
3. "testlib" contains all the ".c" files in "./test/src/". You should add "./test/include" in Additional Directories.
4. "test" is an executing program for test purpose in FASP. The source file is "./test/main/test.c".
5. "regression" is another executing program, which contains several methods to test the problems. The source file is "./test/main/regression.c".

NOTE: If you are using Visual C++, all the C files should be compiled as C++ code (by using the /TP compiling option).

After a successful build on VS, you will have two static libraries named "faspbase-c-vs08.lib" and "faspbase-f-vs08.lib". You can use the "lib" command to wrap them together as one single file (e.g. FASP.lib) for better portability. For example:

```
C:\FASP> lib /ltcg /out:FASP.lib faspbase-c-vs08.lib faspbase-f-vs08.lib
```

Using a TCL based GUI for installation

For users who like more a GUI based installation, we provide a simple TCL Graphical User Interface (GUI) for building the FASP library. On a machine running Linux or Mac OS X with `Tcl/Tk` installed, you may invoke the GUI by typing

```
$ wish FASP_install.tcl
```

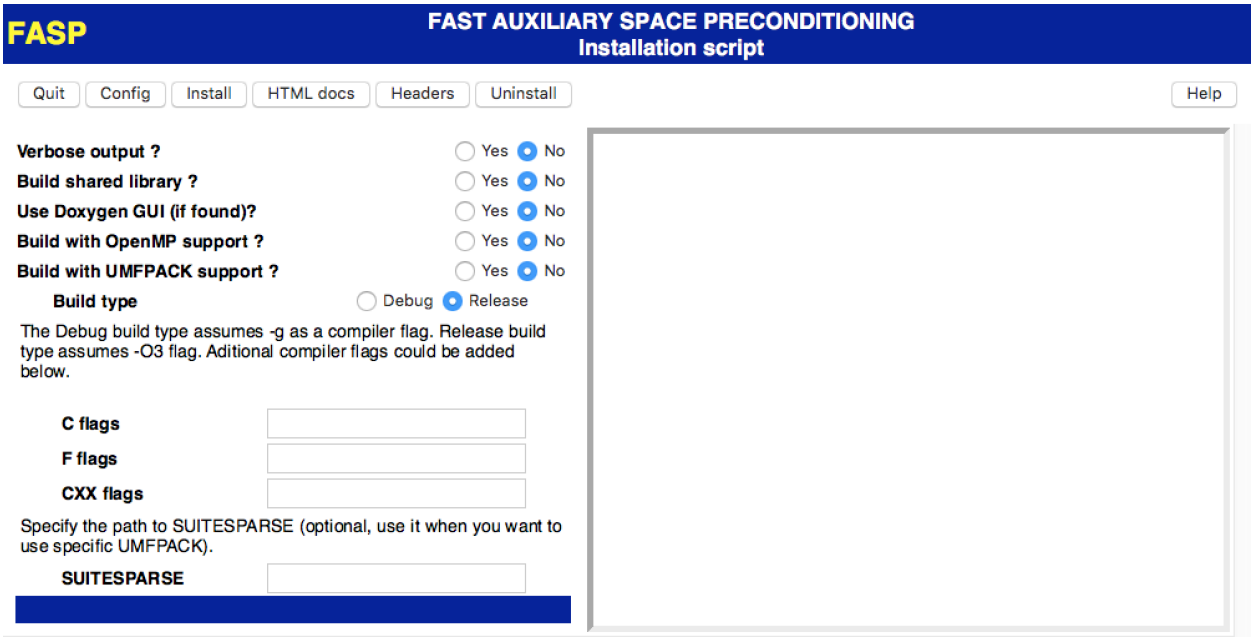

Figure 1.2: Install FASP using the TCL GUI on Mac OS X El Capitan.

If all is OK, you should see on your screen the FASP window as shown in Figure 1.2. The rest of the building process is more or less straightforward: After choosing appropriate parameters, click "Config" first, followed by clicking "Install".

External libraries

There are a few *optional* external libraries that you might want to use, including memory allocation routines, direct solvers, ILU methods, discretization packages, etc. FASP has interfaces to several of them, for example, FASP can be linked to use `UMFPack`, `SuperLU`, `MUMPS`, `SparseKit`, `dlmalloc`.

1.6 Linking your own project with FASP

The FASP distribution comes with two "local" Makefile(s) in the sub-directories for "test" and "tutorial", namely, `$(faspsolver)/test/Makefile` and `$(faspsolver)/tutorial/Makefile`. These two makefiles can be used to build the FASP tests and tutorial examples. They use minimal information about the library built. For convenience, at configuration time, such information is stored in `$(faspsolver)/Config.mk` file for later use. A typical contents of such file is given below:

```
########################## Automatically generated ###################
# Fast Auxiliary Space Preconditioners (FASP)
#
######################################################################
```

```
# This file is rewritten when "make config" is run.
# It is (s)included by test/Makefile and tutorial/Makefile
#
#############################################################################
fasp_prefix=/path/to/faspsolver
fasp_library=libfasp.a
CC=gcc
CXX=g++
FC=gfortran
#############################################################################
```

The variables defined in this file can also be set directly in `$(faspsolver)/test/Makefile`, `$(faspsolver)/tutorial/Makefile`, or, in your own Makefile. An external project can be compiled and linked with FASP by following the rules set in `$(faspsolver)/tutorial/Makefile` (included below):

```
1  #############################################################################
2  # Fast Auxiliary Space Preconditioners (FASP)
3  #
4  #############################################################################
5  # Makefile for building the tutorial executables. If the file
6  # ../Config.mk exists it will take the values of configuration
7  # variables from there. Otherwise, they have to be user supplied below.
8  #############################################################################
9
10 fasp_prefix = not-defined-yet
11 fasp_library = not-defined-yet
12 CC = not-defined-yet
13 FC = not-defined-yet
14 CXX = not-defined-yet
15
16 # include the configuration written by CMake at config time if found
17 sinclude ../Config.mk
18
19 ifeq ($(fasp_prefix),not-defined-yet)
20     fasp_prefix = ..
21 endif
22 ifeq ($(fasp_library),not-defined-yet)
23     fasp_library = libfasp.a
24 endif
25 ifeq ($(CC),not-defined-yet)
26    CC=gcc
27 endif
28 ifeq ($(FC),not-defined-yet)
29    FC=gfortran
30 endif
31 ifeq ($(CXX),not-defined-yet)
32    CXX=g++
33 endif
34
35 CFLAGS=-I$(fasp_prefix)/include
36 CFLAGS+=-O3
```

```
37 FFLAGS=-I$(fasp_prefix)/include
38 FFLAGS+=-O3
39 LINKER = $(FC) # because of linking with Fortran files
40 LFLAGS = -L$(fasp_prefix)/lib -lfasp
41 fasp_lib_file=$(fasp_prefix)/lib/$(fasp_library)
42
43 examples = poisson-amg-c.ex poisson-its-c.ex poisson-pcg-c.ex \
44           poisson-gmg-c.ex spe01-its-c.ex \
45           poisson-amg-f.ex poisson-pcg-f.ex
46 examples_f = $(filter %-f.ex,$(examples))
47 examples_c = $(filter-out %-f.ex,$(examples))
48
49 .PHONY: all clean
50
51 all:    $(examples_c) $(examples_f)
52
53 %-c.ex: main/%.c $(fasp_lib_file)
54     @$(CC) -c $(CFLAGS) -o main/$@.o $<
55     @$(LINKER) -o $@ main/$@.o $(LFLAGS)
56     @echo 'Building executable file $@'
57
58 %-f.ex: main/%.f90 $(fasp_lib_file)
59     @$(FC) -c $(FFLAGS) -o main/$@.o $<
60     @$(FC) -o $@ main/$@.o $(LFLAGS)
61     @echo 'Building executable file $@'
62
63 $(fasp_lib_file):
64     $(error The FASP library $@ is not found)
65
66 clean:
67     @-rm -f *.o main/*.o *~
68
69 distclean: clean
70     @-rm -f poisson-amg-c.ex poisson-its-c.ex poisson-pcg-c.ex \
71                 poisson-gmg-c.ex spe01-its-c.ex \
72                 poisson-amg-f.ex poisson-pcg-f.ex
```

Chapter 2

A brief tutorial

In this chapter, we discuss several simple examples included with this FASP distribution and demonstrating how to use the FASP package for solving linear systems. We read the matrices from disk files (the files are also included in the FASP distribution). All the examples in this section can be found inside "`faspsolver/tutorial/`".

After you successfully build FASP (see §1.5), just go to the "`faspsolver/tutorial/`" directory and the tutorial examples should be ready to run.

In this section we mainly discuss the C version of these examples; the FASP distribution also includes F90 versions of some of the examples.

In the description below, we display a typical output from runs of each of the examples. Note that the actual output depends on the solver parameters, and, on your computer it may be be different than what you see here.

2.1 Example 1: An AMG solver for the Poisson equation

The first example is a standard one: We read a symmetric positive definite matrix A and right-hand side b from harddisk and then we solve $Ax = b$ using the classical AMG method [**?**, **?**, **?**]; see §3.6. In this example the matrix A included with the FASP distribution corresponds to a discretization with continuous piecewise linear finite elements of the Poisson equation

$$-\Delta u = f$$

(with the Dirichlet boundary conditions) on a triangulation of a bounded domain Ω.

```
1 /*! \file  poisson-amg.c
2  *
3  *  \brief The first test example for FASP: using AMG to solve
4  *         the discrete Poisson equation from P1 finite element.
```

```
 *         C version.
 *
 *  \note  Solving the Poisson equation (P1 FEM) with AMG: C version
 *
 *--------------------------------------------------------------------------------
 *  Copyright (C) 2011--2017 by the FASP team. All rights reserved.
 *  Released under the terms of the GNU Lesser General Public License 3.0 or later.
 *--------------------------------------------------------------------------------
 */

#include "fasp.h"
#include "fasp_functs.h"

/**
 * \fn int main (int argc, const char * argv[])
 *
 * \brief This is the main function for the first example.
 *
 * \author Chensong Zhang
 * \date   12/21/2011
 *
 * Modified by Chensong Zhang on 09/22/2012
 */
int main (int argc, const char * argv[])
{
    input_param     inparam;  // parameters from input files
    AMG_param       amgparam; // parameters for AMG

    printf("\n=========================================");
    printf("\n||   FASP: AMG example -- C version   ||");
    printf("\n=========================================\n\n");

    // Step 0. Set parameters: We can use ini/amg.dat
    fasp_param_set(argc, argv, &inparam);
    fasp_param_init(&inparam, NULL, &amgparam, NULL, NULL);

    // Set local parameters using the input values
    const int print_level = inparam.print_level;

    // Step 1. Get stiffness matrix and right-hand side
    // Read A and b -- P1 FE discretization for Poisson. The location
    // of the data files is given in "ini/amg.dat".
    dCSRmat A;
    dvector b, x;
    char filename1[512], *datafile1;
    char filename2[512], *datafile2;

    // Read the stiffness matrix from matFE.dat
    strncpy(filename1, inparam.workdir, 128);
    datafile1="csrmat_FE.dat"; strcat(filename1, datafile1);

    // Read the RHS from rhsFE.dat
    strncpy(filename2, inparam.workdir, 128);
```

```
58      datafile2="rhs_FE.dat"; strcat(filename2, datafile2);
59
60      fasp_dcsrvec_read2(filename1, filename2, &A, &b);
61
62      // Step 2. Print problem size and AMG parameters
63      if (print_level>PRINT_NONE) {
64          printf("A: m = %d, n = %d, nnz = %d\n", A.row, A.col, A.nnz);
65          printf("b: n = %d\n", b.row);
66          fasp_param_amg_print(&amgparam);
67      }
68
69      // Step 3. Solve the system with AMG as an iterative solver
70      // Set the initial guess to be zero and then solve it
71      // with AMG method as an iterative procedure
72      fasp_dvec_alloc(A.row, &x);
73      fasp_dvec_set(A.row, &x, 0.0);
74
75      fasp_solver_amg(&A, &b, &x, &amgparam);
76
77      // Step 4. Clean up memory
78      fasp_dcsr_free(&A);
79      fasp_dvec_free(&b);
80      fasp_dvec_free(&x);
81
82      return FASP_SUCCESS;
83  }
84
85  /*---------------------------------*/
86  /*--        End of File          --*/
87  /*---------------------------------*/
```

Since this is the first example, we will explain it in some detail:

- Line 1 tells the Doxygen documentation system[1] that the filename is "`poisson-amg.c`". Line 3–5 tells the Doxygen what is the purpose of this file (function).

- Line 15–16 includes the main FASP header file "`fasp.h`" and FASP function declarations header "`fasp_functs.h`". These two headers shall be included in all files that requires FASP subroutines. Please also be noted that the function declarations in "`fasp_functs.h`" are automatically generated from the source files by an `awk` script and we do not recommend modifying this file, since your changes may be lost.

- Line 38–39 sets solver parameters using the default parameters or from the command line options; see more discussions in §2.6. In the "`tutorial/ini/amg.dat`" file, we can set the location of the data files, type of solvers, maximal number of iteration numbers, convergence tolerance, and many other parameters for iterative solvers.

[1] Doxygen http://www.doxygen.org is a useful tool for generating documentation from annotated sources. We use it in FASP development.

- Line 47 defines a sparse matrix A in the compressed sparse row (CSR) format. Line 48 defines two vectors: the right-hand side b and the numerical solution x. We refer to §3.1 for definitions of vectors and general sparse matrices.
- Line 60 reads the matrix and the right-hand side from two disk files. Line 54–58 defines the filenames of them.
- Line 60–64 prints basic information of coefficient matrix, right-hand side, and solver parameters.
- Line 72–73 allocates memory for the solution vector x and set its initial value to be all zero.
- Line 75 solves $Ax = b$ using the AMG method. Type of the AMG method and other parameters have been given in "`amgparam`" at Line 36; see §3.6.
- Line 78–80 frees up memory allocated for A, b, and x.

