PETSc Developers Guide

Revision 3.9

Mathematics and Computer Science Division
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PETSc Developers Manual

Revision 3.9

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Abstract:

PETSc is an extensible software library for scientific computation. This document provides useful information for PETSc developers and those wishing to contribute to PETSc. The text assumes that you are familiar with PETSc and have access to PETSc source code and documentation (available via http://www.mcs.anl.gov/petsc) including the PETSc users manual [1].

Before contributing code to PETSc, please read Chapter 2, which contains the source code style guide. Information on how to submit patches and pull requests to PETSc can be found at http://www.mcs.anl.gov/petsc/developers/index.html.

Please direct all comments and questions regarding PETSc design and development to petsc-dev@mcs.anl.gov. Note that all bug reports and questions regarding the use of PETSc should be directed to petsc-maint@mcs.anl.gov.
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Chapter 1

Responding to user requests and questions

PETSc users communicate to the PETSc team via two mailing lists: petsc-maint@mcs.anl.gov and petsc-users@mcs.anl.gov. When responding to such inquiries please follow the guidelines given below.

- Be polite.
- Address the person by name (when it is possible to determine their name).
- Apologize for the problem when it is appropriate (but not otherwise).
- Thank the person for their patience if it is more than six hours since the report came in.
- If the person drops the petsc-maint or petsc-users from the reply list, add it back in.
- Don’t ask too many questions or give too many suggestions in the same email. The user often only responds to the first of them, or becomes confused.
Chapter 2

Style Guide

The PETSc team uses certain conventions to make the source code consistent and hence easier to maintain. We will interchangeably use the terminology subclass, implementation, or type to refer to a concrete realization of an abstract base class. For example, KSPGMRES is a type for the base class KSP.

2.1 Names

Consistency of names for variables, functions, etc. is extremely important. We use several conventions:

1. All function names and enum types consist of acronyms or words, each of which is capitalized, for example KSPSolve() and MatGetOrdering().

2. All enum elements and macro variables are named with all capital letters. When they consist of several complete words, there is an underscore between each word. For example, MAT_FINAL_ASSEMBLY.

3. Functions that are private to PETSc (not callable by the application code) either
   • have an appended _Private (for example, StashValues_Private) or
   • have an appended _Subtype (for example, MatMult_SeqAIJ).

   In addition, functions that are not intended for use outside of a particular file are declared static. Also see item 15 in Section 2.2.3.

4. Function names in structures (for example, _matops are the same as the base application function name without the object prefix, and are in small letters. For example, MatMultTranspose() has a structure name of multtranspose.

5. Names of implementations of class functions should begin with the function name, an underscore, and the name of the implementation, for example KSPSolve_GMRES().

6. Each application usable function begins with the name of the class object, followed by any subclass name, for example, ISInvertPermutation(), MatMult() or KSPGMRESSetRestart().

7. Functions that PETSc provides as defaults for user providable functions end with Default (for example, KSPMonitorDefault() or PetscSignalHandlerDefault())
8. Each application usable function begins with the name of the class object, followed by any subclass name, for example, `MatMult()` or `KSPGMRESSetRestart()`.

9. Options database keys are lower case, have an underscore between words, and match the function name associated with the option without the word “set” or “get”. For example, `-ksp_gmres_restart`.

10. Specific `XXXType` values (for example `MatSolverType`) do not have an underscore in them, unless they refer to another package that uses an underscore, for example `MATSOLVERSUPERLU_DIST`.

### 2.2 Coding Conventions and Style

Within the PETSc source code, we adhere to the following guidelines so that the code is uniform and easily maintained.

**2.2.1 C Formatting**

1. *No* tabs are allowed in *any* of the source code.

2. All PETSc function bodies are indented two characters.

3. Each additional level of loops, if statements, etc. is indented two more characters.

4. Wrapping lines should be avoided whenever possible.

5. Source code lines do not have a hard length limit; generally, we like them less than 150 characters wide.

6. The local variable declarations should be aligned. For example, use the style

   ```c
   PetscScalar a;
   PetscInt i,j;
   ```

   instead of

   ```c
   PetscScalar a;
   PetscInt i,j; /* Incorrect */
   ```

7. Assignment and comparison operations, i.e. `x = 22.0` or `x < 22.0`, should have single spaces around the operator. This is true even when assignments are given directly in a line that declares the variable, such as `PetscReal r = 22.3`. The exception is when these symbols are used in a for loop; then, there should be no spaces, for example, `for (i=0; i<m; i++)`. Comparisons in `while()` constructs should have the spaces.