To run this example, type:

```
$ ./poisson-amg-c.ex
```

A sample output is listed as follows:

```
=============================================
||   FASP: AMG example -- C version    ||
=============================================

fasp_dcsrvec_read2: reading file ../data/csrmat_FE.dat...
fasp_dcsrvec_read2: reading file ../data/rhs_FE.dat...
A: m = 3969, n = 3969, nnz = 27281
b: n = 3969

       Parameters in AMG_param
---------------------------------------------
AMG print level:                    2
AMG max num of iter:                50
AMG type:                           1
AMG tolerance:                      1.00e-06
AMG max levels:                     20
AMG cycle type:                     1
AMG coarse solver type:             0
AMG scaling of coarse correction:   0
AMG smoother type:                  2
AMG smoother order:                 1
AMG num of presmoothing:            1
AMG num of postsmoothing:           1
AMG coarsening type:                1
AMG interpolation type:             1
AMG dof on coarsest grid:           500
```

```
AMG strong threshold:                0.3000
AMG truncation threshold:            0.2000
AMG max row sum:                     0.9000
AMG aggressive levels:               0
AMG aggressive path:                 1
-------------------------------------------------


Setting up Classical AMG ...
-------------------------------------------------------------------
  Level   Num of rows    Num of nonzeros   Avg. NNZ / row
-------------------------------------------------------------------
    0          3969             27281            6.87
    1          1985             28523           14.37
    2           541              7951           14.70
    3           141              1803           12.79
-------------------------------------------------------------------
  Grid complexity = 1.672   |  Operator complexity = 2.403
-------------------------------------------------------------------
Classical AMG setup costs 0.0044 seconds.
-------------------------------------------------------------------
It Num |    ||r||/||b||    |      ||r||       |  Conv. Factor
-------------------------------------------------------------------
     0 |  1.000000e+00    |  7.514358e+00    |      -.--
     1 |  9.851978e-03    |  7.403129e-02    |      0.0099
     2 |  3.507451e-04    |  2.635624e-03    |      0.0356
     3 |  1.764023e-05    |  1.325550e-04    |      0.0503
     4 |  8.820794e-07    |  6.628261e-06    |      0.0500
Number of iterations = 4 with relative residual 8.820794e-07.
AMG solve costs 0.0019 seconds.
AMG totally costs 0.0066 seconds.
```

We also provide a Fortran 90 example, which does the same thing as this C code except it gives less output, in "tutorial/main/poisson-amg.f90". Users who would like to call FASP solver from a Fortran based application can see how to do this example.

```
1  !> \file  poisson-amg.f90
2  !>
3  !> \brief The first test example for FASP: using AMG to solve
4  !>        the discrete Poisson equation from P1 finite element.
5  !>        F90 version.
6  !>
7  !> \note  Solving the Poisson equation (P1 FEM) with AMG: F90 version
8  !>
9  !>--------------------------------------------------------------------------------
10 !>  Copyright (C) 2011--2017 by the FASP team. All rights reserved.
11 !>  Released under the terms of the GNU Lesser General Public License 3.0 or later.
12 !>--------------------------------------------------------------------------------
13
14 program test
15
16   implicit none
```

```
17
18  double precision, dimension(:), allocatable :: u, b, a
19  integer,          dimension(:), allocatable :: ia, ja
20
21  integer          :: iufile, n, nnz, i, prt_lvl, maxit
22  double precision :: tol
23
24  print*, ""
25  write(*,"(A)") "============================================"
26  write(*,"(A)") "||   FASP: AMG example -- F90 version   ||"
27  write(*,"(A)") "============================================"
28  print*, ""
29
30  ! Step 0: user defined variables
31  prt_lvl = 3
32  maxit = 100
33  tol = 1.0d-6
34  iufile = 1
35
36  ! Step 1: read A and b
37
38  !===> Read data A from file
39  open(unit=iufile,file='../data/csrmat_FE.dat')
40
41  read(iufile,*) n
42  allocate(ia(1:n+1))
43  read(iufile,*) (ia(i),i=1,n+1)
44
45  nnz=ia(n+1)-ia(1)
46  allocate(ja(1:nnz),a(1:nnz))
47  read(iufile,*) (ja(i),i=1,nnz)
48  read(iufile,*) (a(i),i=1,nnz)
49
50  close(iufile)
51
52  !===> Read data b from file
53  open(unit=iufile,file='../data/rhs_FE.dat')
54
55  read(iufile,*) n
56  allocate(b(1:n))
57  read(iufile,*) (b(i),i=1,n)
58
59  close(iufile)
60
61  !===> Shift the index to start from 0 (for C routines)
62  forall (i=1:n+1) ia(i)=ia(i)-1
63  forall (i=1:nnz) ja(i)=ja(i)-1
64
65  ! Step 2: Solve the system
66
67  !===> Initial guess
68  allocate(u(1:n))
69  u=0.0d0
```

```
70    call fasp_fwrapper_amg(n,nnz,ia,ja,a,b,u,tol,maxit,prt_lvl)
71
72    ! Step 3: Clean up memory
73    deallocate(ia,ja,a)
74    deallocate(b,u)
75
76  end program test
77
78  !/*---------------------------------*/
79  !/*--        End of File          --*/
80  !/*---------------------------------*/
```

2.2 Example 2: Conjugate gradient without preconditioning

In the second example, we modify the previous example slightly and solve the Poisson equation using iterative methods (here by default we use the Conjugate Gradient method without preconditioning).

```
1   /*! \file  poisson-its.c
2    *
3    *  \brief The second test example for FASP: using ITS to solve
4    *         the discrete Poisson equation from P1 finite element.
5    *
6    *  \note  Solving the Poisson equation (P1 FEM) with iterative methods: C version
7    *
8    *--------------------------------------------------------------------------------
9    *  Copyright (C) 2012--2017 by the FASP team. All rights reserved.
10   *  Released under the terms of the GNU Lesser General Public License 3.0 or later.
11   *--------------------------------------------------------------------------------
12   */
13
14  #include "fasp.h"
15  #include "fasp_functs.h"
16
17  /**
18   * \fn int main (int argc, const char * argv[])
19   *
20   * \brief This is the main function for the second example.
21   *
22   * \author Feiteng Huang
23   * \date   04/13/2012
24   *
25   * Modified by Chensong Zhang on 09/22/2012
26   */
27  int main (int argc, const char * argv[])
28  {
29      input_param     inparam;  // parameters from input files
30      ITS_param       itparam;  // parameters for itsolver
31
32      printf("\n=========================================");
33      printf("\n||   FASP: ITS example -- C version    ||");
```

```
34      printf("\n=========================================\n\n");
35
36      // Step 0. Set parameters: We can use ini/its.dat
37      fasp_param_set(argc, argv, &inparam);
38      fasp_param_init(&inparam, &itparam, NULL, NULL, NULL);
39
40      // Set local parameters
41      const int print_level = inparam.print_level;
42
43      // Step 1. Get stiffness matrix and right-hand side
44      // Read A and b -- P1 FE discretization for Poisson. The location
45      // of the data files is given in "ini/its.dat".
46      dCSRmat A;
47      dvector b, x;
48      char filename1[512], *datafile1;
49      char filename2[512], *datafile2;
50
51      // Read the stiffness matrix from matFE.dat
52      strncpy(filename1, inparam.workdir, 128);
53      datafile1="csrmat_FE.dat"; strcat(filename1, datafile1);
54
55      // Read the RHS from rhsFE.dat
56      strncpy(filename2, inparam.workdir, 128);
57      datafile2="rhs_FE.dat"; strcat(filename2, datafile2);
58
59      fasp_dcsrvec_read2(filename1, filename2, &A, &b);
60
61      // Step 2. Print problem size and ITS parameters
62      if (print_level>PRINT_NONE) {
63          printf("A: m = %d, n = %d, nnz = %d\n", A.row, A.col, A.nnz);
64          printf("b: n = %d\n", b.row);
65          fasp_param_solver_print(&itparam);
66      }
67
68      // Step 3. Solve the system with ITS as an iterative solver
69      // Set the initial guess to be zero and then solve it using standard
70      // iterative methods, without applying any preconditioners
71      fasp_dvec_alloc(A.row, &x);
72      fasp_dvec_set(A.row, &x, 0.0);
73
74      fasp_solver_dcsr_itsolver(&A, &b, &x, NULL, &itparam);
75
76      // Step 4. Clean up memory
77      fasp_dcsr_free(&A);
78      fasp_dvec_free(&b);
79      fasp_dvec_free(&x);
80
81      return FASP_SUCCESS;
82  }
83
84  /*---------------------------------*/
85  /*--        End of File          --*/
86  /*---------------------------------*/
```

This example is very similar to the first example and we briefly explain the differences:

- Line 71–72 allocates memory for the solution vector x and set its initial value to be all zero.
- Line 74 solves $Ax = b$ using the general interface for Krylov subspace methods. Type the iterative method and other parameters have been specified in "`itparam`"; see §3.5 for details.

To run this example, we can simply type:

```
$ ./poisson-its-c.ex
```

A sample output is as follows:

```
=============================================
||   FASP: ITS example -- C version    ||
=============================================

fasp_dcsrvec_read2: reading file ../data/csrmat_FE.dat...
fasp_dcsrvec_read2: reading file ../data/rhs_FE.dat...
A: m = 3969, n = 3969, nnz = 27281
b: n = 3969

       Parameters in ITS_param
-----------------------------------------------
Solver print level:                2
Solver type:                       1
Solver precond type:               2
Solver max num of iter:            500
Solver tolerance:                  1.00e-06
Solver stopping type:              1
-----------------------------------------------


Calling CG solver (CSR) ...
-------------------------------------------------------------
It Num |    ||r||/||b||    |      ||r||       |  Conv. Factor
-------------------------------------------------------------
     0 |   1.000000e+00    |   7.514358e+00   |      -.--
     1 |   5.078029e-01    |   3.815813e+00   |      0.5078
     2 |   3.728856e-01    |   2.801996e+00   |      0.7343
     3 |   3.359470e-01    |   2.524426e+00   |      0.9009
     4 |   2.590574e-01    |   1.946650e+00   |      0.7711
     5 |   2.380797e-01    |   1.789016e+00   |      0.9190
     6 |   1.992579e-01    |   1.497295e+00   |      0.8369
     7 |   1.847971e-01    |   1.388631e+00   |      0.9274
     8 |   1.619777e-01    |   1.217158e+00   |      0.8765
     9 |   1.513446e-01    |   1.137257e+00   |      0.9344
    10 |   1.364935e-01    |   1.025661e+00   |      0.9019
    11 |   1.283425e-01    |   9.644117e-01   |      0.9403
    12 |   1.179652e-01    |   8.864327e-01   |      0.9191
    13 |   1.115146e-01    |   8.379605e-01   |      0.9453
```

```
    14 |  1.038726e-01  |  7.805360e-01  |     0.9315
    15 |  9.863412e-02  |  7.411721e-01  |     0.9496
    16 |  9.277360e-02  |  6.971341e-01  |     0.9406
    17 |  8.842679e-02  |  6.644706e-01  |     0.9531
    18 |  8.378399e-02  |  6.295829e-01  |     0.9475
    19 |  8.011023e-02  |  6.019770e-01  |     0.9562
    20 |  7.633221e-02  |  5.735875e-01  |     0.9528
    21 |  7.317756e-02  |  5.498824e-01  |     0.9587
    22 |  7.003292e-02  |  5.262524e-01  |     0.9570
    23 |  6.728610e-02  |  5.056119e-01  |     0.9608
    24 |  6.461736e-02  |  4.855580e-01  |     0.9603
    25 |  6.219614e-02  |  4.673640e-01  |     0.9625
    26 |  5.989276e-02  |  4.500557e-01  |     0.9630
    27 |  5.773520e-02  |  4.338429e-01  |     0.9640
    28 |  5.571758e-02  |  4.186818e-01  |     0.9651
    29 |  5.377630e-02  |  4.040944e-01  |     0.9652
    30 |  5.198586e-02  |  3.906404e-01  |     0.9667
    31 |  5.022413e-02  |  3.774021e-01  |     0.9661
    32 |  4.861699e-02  |  3.653255e-01  |     0.9680
    33 |  4.700598e-02  |  3.532197e-01  |     0.9669
    34 |  4.554874e-02  |  3.422696e-01  |     0.9690
    35 |  4.406559e-02  |  3.311246e-01  |     0.9674
    36 |  4.273253e-02  |  3.211075e-01  |     0.9697
    37 |  4.135901e-02  |  3.107864e-01  |     0.9679
    38 |  4.013076e-02  |  3.015569e-01  |     0.9703
    39 |  3.885861e-02  |  2.919975e-01  |     0.9683
    40 |  3.776252e-02  |  2.837611e-01  |     0.9718
    41 |  3.678565e-02  |  2.764205e-01  |     0.9741
    42 |  3.648645e-02  |  2.741722e-01  |     0.9919
    43 |  3.725368e-02  |  2.799375e-01  |     1.0210
    44 |  3.922957e-02  |  2.947850e-01  |     1.0530
    45 |  4.003513e-02  |  3.008383e-01  |     1.0205
    46 |  3.683219e-02  |  2.767703e-01  |     0.9200
    47 |  3.161285e-02  |  2.375503e-01  |     0.8583
    48 |  2.944107e-02  |  2.212307e-01  |     0.9313
    49 |  2.961834e-02  |  2.225628e-01  |     1.0060
    50 |  2.774118e-02  |  2.084571e-01  |     0.9366
```