8. When declaring variables there should be no space between multiple variables, that is it should be `PetscReal a, b, c` not `PetscReal a, b, c`.

9. The prototypes for functions should not include the names of the variables; for example write

   ```c
   PETSC_EXTERN PetscErrorCode MyFunction(PetscInt);
   ```

   not

   ```c
   PETSC_EXTERN PetscErrorCode MyFunction(PetscInt myvalue); /* Incorrect */
   ```
10. All local variables of a particular type (e.g., PetscInt) should be listed on the same line if possible; otherwise, they should be listed on adjacent lines.

11. Equal signs should be aligned in regions where possible.

12. There must be a single blank line between the local variable declarations and the body of the function.

13. Indentation for if statements must be done as

```c
if ( ) {
    ....
} else {
    ....
}
```

14. Never have

```c
if ( )
    a single indented line /* Incorrect */
```

or

```c
for ( )
    a single indented line /* Incorrect */
```

instead use either

```c
if ( ) a single statement
```

or

```c
if ( ) {
    a single indented line
}
```

Note that error checking is a separate statement, so the following is incorrect

```c
if ( ) ierr = XXX(); CHKERRQ(ierr); /* Incorrect */
```

and instead one should use

```c
if ( ) {
    ierr = XXX(); CHKERRQ(ierr);
}
```

15. Always have a space between if or for and the following ()

16. The open brace should be on the same line as the if ( ) test, for ( ), etc., never on its own line. For example

```c
} else {
```

never
See item 17 for an exception. The closing brace should always be on its own line.

17. In function declarations, the opening brace should be on the next line, not on the same line as the function name and arguments. This is an exception to item 16.

18. Do not leave chunks of commented-out code in the source files.

19. Do not use C++-style comments (// Comment). Use only C-style comments (/* Comment */).

20. All variables must be declared at the beginning of the code block (C89 style) never mixed in with code.

21. Do not include a space after a ( or before a ). Do not write

   ```c
   ierr = PetscMalloc1( 10,&a );CHKERRQ(ierr); /* Incorrect */
   ```

   but instead write

   ```c
   ierr = PetscMalloc1(10,&a);CHKERRQ(ierr);
   ```

22. Do not use a space after the ) in a cast, or between the type and the * in a cast.

23. Do not include a space before or after a comma in lists. That is, do not write

   ```c
   ierr = func(a, 22.0);CHKERRQ(ierr); /* Incorrect */
   ```

   but instead write

   ```c
   ierr = func(a,22.0);CHKERRQ(ierr);
   ```

2.2.2 C Usage

1. Array and pointer arguments where the array values are not changed should be labeled as const arguments.

2. Scalar values passed to functions should never be labeled as const.

3. Subroutines that would normally have a void** argument to return a pointer to some data should actually be prototyped as void*. This prevents the caller from having to put a (void**) cast in each function call. See, for example, DMDAVecGetArray().

4. Do not use the register directive.

5. Do not use if (rank == 0) or if (v == NULL) or if (flg == PETSC_TRUE) or if (flg == PETSC_FALSE). Instead, use if (!rank) or if (!v) or if (flg) or if (!flg).

6. Do not use #ifdef or #ifndef. Rather, use #if defined(...) or #if !defined(...
2.2.3 Usage of PETSc Functions and Macros

1. Public PETSc includes, `petsc*.h`, should not include private PETSc `petsc/private/*impl.h` includes.

2. Public and private PETSc includes cannot include include files located in the PETSc source tree.

3. The first line of the executable statements in functions must be `PetscFunctionBegin;`

4. Use `PetscFunctionReturn(returnvalue);` not `return(returnvalue);`

5. *Never* put a function call in a return statement; do not do

   ```c
   PetscFunctionReturn( somefunction(...) ); /* Incorrect */
   ```

6. Do *not* put a blank line immediately after `PetscFunctionBegin;` or a blank line immediately before `PetscFunctionReturn(0);`.

7. Do not use `sqrt()`, `pow()`, `sin()`, etc. directly in PETSc C/C++ source code or examples (usage is fine in Fortran source code). Rather, use `PetscSqrtScalar()`, `PetscSqrtReal()`, etc., depending on the context. See `petscmath.h` for expressions to use.

8. `assert.h` should not be included in PETSc source and `assert()` should not be used. It doesn’t play well in the parallel MPI world.

9. The macros `SETERRQ()` and `CHKERRQ()` should be on the same line as the routine to be checked unless this violates the 150 character width rule. Try to make error messages short, but informative.

10. Do not include a space before `CHKXXX()`. That is, do not write

    ```c
    ierr = PetscMalloc1(10,&a); CHKERRQ(ierr); /* Incorrect */
    ```

    but instead write

    ```c
    ierr = PetscMalloc1(10,&a); CHKERRQ(ierr);
    ```

11. Except in code that may be called before PETSc is fully initialized, always use `PetscMallocN()` (for example `PetscMalloc1()`), `PetscCallocN()`, `PetscNew()`, and `PetscFree()`, not `malloc()` and `free()`.

12. MPI routines and macros that are not part of the 1.0 or 1.1 standard should not be used in PETSc without appropriate `./configure` checks and `#if defined()` checks. Code should also be provided that works if the MPI feature is not available. For example

    ```c
    #if defined(PETSC_HAVE_MPI_IN_PLACE)
        ierr = MPI_Allgatherv(MPI_IN_PLACE,0,MPI_DATATYPE_NULL,lens,
                               recvcounts,displs,MPIU_INT,comm);CHKERRQ(ierr);
    #else
        ierr = MPI_Allgatherv(lens,sendcount,MPIU_INT,lens,recvcounts,
                               displs,MPIU_INT,comm);CHKERRQ(ierr);
    #endif
    ```
13. There shall be no PETSc routines introduced that provide essentially the same functionality as an available MPI routine. For example, one should not write a routine PetscGlobalSum() that takes a scalar value and performs an MPI_Allreduce() on it. One should use MPI_Allreduce() directly in the code.

14. Never use a local variable counter like PetscInt flops = 0; to accumulate flops and then call PetscLogFlops(); always just call PetscLogFlops() directly when needed.

15. Library functions should be declared PETSC_INTERN if they are intended to be visible only within a single shared library. They should be declared PETSC_EXTERN if intended to be visible across shared libraries. Note that PETSc can be configured to build a separate shared library for each top-level class (Mat, Vec, KSP, etc.) and that plugin implementations of these classes can be included as separate shared libraries; thus, private functions may be marked PETSC_EXTERN. For example,
   - MatStashCreate_Private is marked PETSC_INTERN as it is used across compilation units, but only within the Mat package.
   - All functions, such as KSPCreate(), included in the public headers (include/petsc*.h) should be marked PETSC_EXTERN.
   - MatHeaderReplace() is not intended for users (it is in include/petsc/private/matimpl.h) but is marked PETSC_EXTERN since it is used both by implementations of the Mat class (which could be defined in plugin implementations) and by functions in the DM and KSP packages.

2.3 Formatted Comments

PETSc uses formatted comments and the Sowing packages [5, 6] to generate documentation (manual pages) and the Fortran interfaces. Documentation for Sowing and the formatting may be found at http://wgropp.cs.illinois.edu/projects/software/sowing/; in particular, see the documentation for doctext.

- /*@
  indicates a formatted comment of a function that will be used for both documentation and a Fortran interface.

- /*@C
  a formatted comment of a function that will be used only for documentation, not to generate a Fortran interface, in general such labeled C functions should have a custom Fortran interface provided. Functions that take char* or function pointer arguments must have the C symbol.

- /*E
  a formatted comment of an enum used for documentation only, note that each of these needs to be listed in lib/petsc/conf/bfort-petsc.txt as a native and defined in the corresponding include/petsc/finclude/petscxxxx.ft fortran include file and the values set as parameters in the file src/SECTION/f90-mod/petscSUBSECTION.h, for example, src/vec/f90-mod/petscvis.h.

- /*S
  a formatted comment for a data type such as KSP, note that each of these needs to be listed in lib/petsc/conf/bfort-petsc.txt as a nativeptr.
2.3. FORMATTED COMMENTS

- /*MC
  a formatted comment of a CPP macro or enum value for documentation.

The Fortran interface files supplied by user go into the two directories `ftn-custom` and `ftn-f90` while those generated by Sowing go into `ftn-auto`.

2.3.1 Manual Page Format

Each function, typedef, class, macro, enum, etc. in the public API should include the following data, correctly formatted (see above section) to generate complete manual pages and Fortran interfaces with Sowing. All entries below should be separated by blank lines. Except where noted, add a newline after the section headings.