2.3 Example 3: Conjugate gradient with preconditioning

This example is a bit more involved and is a modification of the previous one. In this example, we wish to demonstrate how to use a the FASP library and run a preconditioned conjugate conjugate gradient (PCG) method.

```
1 /*! \file  poisson-pcg.c
2  *
3  *  \brief The third test example for FASP: using PCG to solve
4  *         the discrete Poisson equation from P1 finite element.
5  *         C version.
6  *
```

```
 *  \note  Solving the Poisson equation (P1 FEM) with PCG: C version
 *
 *--------------------------------------------------------------------------------
 *  Copyright (C) 2012--2017 by the FASP team. All rights reserved.
 *  Released under the terms of the GNU Lesser General Public License 3.0 or later.
 *--------------------------------------------------------------------------------
 */

#include "fasp.h"
#include "fasp_functs.h"

/**
 * \fn int main (int argc, const char * argv[])
 *
 * \brief This is the main function for the third example.
 *
 * \author Feiteng Huang
 * \date   05/17/2012
 *
 * Modified by Chensong Zhang on 09/22/2012
 */
int main (int argc, const char * argv[])
{
    input_param     inparam;  // parameters from input files
    ITS_param       itparam;  // parameters for itsolver
    AMG_param       amgparam; // parameters for AMG
    ILU_param       iluparam; // parameters for ILU

    printf("\n=========================================");
    printf("\n||   FASP: PCG example -- C version   ||");
    printf("\n=========================================\n\n");

    // Step 0. Set parameters: We can use ini/pcg.dat
    fasp_param_set(argc, argv, &inparam);
    fasp_param_init(&inparam, &itparam, &amgparam, &iluparam, NULL);

    // Set local parameters
    const SHORT print_level = itparam.print_level;
    const SHORT pc_type     = itparam.precond_type;
    const SHORT stop_type   = itparam.stop_type;
    const INT   maxit       = itparam.maxit;
    const REAL  tol         = itparam.tol;

    // Step 1. Get stiffness matrix and right-hand side
    // Read A and b -- P1 FE discretization for Poisson. The location
    // of the data files is given in "ini/pcg.dat".
    dCSRmat A;
    dvector b, x;
    char filename1[512], *datafile1;
    char filename2[512], *datafile2;

    // Read the stiffness matrix from matFE.dat
    strncpy(filename1, inparam.workdir, 128);
```

```
60      datafile1="csrmat_FE.dat"; strcat(filename1, datafile1);
61
62      // Read the RHS from rhsFE.dat
63      strncpy(filename2, inparam.workdir, 128);
64      datafile2="rhs_FE.dat"; strcat(filename2, datafile2);
65
66      fasp_dcsrvec_read2(filename1, filename2, &A, &b);
67
68      // Step 2. Print problem size and PCG parameters
69      if (print_level>PRINT_NONE) {
70          printf("A: m = %d, n = %d, nnz = %d\n", A.row, A.col, A.nnz);
71          printf("b: n = %d\n", b.row);
72          fasp_param_solver_print(&itparam);
73      }
74
75      // Setp 3. Setup preconditioner
76      // Preconditioner type is determined by pc_type
77      precond *pc = fasp_precond_setup(pc_type, &amgparam, &iluparam, &A);
78
79      // Step 4. Solve the system with PCG as an iterative solver
80      // Set the initial guess to be zero and then solve it using PCG solver
81      // Note that we call PCG interface directly. There is another way which
82      // calls the abstract iterative method interface; see possion-its.c for
83      // more details.
84      fasp_dvec_alloc(A.row, &x);
85      fasp_dvec_set(A.row, &x, 0.0);
86
87      fasp_solver_dcsr_pcg(&A, &b, &x, pc, tol, maxit, stop_type, print_level);
88
89      // Step 5. Clean up memory
90      if (pc_type!=PREC_NULL) fasp_mem_free(pc->data);
91      fasp_dcsr_free(&A);
92      fasp_dvec_free(&b);
93      fasp_dvec_free(&x);
94
95      return FASP_SUCCESS;
96  }
97
98  /*---------------------------------*/
99  /*--        End of File          --*/
100 /*---------------------------------*/
```

This example is very similar to the first example, and the details are as follows.

- Line 40–41 sets default parameters. In this example, we need parameters for iterative methods, AMG preconditioner, and ILU preconditioner.
- Line 77 sets up the desired preconditioner and prepare it for the preconditioned iterative methods.
- Line 87 calls PCG to solve $Ax = b$. One can also call the general iterative method interface as in the previous example.

- Line 90 cleans up auxiliary data associated with the preconditioner in use if necessary.

To run this example, we can simply type:

```
$ ./poisson-pcg-c.ex
```

A sample output is given as follows (note that the actual output depends on the solver parameters and might be different than what you see here):

```
=============================================
||   FASP: PCG example -- C version   ||
=============================================

fasp_dcsrvec_read2: reading file ../data/csrmat_FE.dat...
fasp_dcsrvec_read2: reading file ../data/rhs_FE.dat...
A: m = 3969, n = 3969, nnz = 27281
b: n = 3969

       Parameters in ITS_param
-----------------------------------------------------
Solver print level:                2
Solver type:                       1
Solver precond type:               2
Solver max num of iter:            500
Solver tolerance:                  1.00e-06
Solver stopping type:              1
-----------------------------------------------------


Setting up Classical AMG ...
-------------------------------------------------------------------
  Level   Num of rows   Num of nonzeros   Avg. NNZ / row
-------------------------------------------------------------------
    0          3969             27281           6.87
    1          1985             28523          14.37
    2           541              7951          14.70
    3           141              1803          12.79
-------------------------------------------------------------------
  Grid complexity = 1.672   |  Operator complexity = 2.403
-------------------------------------------------------------------
Classical AMG setup costs 0.0041 seconds.

Calling CG solver (CSR) ...
-------------------------------------------------------------------
It Num |    ||r||/||b||    |      ||r||       |  Conv. Factor
-------------------------------------------------------------------
     0 |  1.000000e+00   |  7.514358e+00  |      -.--
     1 |  1.156153e-02   |  8.687750e-02  |      0.0116
     2 |  3.127181e-04   |  2.349876e-03  |      0.0270
     3 |  4.813471e-06   |  3.617014e-05  |      0.0154
     4 |  5.312526e-08   |  3.992022e-07  |      0.0110
Number of iterations = 4 with relative residual 5.312526e-08.
```

We also provide a Fortran 90 example, which does the same thing as this C code except it gives less output, in "tutorial/main/poisson-pcg.f90". Users who would like to call FASP solver from a Fortran based application can see how to do this example.

```
!> \file  poisson-pcg.f90
!>
!> \brief The third test example for FASP: using PCG to solve
!>        the discrete Poisson equation from P1 finite element.
!>        F90 version.
!>
!> \note  Solving the Poisson equation (P1 FEM) with PCG: F90 version
!>
!>--------------------------------------------------------------------------------
!>  Copyright (C) 2012--2017 by the FASP team. All rights reserved.
!>  Released under the terms of the GNU Lesser General Public License 3.0 or later.
!>--------------------------------------------------------------------------------

program test

  implicit none

  double precision, dimension(:), allocatable :: u,b
  double precision, dimension(:), allocatable :: a
  integer,          dimension(:), allocatable :: ia,ja

  integer          :: iufile, n, nnz, i, prt_lvl, maxit
  double precision :: tol

  print*, ""
  write(*,"(A)") "========================================="
  write(*,"(A)") "||   FASP: PCG example -- F90 version   ||"
  write(*,"(A)") "========================================="
  print*, ""

  ! Step 0: user defined variables
  prt_lvl = 3
  maxit = 500
  tol = 1.0d-6
  iufile = 1

  ! Step 1: read A and b

  !===> Read data A from file
  open(unit=iufile,file='../data/csrmat_FE.dat')

  read(iufile,*) n
  allocate(ia(1:n+1))
  read(iufile,*) (ia(i),i=1,n+1)

  nnz=ia(n+1)-ia(1)
```

```
47    allocate(ja(1:nnz),a(1:nnz))
48    read(iufile,*) (ja(i),i=1,nnz)
49    read(iufile,*) (a(i),i=1,nnz)
50
51    close(iufile)
52
53    !===> Read data b from file
54    open(unit=iufile,file='../data/rhs_FE.dat')
55
56    read(iufile,*) n
57    allocate(b(1:n))
58    read(iufile,*) (b(i),i=1,n)
59
60    close(iufile)
61
62    !===> Shift the index to start from 0 (for C routines)
63    forall (i=1:n+1) ia(i)=ia(i)-1
64    forall (i=1:nnz) ja(i)=ja(i)-1
65
66    ! Step 2: Solve the system
67
68    !===> Initial guess
69    allocate(u(1:n))
70    u=0.0d0
71    call fasp_fwrapper_krylov_amg(n,nnz,ia,ja,a,b,u,tol,maxit,prt_lvl);
72
73    ! Step 3: Clean up memory
74    deallocate(ia,ja,a)
75    deallocate(b,u)
76
77  end program test
78
79  !/*---------------------------------*/
80  !/*--        End of File          --*/
81  !/*---------------------------------*/
```

2.4 Example 4: An GMG solver for the Poisson equation

The geometric multigrid method (GMG) is one of the most efficient solving techniques for discrete algebraic systems arising from many types of partial differential equations [**?**, **?**]. GMG utilizes a hierarchy of grids or discretizations and reduces the error at a number of frequencies simultaneously. Because of its plausible linear complexity—i.e., the low computational cost of solving a linear system with N unknowns is $O(N)$—the GMG method is one of the most popular Poisson solvers. Although the GMG's applicability is limited as it requires explicit information on the hierarchy of the discrete system, when it can be applied, GMG is far more efficient than its algebraic version, the algebraic multigrid (AMG) method.

We now give a simple example on calling the geometric multigrid for solving the Poisson's

equation in 2D (discretized by the standard five-point finite difference stencil). Consider the Poisson equation

$$\begin{cases} -\Delta u &= f & \text{in } \Omega \\ u &= 0 & \text{on } \partial\Omega, \end{cases}$$

where $\Omega = (0,1)^2 \subset \mathbb{R}^2$. The main reason why we choose this simplest possible setting is to emphasize that, even for a simple problem, the new heterogeneous architectures present challenges for numerical implementation. Another reason is to allow us to use explicit stencils and to avoid the bottleneck of sparse matrix-vector production. The standard central finite difference method is applied to discretize the Poisson's equation. In other words, the Laplace operator is discretized by the classical second-order central difference scheme. After discretization, we end up with a system of linear equations:

$$\mathbf{A}\vec{u} = \vec{f}.$$

We use the five-point central difference scheme in 2D. Consider a uniform square mesh of $\Omega = [0,1]^2$ with size $h = \frac{1}{n}$ and in which $x_i = ih$, $y_j = jh\,(i,j = 0,1,\ldots,n)$. Let $u_{i,j}$ be the numerical approximation of $u(x_i, y_j)$. The five-point central difference scheme for solving the Poisson's equation in 2D can be written as follows:

$$-u_{i-1,j} - u_{i,j-1} + 4u_{i,j} - u_{i+1,j} - u_{i,j+1} = h^2 f(x_i, y_j) \qquad i,j = 1,2,\ldots,n-1.$$

The sample code for this solver can be found in "tutorial/main/poisson-gmg.c" and a piece of the source code is listed as follows:

```
1  /*! \file  poisson-gmg.c
2   *
3   *  \brief The fourth test example for FASP: using GMG to solve
4   *         the discrete Poisson equation from five-point finite
5   *         difference stencil. C version.
6   *
7   *  \note  Solving the Poisson equation (FDM) with GMG: C version
8   *
9   *
10  *--------------------------------------------------------------------------------
11  *  Copyright (C) 2013--2017 by the FASP team. All rights reserved.
12  *  Released under the terms of the GNU Lesser General Public License 3.0 or later.
13  *--------------------------------------------------------------------------------
14  */
15
16 #include <time.h>
17 #include <math.h>
18
19 #include "fasp.h"
20 #include "fasp_functs.h"
21
22 const REAL pi = 3.14159265;
23
```

```
24 /**
25  * \fn static REAL f2d(INT i, INT j, INT nx, INT ny)
26  *
27  * \brief Setting f in Poisson equation, where
28  *        f = sin(pi x)*sin(pi y)
29  *
30  * \param i      i-th position in x direction
31  * \param j      j-th position in y direction
32  * \param nx     Number of grids in x direction
33  * \param ny     Number of grids in y direction
34  *
35  * \author Ziteng Wang
36  * \date   06/07/2013
37  */
38 static REAL f2d (INT i,
39                  INT j,
40                  INT nx,
41                  INT ny)
42 {
43     return sin(pi *(((REAL) j)/((REAL) ny)))
44           *sin(pi *(((REAL) i)/((REAL) nx)));
45 }
46
47 /**
48  * \fn static REAL L2NormError2d(REAL *u, INT nx, INT ny)
49  *
50  * \brief Computing Discretization Error, where exact solution
51  *        u = sin(pi x)*sin(pi y)/(2*pi*pi)
52  *
53  * \param u      Vector of DOFs
54  * \param nx     Number of grids in x direction
55  * \param ny     Number of grids in y direction
56  *
57  * \author Ziteng Wang
58  * \date   06/07/2013
59  */
60 static REAL L2NormError2d (REAL *u,
61                            INT nx,
62                            INT ny)
63 {
64     const REAL h = 1.0/nx;
65     REAL l2norm  = 0.0, uexact;
66
67     INT i, j;
68     for ( i = 1; i < ny; i++ ) {
69         for ( j = 1; j < nx; j++ ) {
70             uexact  = sin(pi*i*h)*sin(pi*j*h)/(pi*pi*2.0);
71             l2norm += pow((u[i*(nx+1)+j] - uexact), 2);
72         }
73     }
74
75     return sqrt(l2norm*h*h);
76 }
```

```
77
78 /**
79  * \brief An example of GMG method using Full Multigrid cycle
80  *
81  * \author Chensong Zhang
82  * \date   10/12/2015
83  *
84  * \note   Number of grids of nx = ny should be equal to 2^maxlevel.
85  */
86 int main (int argc, const char *argv[])
87 {
88     const REAL rtol   = 1.0e-6;
89     const INT  prtlvl = PRINT_MORE;
90
91     INT        i, j, nx, maxlevel;
92     REAL      *u, *b, h, error0;
93
94     // Step 0. Set number of levels for GMG
95     printf("Enter the desired number of levels:   ");
96     if ( scanf("%d", &maxlevel) > 1 ) {
97         printf("### ERROR: Did not get a valid input !!!\n");
98         return ERROR_INPUT_PAR;
99     }
100
101    // Step 1. Compute right-hand side b and set approximate solution u
102    nx = (int) pow(2.0, maxlevel);
103    h = 1.0/((REAL) nx);
104
105    u = (REAL *)malloc((nx+1)*(nx+1)*sizeof(REAL));
106    fasp_darray_set((nx+1)*(nx+1), u, 0.0);
107
108    b = (REAL *)malloc((nx+1)*(nx+1)*sizeof(REAL));
109    for (i = 0; i <= nx; i++) {
110        for (j = 0; j <= nx; j++) {
111            b[j*(nx+1)+i] = h*h*f2d(i, j, nx, nx);
112        }
113    }
114
115    // Step 2. Solve the Poisson system in 2D with full Multigrid cycle
116    fasp_poisson_fgmg2d(u, b, nx, nx, maxlevel, rtol, prtlvl);
117
118    // Step 3. Compute error in L2 norm
119    error0 = L2NormError2d(u, nx, nx);
120
121    printf("L2 error ||u-u'|| = %e\n",error0);
122
123    // Step 4. Clean up memory
124    free(u);
125    free(b);
126
127    return FASP_SUCCESS;
128 }
129
```

```
/*---------------------------------*/
/*--        End of File          --*/
/*---------------------------------*/
```

2.5 Example 5: Block ILU preconditioner

We now show a simple example for calling iterative solvers in BSR format. The test example is from a test problem given by the Society of Petroleum Engineers (SPE01 Benchmark) using a fully implicit black-oil simulator at certain time step. The test matrix is the Jacobian matrix from the Newton linearization and is stored as a BSR matrix (see §3.2 for details).

The sample code for this solver can be found in "tutorial/main/spe01-its.c" and a piece of the source code is listed as follows:

```
/*! \file  spe01-its.c
 *
 *  \brief The fifth test example for FASP: using ITS_BSR to solve
 *         the Jacobian equation from reservoir simulation benchmark
 *         problem SPE01.
 *
 *  \note  ITS_BSR example for FASP: C version
 *
 *  Solving the Society of Petroleum Engineers SPE01 benchmark problem
 *  with Block ILU preconditioned Krylov methods
 *
 *--------------------------------------------------------------------------------
 *  Copyright (C) 2012--2017 by the FASP team. All rights reserved.
 *  Released under the terms of the GNU Lesser General Public License 3.0 or later.
 *--------------------------------------------------------------------------------
 */

#include "fasp.h"
#include "fasp_functs.h"

/**
 * \fn int main (int argc, const char * argv[])
 *
 * \brief This is the main function for the fourth example.
 *
 * \author Feiteng Huang, Chensong Zhang
 * \date   05/22/2012
 *
 * Modified by Chensong Zhang on 09/22/2012
 */
int main (int argc, const char * argv[])
{
    input_param     inparam;  // parameters from input files
    ITS_param       itparam;  // parameters for itsolver
    ILU_param       iluparam; // parameters for ILU
```

```
36
37      printf("\n=========================================");
38      printf("\n||   FASP: SPE01 -- ITS BSR version   ||");
39      printf("\n=========================================\n\n");
40
41      // Step 0. Set parameters: We can ini/its_bsr.dat
42      fasp_param_set(argc, argv, &inparam);
43      fasp_param_init(&inparam, &itparam, NULL, &iluparam, NULL);
44
45      // Set local parameters
46      const int print_level = inparam.print_level;
47
48      // Step 1. Get stiffness matrix and right-hand side
49      // Read A and b -- P1 FE discretization for Poisson. The location
50      // of the data files is given in "its.dat".
51      dBSRmat A;
52      dvector b, x;
53      char filename1[512], *datafile1;
54      char filename2[512], *datafile2;
55
56      // Read the stiffness matrix from bsrmat_SPE01.dat
57      strncpy(filename1, inparam.workdir, 128);
58      datafile1="bsrmat_SPE01.dat"; strcat(filename1, datafile1);
59      fasp_dbsr_read(filename1, &A);
60
61      // Read the RHS from rhs_SPE01.dat
62      strncpy(filename2, inparam.workdir, 128);
63      datafile2="rhs_SPE01.dat"; strcat(filename2, datafile2);
64      fasp_dvec_read(filename2, &b);
65
66      // Step 2. Print problem size and ITS_bsr parameters
67      if (print_level>PRINT_NONE) {
68          printf("A: m = %d, n = %d, nnz = %d\n", A.ROW, A.COL, A.NNZ);
69          printf("b: n = %d\n", b.row);
70          fasp_param_solver_print(&itparam);
71          fasp_param_ilu_print(&iluparam);
72      }
73
74      // Step 3. Solve the system with ITS_BSR as an iterative solver
75      // Set the initial guess to be zero and then solve it using standard
76      // iterative methods, without applying any preconditioners
77      fasp_dvec_alloc(b.row, &x);
78      fasp_dvec_set(b.row, &x, 0.0);
79
80      itparam.itsolver_type = SOLVER_GMRES;
81      fasp_solver_dbsr_krylov_ilu(&A, &b, &x, &itparam, &iluparam);
82
83      // Step 4. Clean up memory
84      fasp_dbsr_free(&A);
85      fasp_dvec_free(&b);
86      fasp_dvec_free(&x);
87
88      return FASP_SUCCESS;
```

```
89 }
90
91 /*----------------------------------*/
92 /*--        End of File           --*/
93 /*----------------------------------*/
```

A sample output is given as follows (note that the actual output depends on the solver parameters and might be different than what you see here):

```
=============================================
||   FASP: SPE01 -- ITS BSR version   ||
=============================================

fasp_dbsr_read: reading file ../data/bsrmat_SPE01.dat...
fasp_dvec_read: reading file ../data/rhs_SPE01.dat...
A: m = 302, n = 302, nnz = 1788
b: n = 906

       Parameters in ITS_param
-----------------------------------------------------
Solver print level:                2
Solver type:                       1
Solver precond type:               2
Solver max num of iter:            500
Solver tolerance:                  1.00e-06
Solver stopping type:              1
-----------------------------------------------------



       Parameters in ILU_param
-----------------------------------------------------
ILU print level:                   2
ILU type:                          1
ILU level of fill-in:              0
ILU relaxation factor:             0.0000
ILU drop tolerance:                1.00e-03
ILU permutation tolerance:         0.00e+00
-----------------------------------------------------

BSR ILU(0) setup costs 0.000185 seconds.

Calling GMRes solver (BSR) ...
-------------------------------------------------------------------
It Num |    ||r||/||b||    |      ||r||       |  Conv. Factor
-------------------------------------------------------------------
     0 |  1.000000e+00   |  8.207069e+03  |     -.--
     1 |  9.999991e-01   |  8.207062e+03  |     1.0000
     2 |  9.991891e-01   |  8.200415e+03  |     0.9992
     3 |  9.984917e-01   |  8.194691e+03  |     0.9993
     4 |  9.581382e-01   |  7.863507e+03  |     0.9596
     5 |  9.387736e-01   |  7.704580e+03  |     0.9798
     6 |  8.996932e-01   |  7.383844e+03  |     0.9584
```

```
     7 |   8.970099e-01    |   7.361822e+03   |      0.9970
     8 |   8.570704e-01    |   7.034036e+03   |      0.9555
     9 |   5.309276e-01    |   4.357360e+03   |      0.6195
    10 |   1.462587e-01    |   1.200355e+03   |      0.2755
    11 |   3.520599e-02    |   2.889380e+02   |      0.2407
    12 |   8.488230e-03    |   6.966349e+01   |      0.2411
    13 |   2.019708e-03    |   1.657588e+01   |      0.2379
    14 |   4.524916e-04    |   3.713630e+00   |      0.2240
    15 |   9.670973e-05    |   7.937035e-01   |      0.2137
    16 |   1.970931e-05    |   1.617557e-01   |      0.2038
    17 |   3.905034e-06    |   3.204889e-02   |      0.1981
    18 |   8.553378e-07    |   7.019817e-03   |      0.2190
Number of iterations = 18 with relative residual 8.553446e-07.
Iterative method costs 0.0009 seconds.
ILUk_Krylov method totally costs 0.0011 seconds.
```

2.6 How to change parameters for solvers/preconditioners

In the previous examples, we have seen how to use the default parameters in FASP. In this section we discuss changing such parameters by reading them from a disk file or from the command line. An example of parameter initialization file is found in the FASP tutorial directory and is named "tutorial/ini/amg.dat".

```
$ ./poisson-amg-c.ex -ini ini/amg.dat
```

We take "`tutorial/ini/amg.dat`" as an example:

```
1  %-------------------------------------------------%
2  % input parameters                                %
3  % lines starting with % are comments              %
4  % must have spaces around the equal sign "="      %
5  %-------------------------------------------------%
6
7  workdir = ../data/    % work directory, no more than 128 characters
8  print_level = 3       % How much information to print out
9
10 %-------------------------------------------------%
11 % parameters for multilevel iteration             %
12 %-------------------------------------------------%
13
14 AMG_type                 = C      % C classic AMG
15                                    % SA smoothed aggregation
16                                    % UA unsmoothed aggregation
17 AMG_cycle_type           = V      % V V-cycle | W W-cycle
18                                    % A AMLI-cycle | NA Nonlinear AMLI-cycleA
19 AMG_tol                  = 1e-8   % tolerance for AMG
20 AMG_maxit                = 100    % number of AMG iterations
21 AMG_levels               = 20     % max number of levels
22 AMG_coarse_dof           = 500    % max number of coarse degrees of freedom
```

```
23 AMG_coarse_scaling       = OFF    % switch of scaling of the coarse grid correction
24 AMG_amli_degree          = 2      % degree of the polynomial used by AMLI cycle
25 AMG_nl_amli_krylov_type  = 6      % Krylov method in NLAMLI cycle: 6 FGMRES | 7 GCG
26
27 %-------------------------------------------------%
28 % parameters for AMG smoothing                    %
29 %-------------------------------------------------%
30
31 AMG_smoother             = GS     % GS | JACOBI | SGS
32                                   % SOR | SSOR | GSOR | SGSOR | POLY
33 AMG_ILU_levels           = 0      % number of levels using ILU smoother
34 AMG_SWZ_levels           = 0      % number of levels using Schwarz smoother
35 AMG_relaxation           = 1.1    % relaxation parameter for SOR smoother
36 AMG_polynomial_degree    = 3      % degree of the polynomial smoother
37 AMG_presmooth_iter       = 2      % number of presmoothing sweeps
38 AMG_postsmooth_iter      = 2      % number of postsmoothing sweeps
39
40 %-------------------------------------------------%
41 % parameters for classical AMG SETUP              %
42 %-------------------------------------------------%
43
44 AMG_coarsening_type      = 1      % 1 Modified RS
45                                   % 3 Compatible Relaxation
46                                   % 4 Aggressive
47 AMG_interpolation_type   = 1      % 1 Direct | 2 Standard | 3 Energy-min
48 AMG_strong_threshold     = 0.6    % Strong threshold
49 AMG_truncation_threshold = 0.4    % Truncation threshold
50 AMG_max_row_sum          = 0.9    % Max row sum
51
52 %-------------------------------------------------%
53 % parameters for aggregation-type AMG SETUP       %
54 %-------------------------------------------------%
55
56 AMG_strong_coupled       = 0.08   % Strong coupled threshold
57 AMG_max_aggregation      = 20     % Max size of aggregations
58 AMG_tentative_smooth     = 0.67   % Smoothing factor for tentative prolongation
59 AMG_smooth_filter        = OFF    % Switch for filtered matrix for smoothing
60 AMG_smooth_restriction   = ON     % Switch for smoothing restriction or not
```

We now briefly discuss the parameters above: This example is very similar to the first example and we now briefly explain it:

- Line 7 sets the working directory, which should contain data files for the matrices (and right-hand side vectors when necessary).

- Line 8 sets the level of output for FASP routines. It should range from 0 to 10 with 0 means no output and 10 means output everything possible.

- Line 14–25 sets the basic parameters for multilevel iterations. For example, type of AMG, type of multilevel cycles, number of maximal levels, etc.

- Line 31–38 sets the type of smoothers, number of smoothing sweeps, etc.
- Line 44–50 sets the parameters for the setup phase of the classical AMG method (§3.6).
- Line 56–60 gives the parameters for the setup phase of the aggregation-base AMG methods (§3.6).

You can do a very simple experiment—Simply change the AMG type from the classical AMG to smoothed aggregation AMG by revise Line 14 to:

```
AMG_type                = SA
```

Then you run "poisson-amg-c.ex" one more time and will get

```
=============================================
||   FASP: AMG example -- C version    ||
=============================================

fasp_dcsrvec_read2: reading file ../data/csrmat_FE.dat...
fasp_dcsrvec_read2: reading file ../data/rhs_FE.dat...
A: m = 3969, n = 3969, nnz = 27281
b: n = 3969

       Parameters in AMG_param
-----------------------------------------------
AMG print level:                    3
AMG max num of iter:                100
AMG type:                           2
AMG tolerance:                      1.00e-08
AMG max levels:                     20
AMG cycle type:                     1
AMG coarse solver type:             0
AMG scaling of coarse correction:   0
AMG smoother type:                  2
AMG smoother order:                 1
AMG num of presmoothing:            2
AMG num of postsmoothing:           2
Aggregation type:                   1
Aggregation number of pairs:        2
Aggregation quality bound:          8.00
-----------------------------------------------


Setting up SA AMG ...
-------------------------------------------------------------
  Level   Num of rows    Num of nonzeros   Avg. NNZ / row
-------------------------------------------------------------
    0          3969              27281            6.87
    1           541               6531           12.07
    2            41                421           10.27
-------------------------------------------------------------
```

```
  Grid complexity = 1.147  |  Operator complexity = 1.255
-------------------------------------------------------------
Smoothed aggregation setup costs 0.0027 seconds.
-------------------------------------------------------------
It Num |    ||r||/||b||    |      ||r||       |  Conv. Factor
-------------------------------------------------------------
     0 |  1.000000e+00   |  7.514358e+00  |     -.--
     1 |  4.345463e-02   |  3.265336e-01  |     0.0435
     2 |  8.041967e-03   |  6.043022e-02  |     0.1851
     3 |  3.808810e-03   |  2.862076e-02  |     0.4736
     4 |  1.838990e-03   |  1.381883e-02  |     0.4828
     5 |  8.675952e-04   |  6.519421e-03  |     0.4718
     6 |  4.089274e-04   |  3.072827e-03  |     0.4713
     7 |  1.939823e-04   |  1.457653e-03  |     0.4744
     8 |  9.276723e-05   |  6.970862e-04  |     0.4782
     9 |  4.471799e-05   |  3.360270e-04  |     0.4820
    10 |  2.171249e-05   |  1.631554e-04  |     0.4855
    11 |  1.060934e-05   |  7.972239e-05  |     0.4886
    12 |  5.212246e-06   |  3.916668e-05  |     0.4913
    13 |  2.572464e-06   |  1.933042e-05  |     0.4935
    14 |  1.274466e-06   |  9.576797e-06  |     0.4954
    15 |  6.333891e-07   |  4.759512e-06  |     0.4970
    16 |  3.155926e-07   |  2.371476e-06  |     0.4983
    17 |  1.575755e-07   |  1.184079e-06  |     0.4993
    18 |  7.881043e-08   |  5.922098e-07  |     0.5001
    19 |  3.947044e-08   |  2.965950e-07  |     0.5008
    20 |  1.978978e-08   |  1.487075e-07  |     0.5014
    21 |  9.931176e-09   |  7.462641e-08  |     0.5018
Number of iterations = 21 with relative residual 9.931176e-09.
AMG solve costs 0.0060 seconds.
AMG totally costs 0.0090 seconds.
```

You can compare this with the results in §2.1.

Similarly, you can solve the same problem using pairwise unsmoothed aggregation AMG preconditioned conjugated gradient method by calling

```
$ ./poisson-pcg-c.ex -ini ini/amg_ua.dat
```

and it will yield the following result:

```
-----------------------------------------
||   FASP: PCG example -- C version   ||
-----------------------------------------

fasp_dcsrvec_read2: reading file ../data/csrmat_FE.dat...
fasp_dcsrvec_read2: reading file ../data/rhs_FE.dat...
A: m = 3969, n = 3969, nnz = 27281
b: n = 3969

       Parameters in ITS_param
-------------------------------------------
```

```
Solver print level:                3
Solver type:                       1
Solver precond type:               2
Solver max num of iter:            1000
Solver tolerance:                  1.00e-06
Solver stopping type:              1
-------------------------------------------------


Setting up UA AMG ...
-------------------------------------------------------------------
  Level   Num of rows    Num of nonzeros    Avg. NNZ / row
-------------------------------------------------------------------
    0          3969              27281             6.87
    1          1059               7169             6.77
    2           286               1884             6.59
    3            71                431             6.07
-------------------------------------------------------------------
  Grid complexity = 1.357   |   Operator complexity = 1.348
-------------------------------------------------------------------
Unsmoothed aggregation setup costs 0.0015 seconds.

Calling CG solver (CSR) ...
-------------------------------------------------------------------
It Num |    ||r||/||b||    |      ||r||       |   Conv. Factor
-------------------------------------------------------------------
     0 |   1.000000e+00    |   7.514358e+00   |      -.--
     1 |   5.078363e-01    |   3.816064e+00   |      0.5078
     2 |   8.526434e-02    |   6.407068e-01   |      0.1679
     3 |   3.081067e-02    |   2.315224e-01   |      0.3614
     4 |   7.522033e-03    |   5.652325e-02   |      0.2441
     5 |   1.997295e-03    |   1.500839e-02   |      0.2655
     6 |   5.914181e-04    |   4.444127e-03   |      0.2961
     7 |   1.498444e-04    |   1.125985e-03   |      0.2534
     8 |   4.380269e-05    |   3.291491e-04   |      0.2923
     9 |   1.120054e-05    |   8.416489e-05   |      0.2557
    10 |   2.772669e-06    |   2.083482e-05   |      0.2475
    11 |   8.491093e-07    |   6.380511e-06   |      0.3062
Number of iterations = 11 with relative residual 8.491093e-07.
```

The input parameters allowed in FASP are not limited to the ones listed in this example. A list of possible iterative methods and preconditioners can be found in "`base/include/fasp_const.h`"; see §4.2. For more parameters and their ranges, we refer to the FASP Reference Manual.

Using "-ini [FILE]" is just one example of allowed command line option. To find out more what command line options are acceptable, you can type in a terminal window:

```
$ ./poisson-amg-c.ex -help
```

which will give you something like

```
=========================================
||   FASP: AMG example -- C version    ||
=========================================

FASP command line options:
=============================================================================
  -ini               [CharValue] : Ini file name
  -print             [IntValue]  : Print level
  -output            [IntValue]  : Output to screen or a log file
  -solver            [IntValue]  : Solver type
  -precond           [IntValue]  : Preconditioner type
  -maxit             [IntValue]  : Max number of iterations
  -tol               [RealValue] : Tolerance for iterative solvers
  -amgmaxit          [IntValue]  : Max number of AMG iterations
  -amgtol            [RealValue] : Tolerance for AMG methods
  -amgtype           [IntValue]  : AMG type
  -amgcycle          [IntValue]  : AMG cycle type
  -amgcoarsening     [IntValue]  : AMG coarsening type
  -amginterpolation  [IntValue]  : AMG interpolation type
  -amgsmoother       [IntValue]  : AMG smoother type
  -amgsthreshold     [RealValue] : AMG strong threshold
  -amgscoupled       [RealValue] : AMG strong coupled threshold
  -help                          : Brief help messages
```

For example, in order to the change the AMG type to the smoothed aggregation (SA) used by the preconditioner for PCG, you can also use the command line options:

```
./poisson-amg-c.ex -amgtype 2 -amgmaxit 100
```

Here we only changed two parameters from the default setting without changing anything else. So it might not give the same output as in the previous example.

Chapter 3

Data structures and basic usage

In this chapter, we discuss the basic data structures and the important building blocks which are useful for constructing auxiliary space preconditioners for systems of PDEs in Chapter 4. In particular, we will discuss vectors, sparse matrices, iterative methods, and multigrid methods.

3.1 Vectors and sparse matrices

The data structures most often used for implementing iterative methods are sparse matrices and vectors. In this section, we first discuss the data structures for vectors and matrices in FASP; and then we discuss BLAS operations for sparse matrices. The definitions can be found in "base/include/fasp.h".

Vectors

The data structure for vectors is very simple. It only contains the length of the vector and an array which contains the entries of this vector.

```
337 /**
338  * \struct dvector
339  * \brief  Vector with n entries of REAL type
340  */
341 typedef struct dvector{
342
343     //! number of rows
344     INT row;
345
346     //! actual vector entries
347     REAL *val;
348
349 } dvector; /**< Vector of REAL type */
```

Sparse matrices

On the other hand, sparse matrices for PDE applications are very complicated. It depends on the particular applications, discretization methods, as well as solution algorithms. In FASP, there are several types of sparse matrices, COO, CSR, CSRL, BSR, and CSR Block, etc. The presentation closely follows ideas from Pissanetzky [**?**].

In this section, we use the following sparse matrix as an example to explain different formats for sparse matrices:

Example 3.1.1 *Consider the following* 4×5 *matrix with 12 non-zero entries*

$$\begin{pmatrix} 1 & 1.5 & 0 & 0 & 12 \\ 0 & 1 & 6 & 7 & 1 \\ 3 & 0 & 6 & 0 & 0 \\ 1 & 0 & 2 & 0 & 5 \end{pmatrix}$$

(i) COO format

The coordinate (COO) format or IJ format is the simplest sparse matrix format.

```
199 /**
200  * \struct dCOOmat
201  * \brief  Sparse matrix of REAL type in COO (IJ) format
202  *
203  * Coordinate Format (I,J,A)
204  *
205  * \note The starting index of A is 0.
206  * \note Change I to rowind, J to colind. To avoid with complex.h confliction on I.
207  */
208 typedef struct dCOOmat{
209
210     //! row number of matrix A, m
211     INT row;
212
213     //! column of matrix A, n
214     INT col;
215
216     //! number of nonzero entries
217     INT nnz;
218
219     //! integer array of row indices, the size is nnz
220     INT *rowind;
221
222     //! integer array of column indices, the size is nnz
223     INT *colind;
224
225     //! nonzero entries of A
226     REAL *val;
227
```

```
228 } dCOOmat; /**< Sparse matrix of REAL type in COO format */
```

So it clear that the sparse matrix in Example 3.1.1 in COO format is stored as:

```
row = 4
col = 5
nnz = 12

 I J  val
------------
 0 0   1.0
 0 1   1.5
 0 4  12.0
 1 1   1.0
 1 2   6.0
 1 3   7.0
 1 4   1.0
 .......
```

Although the COO format is easy to understand or use, it wastes storage space and has little advantages in sparse BLAS operations.

NOTE: In FASP, the indices always start from 0, instead of from 1. This is often the source of problems related to vectors and matrices.

(ii) CSR format

The most commonly used data structure for sparse matrices nowadays is probably the so-called *compressed sparse row* (CSR) format, according to Saad [**?**]. The compressed row storage format of a matrix $A \in \mathbb{R}^{n\times m}$ (n rows and m columns) consists of three arrays, as follows:

1. An integer array of row pointers of size n+1;
2. An integer array of column indexes of size nnz;
3. An array of actual matrix entries.

In FASP, we define:

```
139 /**
140  * \struct dCSRmat
141  * \brief  Sparse matrix of REAL type in CSR format
142  *
143  * CSR Format (IA,JA,A) in REAL
144  *
145  * \note The starting index of A is 0.
146  */
147 typedef struct dCSRmat{
```

```
148
149     //! row number of matrix A, m
150     INT row;
151
152     //! column of matrix A, n
153     INT col;
154
155     //! number of nonzero entries
156     INT nnz;
157
158     //! integer array of row pointers, the size is m+1
159     INT *IA;
160
161     //! integer array of column indexes, the size is nnz
162     INT *JA;
163
164     //! nonzero entries of A
165     REAL *val;
166
167 } dCSRmat; /**< Sparse matrix of REAL type in CSR format */
```

The matrix (only nonzero elements) is stored in the array val row after row, in a way that i-th row begins at $val(IA(i))$ and ends at $val(IA(i+1)-1)$. In the same way, $JA(IA(i)$ to $JA(IA(i+1)-1)$ will contain the column indexes of the non-zeros in row i. Thus IA is of size $n+1$ (number of rows in val plus one), JA and val are of size equal to the number of non-zeroes. The total number of non-zeroes is equal to $IA(n+1)-1$.

NOTE: When the sparse matrix A is a boolean (i.e. all entries are either 0 or 1), the actual non-zeroes are not stored because it is understood that, if it is nonzero, it could only be 1 and there is no need to store it.

The matrix in Example 3.1.1 in CSR format is represented in the following way:

- IA is of size 5 and
$$IA = \| \ 0 \ \| \ 3 \ \| \ 7 \ \| \ 9 \ \| \ 12 \ \|$$
- JA is of size $IA(5)-1 = 12$
$$JA = \| \ 0 \ | \ 1 \ | \ 4 \ \| \ 1 \ | \ 3 \ | \ 2 \ | \ 4 \ \| \ 0 \ | \ 2 \ \| \ 2 \ | \ 4 \ | \ 0 \ \|$$
- val is of the same size as JA and
$$val = \| \ 1. \ | \ 1.5 \ | \ 12. \ \| \ 1. \ | \ 7. \ | \ 6. \ | \ 1. \ \| \ 3. \ | \ 6. \ \| \ 2. \ | \ 5. \ | \ 1. \ \|$$

Here we use double vertical bars to separate rows and single vertical bars to separate values.

NOTE: The indices in JA and entries of val does NOT have to be ordered as seen in this example. Sometimes they are sorted in ascending order in each row. More often, the diagonal entries are stored in the first position in each row and the rest are sorted in ascending order.

Below is a "non-numeric" example.

Example 3.1.2 *Consider the following sparse matrix:*

$$\begin{pmatrix} a_{11} & 0 & a_{13} & 0 \\ 0 & a_{22} & a_{23} & a_{24} \\ 0 & a_{32} & 0 & a_{34} \\ a_{41} & a_{42} & a_{43} & 0 \end{pmatrix}$$

For this matrix, we have that the number of non-zeros $nnz = 10$*. Furthermore, the three arrays of in the CSR format are:*

$$IA = \| \ 0 \ \| \ 2 \ \| \ 5 \ \| \ 7 \ \|,$$
$$JA = \| \ 0 \ | \ 2 \ \| \ 1 \ | \ 2 \ | \ 3 \ \| \ 1 \ | \ 3 \ \| \ 0 \ | \ 1 \ | \ 2 \ \|,$$

and

$$val = \| \ a_{11} \ | \ a_{13} \ \| \ a_{22} \ | \ a_{23} \ | \ a_{24} \ \| \ a_{32} \ | \ a_{34} \ \| \ a_{41} \ | \ a_{42} \ | \ a_{43} \ \|.$$

NOTE: The CSR format presents challenges to sparse matrix-vector product mainly because of the high cache missing rate due to indirect memory access and irregular access pattern. In order to reduce the cache missing rate, we introduce an improved data format, CSRL.

(iii) CSRL format

CSRL matrix format [**?**] groups rows with same number of nonzeros together and improves cache hitting rate.

```
260 /*!
261  * \struct dCSRLmat
262  * \brief  Sparse matrix of REAL type in CSRL format
263  */
264 typedef struct dCSRLmat{
265
266     //! number of rows
267     INT row;
268
269     //! number of cols
270     INT col;
271
272     //! number of nonzero entries
273     INT nnz;
```

```
274
275     //! number of different values in i-th row, i=0:nrows-1
276     INT dif;
277
278     //! nz_diff[i]: the i-th different value in 'nzrow'
279     INT *nz_diff;
280
281     //! row index of the matrix (length-grouped): rows with same nnz are together
282     INT *index;
283
284     //! j in {start[i],...,start[i+1]-1} means nz_diff[i] nnz in index[j]-row
285     INT *start;
286
287     //! column indices of all the nonzeros
288     INT *ja;
289
290     //! values of all the nonzero entries
291     REAL *val;
292
293 } dCSRLmat; /**< Sparse matrix of REAL type in CSRL format */
```

3.2 Block sparse matrices

For PDE applications, we often need to solve systems of partial differential equations. Many iterative methods and preconditioners could take advantages of the structure of PDE systems and improve efficiency. So we often need to use semi-structured (block) sparse data structures to store the coefficient matrix arising from PDE systems.

Depending on different applications and different solving algorithms, we can use two types of block matrices: dBSRmat (or BSR Block Compressed Sparse Row) and block_dCSRmat (CSR Block or Block of CSR matrices).

For more details as well as other specialized block matrices, readers are referred to the header file "base/include/fasp_block.h".

As an example, we consider the following matrix, which have been used in §3.1 for the CSR format. We add structure to this matrix and divide it as a 2×2 block matrix:

Example 3.2.1

$$\left(\begin{array}{cc|cc} a_{11} & 0 & a_{13} & 0 \\ 0 & a_{22} & a_{23} & a_{24} \\ \hline 0 & a_{32} & 0 & a_{34} \\ a_{41} & a_{42} & a_{43} & 0 \end{array}\right)$$

(i) BSR format

This format is a standard data structure for storing block sparse matrices which has been used by the Intel MKL library.

```
24 /**
25  * \struct dBSRmat
26  * \brief Block sparse row storage matrix of REAL type
27  *
28  * \note This data structure is adapted from the Intel MKL library. Refer to:
29  * http://software.intel.com/sites/products/documentation/hpc/mkl/lin/index.htm
30  *
31  * \note Some of the following entries are capitalized to stress that they are
32  *       for blocks!
33  */
34 typedef struct dBSRmat {
35
36     //! number of rows of sub-blocks in matrix A, M
37     INT ROW;
38
39     //! number of cols of sub-blocks in matrix A, N
40     INT COL;
41
42     //! number of nonzero sub-blocks in matrix A, NNZ
43     INT NNZ;
44
45     //! dimension of each sub-block
46     INT nb; // NOTE: for the moment, allow nb*nb full block
47
48     //! storage manner for each sub-block
49     INT storage_manner; // 0: row-major order, 1: column-major order
50
51     //! A real array that contains the elements of the non-zero blocks of
52     //! a sparse matrix. The elements are stored block-by-block in row major
53     //! order. A non-zero block is the block that contains at least one non-zero
54     //! element. All elements of non-zero blocks are stored, even if some of
55     //! them is equal to zero. Within each nonzero block elements are stored
56     //! in row-major order and the size is (NNZ*nb*nb).
57     REAL *val;
58
59     //! integer array of row pointers, the size is ROW+1
60     INT *IA;
61
62     //! Element i of the integer array columns is the number of the column in the
63     //! block matrix that contains the i-th non-zero block. The size is NNZ.
64     INT *JA;
65
66 } dBSRmat; /**< Matrix of REAL type in BSR format */
```

For the matrix in Example 3.2.1, we have that the number of block rows $ROW = 2$, the number of block columns $COL = 2$, and the number of block nonzeros $NNZ = 4$. The block size is $nb = 2$.

We can choose different storage manners for storing the small blocks. Suppose that we set it to be 0, i.e. row-major format. Then the three arrays of in the BSR format are:

$$IA = \left\| 0 \right\| 8 \left\| 16 \right\|,$$

$$JA = \left\| 0 \right| 1 \left\| 0 \right| 1 \left\|,\right.$$

and

$$val = \left\| a_{11} \right| 0 \left| 0 \right| a_{22} \left\| a_{13} \right| 0 \left| a_{23} \right| a_{24} \left\| \right.$$
$$\left\| 0 \right| a_{32} \left| a_{41} \right| a_{42} \left\| 0 \right| a_{34} \left| a_{43} \right| 0 \left\|.\right.$$

We immediately notice that this format might be not be the best choice for this particular matrix due to all the blocks are nonzero blocks, i.e., contain nonzero entries. However, for PDE applications, this does not usually happen.

(ii) BLC format

This format is simple and is derived from the dCSRmat data structure. The following definition explains itself.

```
68 /**
69  * \struct dBLCmat
70  * \brief Block REAL CSR matrix format
71  *
72  * \note The starting index of A is 0.
73  */
74 typedef struct dBLCmat {
75
76     //! row number of blocks in A, m
77     INT brow;
78
79     //! column number of blocks A, n
80     INT bcol;
81
82     //! blocks of dCSRmat, point to blocks[brow][bcol]
83     dCSRmat **blocks;
84
85 } dBLCmat; /**< Matrix of REAL type in Block CSR format */
```

3.3 I/O subroutines for sparse matrices

In FASP, we provided several functions for reading, writing, and printing different formats of sparse matrices in plain text or binary formats. These functions can be found in "base/src/BlaIO.c" and we list the available functions as follows:

```
470 void fasp_dcsrvec_read1 (const char  *filename,
471                          dCSRmat     *A,
472                          dvector     *b);
473
474 void fasp_dcsrvec_read2 (const char  *filemat,
475                          const char  *filerhs,
476                          dCSRmat     *A,
477                          dvector     *b);
478
479 void fasp_dcsr_read (const char  *filename,
480                      dCSRmat     *A);
481
482 void fasp_dcoo_read (const char  *filename,
483                      dCSRmat     *A);
484
485 void fasp_dcoo_read1 (const char  *filename,
486                       dCOOmat     *A);
487
488 void fasp_dcoo_shift_read (const char  *filename,
489                            dCSRmat     *A);
490
491 void fasp_dmtx_read (const char  *filename,
492                      dCSRmat     *A);
493
494 void fasp_dmtxsym_read (const char  *filename,
495                         dCSRmat     *A);
496
497 void fasp_dstr_read (const char  *filename,
498                      dSTRmat     *A);
499
500 void fasp_dbsr_read (const char  *filename,
501                      dBSRmat     *A);
502
503 void fasp_dvecind_read (const char  *filename,
504                         dvector     *b);
505
506 void fasp_dvec_read (const char  *filename,
507                      dvector     *b);
508
509 void fasp_ivecind_read (const char  *filename,
510                         ivector     *b);
511
512 void fasp_ivec_read (const char  *filename,
513                      ivector     *b);
514
515 void fasp_dcsrvec_write1 (const char  *filename,
516                           dCSRmat     *A,
517                           dvector     *b);
518
519 void fasp_dcsrvec_write2 (const char  *filemat,
520                           const char  *filerhs,
521                           dCSRmat     *A,
522                           dvector     *b);
```

```
523
524 void fasp_dcoo_write (const char  *filename,
525                       dCSRmat     *A);
526
527 void fasp_dstr_write (const char  *filename,
528                       dSTRmat     *A);
529
530 void fasp_dbsr_write (const char *filename,
531                       dBSRmat *A);
532
533 void fasp_dvec_write (const char  *filename,
534                       dvector     *vec);
535
536 void fasp_dvecind_write (const char  *filename,
537                          dvector     *vec);
538
539 void fasp_ivec_write (const char  *filename,
540                       ivector     *vec);
541
542 void fasp_dvec_print (const INT  n,
543                       dvector   *u);
544
545 void fasp_ivec_print (const INT  n,
546                       ivector   *u);
547
548 void fasp_dcsr_print (const dCSRmat *A);
549
550 void fasp_dcoo_print (const dCOOmat *A);
551
552 void fasp_dbsr_print (const dBSRmat *A);
553
554 void fasp_dbsr_write_coo (const char    *filename,
555                           const dBSRmat *A);
556
557 void fasp_dcsr_write_coo (const char    *filename,
558                           const dCSRmat *A);
559
560 void fasp_dstr_print (const dSTRmat *A);
561
562 void fasp_matrix_read (const char  *filename,
563                        void        *A);
564
565 void fasp_matrix_read_bin (const char *filename,
566                            void       *A);
567
568 void fasp_matrix_write (const char *filename,
569                         void       *A,
570                         const INT   flag);
571
572 void fasp_vector_read (const char *filerhs,
573                        void       *b);
574
575 void fasp_vector_write (const char *filerhs,
```

```
576                          void        *b,
577                          const INT    flag);
578
579 void fasp_hb_read (const char *input_file,
580                     dCSRmat    *A,
581                     dvector    *b);
```

NOTE: The above function declarations are taken from "base/include/fasp_functs.h". This header file is automatically generated based on the source codes. Users are discouraged from changing it by hand; their changes may be lost.

3.4 Sparse matrix-vector multiplication

The matrix-vector multiplication: $y = Ax$ can be performed in the following simple way:

```
1  /**
2   * \fn void fasp_blas_dcsr_mxv (dCSRmat *A, REAL *x, REAL *y)
3   *
4   * \brief Matrix-vector multiplication y = A*x
5   *
6   * \param A   Pointer to dCSRmat matrix A
7   * \param x   Pointer to array x
8   * \param y   Pointer to array y
9   *
10  * \author Chensong Zhang
11  * \date   07/01/2009
12  */
13 void fasp_blas_dcsr_mxv (dCSRmat *A,
14                          REAL *x,
15                          REAL *y)
16 {
17     const INT    m  = A->row;
18     const INT   *ia = A->IA, *ja = A->JA;
19     const REAL *aj = A->val;
20
21     INT i, k, beg, end;
22     register REAL tmp;
23
24     for ( i=0; i<m; ++i ) {
25         tmp = 0.0;
26         beg = ia[i]; end = ia[i+1];
27         for ( k=beg; k<end; ++k ) tmp += aj[k]*x[ja[k]];
28         y[i] = tmp;
29     }
30 }
```

This is only a simple example for sparse matrix-vector multiplication (SpMV) kernel. Since we need many types of sparse matrices, there are various of versions of SpMV for different data structures. See the Reference Manual for more details.

3.5 Iterative methods

In FASP, there are a couple of standard preconditioned iterative methods [**?**] implemented, including preconditioned CG, BiCGstab, GMRES, Variable Restarting GMRES, Flexible GMRES, etc. In this section, we use the CSR matrix format as example to introduce how to call these iterative methods. To learn more details, we refer to the Reference Manual.

We first show the abstract interface for the iterative methods. The following code segment is taken from "base/src/SolCSR.c":

```
37 /**
38  * \fn INT fasp_solver_dcsr_itsolver (dCSRmat *A, dvector *b, dvector *x,
39  *                                    precond *pc, ITS_param *itparam)
40  *
41  * \brief Solve Ax=b by preconditioned Krylov methods for CSR matrices
42  *
43  * \note  This is an abstract interface for iterative methods.
44  *
45  * \param A         Pointer to the coeff matrix in dCSRmat format
46  * \param b         Pointer to the right hand side in dvector format
47  * \param x         Pointer to the approx solution in dvector format
48  * \param pc        Pointer to the preconditioning action
49  * \param itparam   Pointer to parameters for iterative solvers
50  *
51  * \return          Iteration number if converges; ERROR otherwise.
52  *
53  * \author Chensong Zhang
54  * \date   09/25/2009
55  *
56  * Modified by Chunsheng Feng on 03/04/2016: add VBiCGstab solver
57  */
58 INT fasp_solver_dcsr_itsolver (dCSRmat    *A,
59                                dvector    *b,
60                                dvector    *x,
61                                precond    *pc,
62                                ITS_param  *itparam)
```

The names of the input arguments explain themselves mostly and they are explained in the Reference Manual in detail.

We briefly discuss how to call this function; and, once you understand PCG, you can easily call other Krylov-type iterative methods.

```
477     // ILU setup for whole matrix
```

```
478     ILU_data LU;
479     if ( (status = fasp_ilu_dcsr_setup(A, &LU, iluparam)) < 0 ) goto FINISHED;
480
481     // check iludata
482     if ( (status = fasp_mem_iludata_check(&LU)) < 0 ) goto FINISHED;
483
484     // set preconditioner
485     precond pc;
486     pc.data = &LU;
487     pc.fct  = fasp_precond_ilu;
488
489     // call iterative solver
490     status = fasp_solver_dcsr_itsolver(A, b, x, &pc, itparam);
```

Now we explain this code segment a little bit:

- Line 478–479 performs the setup phase for ILU method. The particular type of ILU method is determined by "`iluparam`"; see §2.6. Line 7 performs a simple memory check for ILU.
- Line 485–487 defines the preconditioner data structure "`pc`", which contains two parts: one is the actual preconditioning action "`pc.fct`", the other is the auxiliary data which is needed to perform the preconditioning action "`pc.data`".
- Line 490 calls iterative methods. "A" is the matrix in dCSRmat format; "b" and "x" are the right-hand side and the solution vectors, respectively. Similar to ILU setup, the type of iterative methods is determined by "`itparam`".

Apparently, we should now explain the data structure "`itparam`".

```
/**
 * \struct ITS_param
 * \brief  Parameters for iterative solvers
 */
typedef struct {

    SHORT print_level;   /**< print level: 0--10 */
    SHORT itsolver_type; /**< solver type: see fasp_const.h */
    SHORT precond_type;  /**< preconditioner type: see fasp_const.h */
    SHORT stop_type;     /**< stopping criteria type */
    INT   restart;       /**< number of steps for restarting: for GMRES etc */
    INT   maxit;         /**< max number of iterations */
    REAL  tol;           /**< convergence tolerance */

} ITS_param; /**< Parameters for iterative solvers */
```

Possible "`itsolver_type`" includes:

```
/**
 * \brief Definition of solver types for iterative methods
```

```
 */
#define SOLVER_DEFAULT          0  /**< Use default solver in FASP */
//-----------------------------------------------------------------------------
#define SOLVER_CG               1  /**< Conjugate Gradient */
#define SOLVER_BiCGstab         2  /**< Bi-Conjugate Gradient Stabilized */
#define SOLVER_MinRes           3  /**< Minimal Residual */
#define SOLVER_GMRES            4  /**< Generalized Minimal Residual */
#define SOLVER_VGMRES           5  /**< Variable Restarting GMRES */
#define SOLVER_VFGMRES          6  /**< Variable Restarting Flexible GMRES */
#define SOLVER_GCG              7  /**< Generalized Conjugate Gradient */
#define SOLVER_GCR              8  /**< Generalized Conjugate Residual */
//-----------------------------------------------------------------------------
#define SOLVER_SCG             11  /**< Conjugate Gradient with safety net */
#define SOLVER_SBiCGstab       12  /**< BiCGstab with safety net */
#define SOLVER_SMinRes         13  /**< MinRes with safety net */
#define SOLVER_SGMRES          14  /**< GMRes with safety net */
#define SOLVER_SVGMRES         15  /**< Variable-restart GMRES with safety net */
#define SOLVER_SVFGMRES        16  /**< Variable-restart FGMRES with safety net */
#define SOLVER_SGCG            17  /**< GCG with safety net */
//-----------------------------------------------------------------------------
#define SOLVER_AMG             21  /**< AMG as an iterative solver */
#define SOLVER_FMG             22  /**< Full AMG as an solver */
```

3.6 Algebraic multigrid

The classical algebraic multigrid method [**?**] is an important component in many of our auxiliary space preconditioners. Because of its user-friendly and scalability, AMG becomes increasingly popular in scientific and engineering computing, especially when GMG is difficult or not possible to be applied. Various of new AMG techniques [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**] have emerged in recent years.

The following code segment is part of "base/src/SolAMG.c" and it is a good example which shows how to call different AMG methods (classical AMG, smoothed aggregation, un-smoothed aggregation) and different multilevel iterative methods (V-cycle, W-cycle, AMLI-cycle, Nonlinear AMLI-cycle, etc).

```
46 void fasp_solver_amg (const dCSRmat  *A,
47                       const dvector  *b,
48                       dvector        *x,
49                       AMG_param      *param)
50 {
51     const SHORT   max_levels  = param->max_levels;
52     const SHORT   prtlvl      = param->print_level;
53     const SHORT   amg_type    = param->AMG_type;
54     const SHORT   cycle_type  = param->cycle_type;
55     const INT     nnz = A->nnz, m = A->row, n = A->col;
56
57     // local variables
```

```
58      SHORT          status;
59      AMG_data *     mgl = fasp_amg_data_create(max_levels);
60      REAL           AMG_start = 0, AMG_end;
61
62  #if DEBUG_MODE > 0
63      printf("### DEBUG: [-Begin-] %s ...\n", __FUNCTION__);
64  #endif
65
66      if ( prtlvl > PRINT_NONE ) fasp_gettime(&AMG_start);
67
68      // check matrix data
69      fasp_check_dCSRmat(A);
70
71      // Step 0: initialize mgl[0] with A, b and x
72      mgl[0].A = fasp_dcsr_create(m, n, nnz);
73      fasp_dcsr_cp(A, &mgl[0].A);
74
75      mgl[0].b = fasp_dvec_create(n);
76      fasp_dvec_cp(b, &mgl[0].b);
77
78      mgl[0].x = fasp_dvec_create(n);
79      fasp_dvec_cp(x, &mgl[0].x);
80
81      // Step 1: AMG setup phase
82      switch (amg_type) {
83
84          case SA_AMG: // Smoothed Aggregation AMG setup
85              status = fasp_amg_setup_sa(mgl, param); break;
86
87          case UA_AMG: // Unsmoothed Aggregation AMG setup
88              status = fasp_amg_setup_ua(mgl, param); break;
89
90          default: // Classical AMG setup
91              status = fasp_amg_setup_rs(mgl, param); break;
92
93      }
94
95      // Step 2: AMG solve phase
96      if ( status == FASP_SUCCESS ) { // call a multilevel cycle
97
98          switch (cycle_type) {
99
100             case AMLI_CYCLE: // AMLI-cycle
101                 fasp_amg_solve_amli(mgl, param); break;
102
103             case NL_AMLI_CYCLE: // Nonlinear AMLI-cycle
104                 fasp_amg_solve_namli(mgl, param); break;
105
106             default: // V,W-cycles (determined by param)
107                 fasp_amg_solve(mgl, param); break;
108
109         }
110
```

```
111         fasp_dvec_cp(&mgl[0].x, x);
112
113     }
114
115     else { // call a backup solver
116
117         if ( prtlvl > PRINT_MIN ) {
118             printf("### WARNING: AMG setup failed!\n");
119             printf("### WARNING: Use a backup solver instead!\n");
120         }
121         fasp_solver_dcsr_spgmres (A, b, x, NULL, param->tol, param->maxit,
122                                   20, 1, prtlvl);
123
124     }
125
126     // clean-up memory
127     fasp_amg_data_free(mgl, param);
128
129     // print out CPU time if needed
130     if ( prtlvl > PRINT_NONE ) {
131         fasp_gettime(&AMG_end);
132         fasp_cputime("AMG totally", AMG_end - AMG_start);
133     }
134
135 #if DEBUG_MODE > 0
136     printf("### DEBUG: [--End--] %s ...\n", __FUNCTION__);
137 #endif
138
139     return;
140 }
```

The code above is very simple and we only wish to point out that:

- Line 51–54 reads some of the parameters from "`AMG_param`", which can be set in an input file; see §2.6.
- Line 72–79 initializes the "`AMG_data`" with a copy of the coefficient matrix, the right-hand side, and the initial solution (it will store the final solution eventually).
- Line 82–93 calls three different AMG setup methods, determined by "`amg_type`".
- Line 98–109 calls three different multilevel iterative methods, determined by "`cycle_type`".

Parameters for AMG

There are a couple of controlling parameters for algebraic multigrid methods in FASP. Basically, there are four types of parameters for AMG—They control multilevel iterations, smoothing, classical AMG setup, and aggregation AMG setup. The following is a sample from "`test/ini/input.dat`" and a brief explanation of each parameter is given.

```
55 %-------------------------------------------------%
56 % parameters for multilevel iteration           %
57 %-------------------------------------------------%
58
59 AMG_type                 = C      % C classic AMG
60                                    % SA smoothed aggregation
61                                    % UA unsmoothed aggregation
62 AMG_cycle_type           = V      % V V-cycle | W W-cycle
63                                    % A AMLI-cycle | NA Nonlinear AMLI-cycleA
64 AMG_tol                  = 1e-6   % tolerance for AMG
65 AMG_maxit                = 1      % number of AMG iterations
66 AMG_levels               = 20     % max number of levels
67 AMG_coarse_dof           = 500    % max number of coarse degrees of freedom
68 AMG_coarse_solver        = 0      % coarsest solver: 0 iterative |
69                                    % 31 SuperLU | 32 UMFPack | 33 MUMPS
70 AMG_coarse_scaling       = OFF    % switch of scaling of the coarse grid correction
71 AMG_amli_degree          = 2      % degree of the polynomial used by AMLI cycle
72 AMG_nl_amli_krylov_type  = 6      % Krylov method in NLAMLI cycle: 6 FGMRES | 7 GCG
73
74 %-------------------------------------------------%
75 % parameters for AMG smoothing                   %
76 %-------------------------------------------------%
77
78 AMG_smoother              = GS     % GS | JACOBI | SGS SOR | SSOR |
79                                    % GSOR | SGSOR | POLY | L1DIAG | CG
80 AMG_smooth_order         = CF     % NO: natural order | CF: CF order
81 AMG_ILU_levels           = 0      % number of levels using ILU smoother
82 AMG_SWZ_levels           = 0      % number of levels using Schwarz smoother
83 AMG_relaxation           = 1.0    % relaxation parameter for SOR smoother
84 AMG_polynomial_degree    = 3      % degree of the polynomial smoother
85 AMG_presmooth_iter       = 1      % number of presmoothing sweeps
86 AMG_postsmooth_iter      = 1      % number of postsmoothing sweeps
87
88 %-------------------------------------------------%
89 % parameters for classical AMG SETUP             %
90 %-------------------------------------------------%
91
92 AMG_coarsening_type      = 1      % 1 Modified RS
93                                    % 2 Mofified RS for positive off-diags
94                                    % 3 Compatible Relaxation
95                                    % 4 Aggressive
96 AMG_interpolation_type   = 1      % 1 Direct | 2 Standard | 3 Energy-min
97 AMG_strong_threshold     = 0.3    % Strong threshold
98 AMG_truncation_threshold = 0.1    % Truncation threshold
99 AMG_max_row_sum          = 0.9    % Max row sum
100
101 %-------------------------------------------------%
102 % parameters for aggregation-type AMG SETUP      %
103 %-------------------------------------------------%
104
105 AMG_aggregation_type     = 2      % 1 Matching | 2 VMB
106 AMG_pair_number          = 2      % Number of pairs in matching
107 AMG_strong_coupled       = 0.08   % Strong coupled threshold
```

```
AMG_max_aggregation      = 20     % Max size of aggregations
AMG_tentative_smooth     = 0.67   % Smoothing factor for tentative prolongation
AMG_smooth_filter        = OFF    % Switch for filtered matrix for smoothing
AMG_smooth_restriction   = ON     % Switch for smoothing restriction or not
AMG_quality_bound        = 8.0    % quality of aggregation: 8.0 sysmm | 10.0 unsymm
```

NOTE: Here we can not discuss the details of these parameters as a full discussion requires more understand of the underlying algorithms which we have completely omitted. So to learn more about, we refer to the Reference Manual.

Chapter 4

More advanced features

In this chapter, we discuss a few more advanced features of FASP. We will discuss parallel versions of FASP and its build-in features for debugging purposes. These features will be helpful for people who would like to develop on the top of FASP. For users who only wish to call a few standard solvers, they can skip this chapter.

4.1 Enabling OpenMP

OpenMP[1] (Open Multiprocessing) is an API that supports multi-platform shared memory multiprocessing programming in C, C++, and Fortran, on most processor architectures and operating systems. It consists of a set of compiler directives, library routines, and environment variables that influence run-time behavior. Some preliminary OpenMP support has been included since the very beginning of FASP. We consistently improves and expands OpenMP support as multiprocessor architectures become the dominant desktop computing environment.

NOTE: By default, OpenMP is disabled in FASP. In order to turn it on, you need to modify FASP.mk slightly as follows.

To enable OpenMP support in FASP, you can simply use the following option during the configuration stage of cmake:

```
$ make config openmp=yes
```

If you use OpenMP very often and do not want type in this extra command-line option, you need to uncomment one line in "FASP.mk". If you do not have "FASP.mk" file, just copy "FASP.mk.example" to "FASP.mk". Then set "openmp" to "yes" on line 44 "FASP.mk":

[1] Official website: http://openmp.org/

```
#
# You may use multithread version after you enable OpenMP support. To
# setup the environment, you need
#  >> export OMP_NUM_THREADS=4 (for bash)
#  >> setenv OMP_NUM_THREADS 4 (for tcsh)
# If you want to compile with OpenMP support, uncomment the next line:
#
# openmp=yes
#
```

After you build FASP with "openmp=yes", OpenMP is turned on and the number of threads is determined by the environment variable OMP_NUM_THREADS. For example, to use 8 threads in sh/bash on a Linux or Mac OS X machine, you need to set:

```
$ export OMP_NUM_THREADS=8
```

On a Windows computer, you need to use

```
C:\FASP> set OMP_NUM_THREADS=8
```

in order to use eight threads for the current sessions. In case you need to use eight threads by default, you should set it as a system environment variable.

4.2 Predefined constants

FASP has many predefined constants used in the source files. Using these macros makes the source codes more readable. These constants are defined in "base/include/fasp_const.h" and a printout of this file is below:

```
/*! \file  fasp_const.h
 *
 *  \brief Definition of FASP constants, including messages, solver types, etc.
 *
 *--------------------------------------------------------------------------------
 *  Copyright (C) 2009--2017 by the FASP team. All rights reserved.
 *  Released under the terms of the GNU Lesser General Public License 3.0 or later.
 *--------------------------------------------------------------------------------
 *
 *  \warning This is for internal use only. Do NOT change!
 */

#ifndef __FASP_CONST__              /*-- allow multiple inclusions --*/
#define __FASP_CONST__

/**
 * \brief Definition of return status and error messages
 */
```

```
19 #define FASP_SUCCESS            0  /**< return from function successfully */
20 //-----------------------------------------------------------------------------
21 #define ERROR_OPEN_FILE       -10  /**< fail to open a file */
22 #define ERROR_WRONG_FILE      -11  /**< input contains wrong format */
23 #define ERROR_INPUT_PAR       -13  /**< wrong input argument */
24 #define ERROR_REGRESS         -14  /**< regression test fail */
25 #define ERROR_MAT_SIZE        -15  /**< wrong problem size */
26 #define ERROR_NUM_BLOCKS      -18  /**< wrong number of blocks */
27 #define ERROR_MISC            -19  /**< other error */
28 //-----------------------------------------------------------------------------
29 #define ERROR_ALLOC_MEM       -20  /**< fail to allocate memory */
30 #define ERROR_DATA_STRUCTURE  -21  /**< problem with data structures */
31 #define ERROR_DATA_ZERODIAG   -22  /**< matrix has zero diagonal entries */
32 #define ERROR_DUMMY_VAR       -23  /**< unexpected input data */
33 //-----------------------------------------------------------------------------
34 #define ERROR_AMG_INTERP_TYPE -30  /**< unknown interpolation type */
35 #define ERROR_AMG_SMOOTH_TYPE -31  /**< unknown smoother type */
36 #define ERROR_AMG_COARSE_TYPE -32  /**< unknown coarsening type */
37 #define ERROR_AMG_COARSEING   -33  /**< coarsening step failed to complete */
38 #define ERROR_AMG_SETUP       -39  /**< AMG setup failed to complete */
39 //-----------------------------------------------------------------------------
40 #define ERROR_SOLVER_TYPE     -40  /**< unknown solver type */
41 #define ERROR_SOLVER_PRECTYPE -41  /**< unknown precond type */
42 #define ERROR_SOLVER_STAG     -42  /**< solver stagnates */
43 #define ERROR_SOLVER_SOLSTAG  -43  /**< solver's solution is too small */
44 #define ERROR_SOLVER_TOLSMALL -44  /**< solver's tolerance is too small */
45 #define ERROR_SOLVER_ILUSETUP -45  /**< ILU setup error */
46 #define ERROR_SOLVER_MISC     -46  /**< misc solver error during run time */
47 #define ERROR_SOLVER_MAXIT    -48  /**< maximal iteration number exceeded */
48 #define ERROR_SOLVER_EXIT     -49  /**< solver does not quit successfully */
49 //-----------------------------------------------------------------------------
50 #define ERROR_QUAD_TYPE       -60  /**< unknown quadrature type */
51 #define ERROR_QUAD_DIM        -61  /**< unsupported quadrature dim */
52 //-----------------------------------------------------------------------------
53 #define ERROR_LIC_TYPE        -80  /**< wrong license type */
54 //-----------------------------------------------------------------------------
55 #define ERROR_UNKNOWN         -99  /**< an unknown error type */
56
57 /**
58  * \brief Definition of logic type
59  */
60 #define TRUE                    1  /**< logic TRUE */
61 #define FALSE                   0  /**< logic FALSE */
62
63 /**
64  * \brief Definition of switch
65  */
66 #define ON                      1  /**< turn on certain parameter */
67 #define OFF                     0  /**< turn off certain parameter */
68
69 /**
70  * \brief Print level for all subroutines -- not including DEBUG output
71  */
```

```
72  #define PRINT_NONE              0  /**< silent: no printout at all */
73  #define PRINT_MIN               1  /**< quiet:  print error, important warnings */
74  #define PRINT_SOME              2  /**< some:   print less important warnings */
75  #define PRINT_MORE              4  /**< more:   print some useful debug info */
76  #define PRINT_MOST              8  /**< most:   maximal printouts, no files */
77  #define PRINT_ALL              10  /**< all:    all printouts, including files */
78
79  /**
80   * \brief Definition of matrix format
81   **/
82  #define MAT_FREE                0  /**< matrix-free format: only mxv action */
83  //-----------------------------------------------------------------------------
84  #define MAT_CSR                 1  /**< compressed sparse row */
85  #define MAT_BSR                 2  /**< block-wise compressed sparse row */
86  #define MAT_STR                 3  /**< structured sparse matrix */
87  #define MAT_CSRL                6  /**< modified CSR to reduce cache missing */
88  #define MAT_SymCSR              7  /**< symmetric CSR format */
89  #define MAT_BLC                 8  /**< block CSR matrix */
90  //-----------------------------------------------------------------------------
91  //    For bordered systems in reservoir simulation
92  //-----------------------------------------------------------------------------
93  #define MAT_bCSR               11  /**< block CSR/CSR matrix == 2*2 BLC matrix */
94  #define MAT_bBSR               12  /**< block BSR/CSR matrix */
95  #define MAT_bSTR               13  /**< block STR/CSR matrix */
96
97  /**
98   * \brief Definition of solver types for iterative methods
99   */
100 #define SOLVER_DEFAULT          0  /**< Use default solver in FASP */
101 //-----------------------------------------------------------------------------
102 #define SOLVER_CG               1  /**< Conjugate Gradient */
103 #define SOLVER_BiCGstab         2  /**< Bi-Conjugate Gradient Stabilized */
104 #define SOLVER_MinRes           3  /**< Minimal Residual */
105 #define SOLVER_GMRES            4  /**< Generalized Minimal Residual */
106 #define SOLVER_VGMRES           5  /**< Variable Restarting GMRES */
107 #define SOLVER_VFGMRES          6  /**< Variable Restarting Flexible GMRES */
108 #define SOLVER_GCG              7  /**< Generalized Conjugate Gradient */
109 #define SOLVER_GCR              8  /**< Generalized Conjugate Residual */
110 //-----------------------------------------------------------------------------
111 #define SOLVER_SCG             11  /**< Conjugate Gradient with safety net */
112 #define SOLVER_SBiCGstab       12  /**< BiCGstab with safety net */
113 #define SOLVER_SMinRes         13  /**< MinRes with safety net */
114 #define SOLVER_SGMRES          14  /**< GMRes with safety net */
115 #define SOLVER_SVGMRES         15  /**< Variable-restart GMRES with safety net */
116 #define SOLVER_SVFGMRES        16  /**< Variable-restart FGMRES with safety net */
117 #define SOLVER_SGCG            17  /**< GCG with safety net */
118 //-----------------------------------------------------------------------------
119 #define SOLVER_AMG             21  /**< AMG as an iterative solver */
120 #define SOLVER_FMG             22  /**< Full AMG as an solver */
121 //-----------------------------------------------------------------------------
122 #define SOLVER_SUPERLU         31  /**< Direct Solver: SuperLU */
123 #define SOLVER_UMFPACK         32  /**< Direct Solver: UMFPack */
124 #define SOLVER_MUMPS           33  /**< Direct Solver: MUMPS */
```

```
125 #define SOLVER_PARDISO         34  /**< Direct Solver: PARDISO */
126
127 /**
128  * \brief Definition of iterative solver stopping criteria types
129  */
130 #define STOP_REL_RES            1  /**< relative residual ||r||/||b|| */
131 #define STOP_REL_PRECRES        2  /**< relative B-residual ||r||_B/||b||_B */
132 #define STOP_MOD_REL_RES        3  /**< modified relative residual ||r||/||x|| */
133
134 /**
135  * \brief Definition of preconditioner type for iterative methods
136  */
137 #define PREC_NULL               0  /**< with no precond */
138 #define PREC_DIAG               1  /**< with diagonal precond */
139 #define PREC_AMG                2  /**< with AMG precond */
140 #define PREC_FMG                3  /**< with full AMG precond */
141 #define PREC_ILU                4  /**< with ILU precond */
142 #define PREC_SCHWARZ            5  /**< with Schwarz preconditioner */
143
144 /**
145  * \brief Type of ILU methods
146  */
147 #define ILUk                    1  /**< ILUk */
148 #define ILUt                    2  /**< ILUt */
149 #define ILUtp                   3  /**< ILUtp */
150
151 /**
152  * \brief Type of Schwarz smoother
153  */
154 #define SCHWARZ_FORWARD         1  /**< Forward ordering */
155 #define SCHWARZ_BACKWARD        2  /**< Backward ordering */
156 #define SCHWARZ_SYMMETRIC       3  /**< Symmetric smoother */
157
158 /**
159  * \brief Definition of AMG types
160  */
161 #define CLASSIC_AMG             1  /**< classic AMG */
162 #define SA_AMG                  2  /**< smoothed aggregation AMG */
163 #define UA_AMG                  3  /**< unsmoothed aggregation AMG */
164
165 /**
166  * \brief Definition of aggregation types
167  */
168 #define PAIRWISE                1  /**< pairwise aggregation, default is SPAIR */
169 #define VMB                     2  /**< VMB aggregation */
170 #define USPAIR                  3  /**< unsymmetric pairwise aggregation */
171 #define SPAIR                   4  /**< symmetric pairwise aggregation */
172
173 /**
174  * \brief Definition of cycle types
175  */
176 #define V_CYCLE                 1  /**< V-cycle */
177 #define W_CYCLE                 2  /**< W-cycle */
```

```
178 #define AMLI_CYCLE              3  /**< AMLI-cycle */
179 #define NL_AMLI_CYCLE           4  /**< Nonlinear AMLI-cycle */
180
181 /**
182  * \brief Definition of standard smoother types
183  */
184 #define SMOOTHER_JACOBI         1  /**< Jacobi smoother */
185 #define SMOOTHER_GS             2  /**< Gauss-Seidel smoother */
186 #define SMOOTHER_SGS            3  /**< Symmetric Gauss-Seidel smoother */
187 #define SMOOTHER_CG             4  /**< CG as a smoother */
188 #define SMOOTHER_SOR            5  /**< SOR smoother */
189 #define SMOOTHER_SSOR           6  /**< SSOR smoother */
190 #define SMOOTHER_GSOR           7  /**< GS + SOR smoother */
191 #define SMOOTHER_SGSOR          8  /**< SGS + SSOR smoother */
192 #define SMOOTHER_POLY           9  /**< Polynomial smoother */
193 #define SMOOTHER_L1DIAG        10  /**< L1 norm diagonal scaling smoother */
194
195 /**
196  * \brief Definition of specialized smoother types
197  */
198 #define SMOOTHER_BLKOIL        11  /**< Used in monolithic AMG for black-oil */
199 #define SMOOTHER_SPETEN        19  /**< Used in monolithic AMG for black-oil */
200
201 /**
202  * \brief Definition of coarsening types
203  */
204 #define COARSE_RS               1  /**< Classical */
205 #define COARSE_RSP              2  /**< Classical, with positive offdiags */
206 #define COARSE_CR               3  /**< Compatible relaxation */
207 #define COARSE_AC               4  /**< Aggressive coarsening */
208 #define COARSE_MIS              5  /**< Aggressive coarsening based on MIS */
209
210 /**
211  * \brief Definition of interpolation types
212  */
213 #define INTERP_DIR              1  /**< Direct interpolation */
214 #define INTERP_STD              2  /**< Standard interpolation */
215 #define INTERP_ENG              3  /**< Energy minimization interpolation */
216 #define INTERP_EXT              6  /**< Extended interpolation */
217
218 /**
219  * \brief Type of vertices (DOFs) for coarsening
220  */
221 #define GOPT                   -5  /**< Cannot fit in aggregates */
222 #define UNPT                   -1  /**< Undetermined points */
223 #define FGPT                    0  /**< Fine grid points  */
224 #define CGPT                    1  /**< Coarse grid points */
225 #define ISPT                    2  /**< Isolated points */
226
227 /**
228  * \brief Definition of smoothing order
229  */
230 #define NO_ORDER                0  /**< Natural order smoothing */
```

```
231 #define CF_ORDER                1  /**< C/F order smoothing */
232 #define ILU_MC_OMP              1  /**< Multi-colors Parallel smoothing */
233
234 /**
235  * \brief Type of ordering for smoothers
236  */
237 #define USERDEFINED             0  /**< User defined order */
238 #define CPFIRST                 1  /**< C-points first order */
239 #define FPFIRST                -1  /**< F-points first order */
240 #define ASCEND                 12  /**< Ascending order */
241 #define DESCEND                21  /**< Descending order */
242
243 /**
244  * \brief Some global constants
245  */
246 #define BIGREAL             1e+20  /**< A large real number */
247 #define SMALLREAL           1e-20  /**< A small real number */
248 #define SMALLREAL2          1e-40  /**< An extremely small real number */
249 #define MAX_REFINE_LVL         20  /**< Maximal refinement level */
250 #define MAX_AMG_LVL            20  /**< Maximal AMG coarsening level */
251 #define MIN_CDOF               20  /**< Minimal number of coarsest variables */
252 #define MIN_CRATE             0.9  /**< Minimal coarsening ratio */
253 #define MAX_CRATE            20.0  /**< Maximal coarsening ratio */
254 #define MAX_RESTART            20  /**< Maximal restarting number */
255 #define MAX_STAG               20  /**< Maximal number of stagnation times */
256 #define STAG_RATIO           1e-4  /**< Stagnation tolerance = tol*STAGRATIO */
257 #define OPENMP_HOLDS         2000  /**< Smallest size for OpenMP version */
258
259 #endif                             /* end if for __FASP_CONST__ */
260
261 /*---------------------------------*/
262 /*--        End of File          --*/
263 /*---------------------------------*/
```

4.3 Debugging and how to enable it

NOTE: The default FSP build is a RELEASE version (`/O3` or equivalent compiler options are enabled) and such version is compiled with optimization and no warnings are displayed during the build. How to build the FASP library with debugging enabled is described below.

There is a built-in debug feature which is intended to help developers and users to locate malfunctions and bugs in FASP (and hopefully fix them). In order to turn this feature on, you need to add the `debug` option during the config stage by

```
$ make config debug=all
```

When this debug feature is turned on, there will be a lot more information printed when you run FASP. If you just want to enable the debugging and warnings during the compile stage, you can do so by using

```
$ make config debug=yes
```