- The item’s name, followed by a dash and brief (one-sentence) description
- If documenting a function, a description of the function’s “collectivity” (whether all ranks in an MPI communicator need to participate)
  - Not Collective if the function need not be called on all MPI ranks
  - Collective [on XXX] if the function is a collective operation [with respect to the data of class XXX]
  - Logically Collective [on XXX] if the function is collective but does not require any actual synchronization (say, setting class parameters uniformly).
- If documenting a function with input parameters, a list of input parameter descriptions in an Input Parameters: section
- If documenting a function with output parameters, a list of output parameter descriptions in an Output Parameters: section
- If documenting a function which interacts with the options database, a list of options database keys in an Options Database Keys: section
- (Optional) a Notes: section. In-depth discussion, technical caveats, special cases, and so on should be listed here. If it is ambiguous whether returned pointers/objects need to be freed/destroyed by the user or not, this information should be mentioned here.
- (If applicable) a Fortran Notes: section detailing any relevant differences in calling or using the item from Fortran.
- Level: (no newline) followed by beginner, intermediate, advanced, or developer.
- (Optional) Concepts: (no newline), followed by a list of concepts.
- (Optional) Keywords: (no newline), followed by a list of keywords.
- .seealso: (no newline), followed by a list of related manual pages. These manual pages should usually also point back to this manual page in their .seealso: sections.
Chapter 3

The PETSc Kernel

PETSc provides a variety of basic services for writing scalable, component based libraries; these are referred to as the PETSc kernel, [4]. The source code for the kernel is in src/sys. It contains systematic support for

- PETSc types,
- error handling,
- memory management,
- profiling,
- object management,
- Fortran interfaces, see [2],
- mechanism for generating appropriate citations for algorithms and software used in PETSc, see [7],
- file IO,
- an options database, and
- objects and code for viewing, drawing, and displaying data and solver objects.

Each of these is discussed in a section below.

3.1 PETSc Types

For maximum flexibility, the basic data types int, double, etc. are not used in PETSc source code. Rather it has:

- PetscScalar,
- PetscInt,
- PetscMPIInt,
- PetscBLASInt,
- PetscBool, and
- PetscBT - bit storage of logical true and false.

PetscInt can be set using ./configure to be either int (32 bit, the default) or long long (64 bit, with configure --with-64-bit-indices) to allow indexing into very large arrays. PetscMPIInt are used for integers passed to MPI as counts and sizes. These are always int since that is what the MPI standard uses. Similarly, PetscBLASInt is for counts, etc. passed to BLAS and LAPACK

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routines. These are almost always int unless one is using a special “64 bit integer” BLAS/LAPACK (this is available, for example, with Intel’s MKL and OpenBLAS).

In addition, there are special types:

- PetscClassId
- PetscErrorCode
- PetscLogEvent

These are currently always int but their use clarifies the code.

## 3.2 Implementation of Error Handling

PETSc uses a “call error handler; then (depending on result) return error code” model when problems are detected in the running code. The public include file for error handling is `include/petscerror.h`, and the source code for the PETSc error handling is in `src/sys/error/`.

### 3.2.1 Simplified Interface

The simplified macro-based interface consists of the following two calls:

- `SETERRQ(comm,error code,"Error message");`
- `CHKERRQ(ierr);`

The macro `SETERRQ()` is given by

```c
return PetscError(comm,__LINE__,PETSC_FUNCTION_NAME,__FILE__,error code,error type,"Error message");
```

It calls the error handler with the current function name and location: line number, and file, plus an error code and an error message. Normally `comm` is `PETSC_COMM_SELF`; it can only be another communicator if one is absolutely sure the same error will be generated on all processes in the communicator. This feature is to prevent the same error message from being printed by many processes. The `error type` is `PETSC_ERROR_INITIAL` on detection of the initial error and `PETSC_ERROR_REPEAT` for additional calls as the error calls go up the function call stack. This is so that the detailed error information is only printed once instead of for all levels of returned errors.

The macro `CHKERRQ()` is defined by

```c
if (ierr) PetscError(PETSC_COMM_SELF,__LINE__,PETSC_FUNCTION_NAME_,__FILE__,ierr,PETSC_ERROR_REPEAT," ");
```

In addition to `SETERRQ()`, there are macros `SETERRQ1()`, `SETERRQ2()`, `SETERRQ3()` and `SETERRQ4()` that allow one to provide additional arguments to a formatted message string. For example,

```c
SETERRQ2(comm,PETSC_ERR,"Iteration overflow: its %d norm %g",its,norm);
```

The reason for the numbered format is that C89 CPP macros cannot handle a variable number of arguments.

### 3.2.2 Error Handlers

The error handling function `PetscError()` calls the “current” error handler with the code
The variable `eh` is the current error handler context and is defined in `src/sys/error/err.c` as:

```c
typedef struct _PetscEH* PetscEH;
struct _PetscEH {
  PetscErrorCode handler(MPI_Comm,int,const char*,const char*,const char*,
                         PetscErrorCode,PetscErrorType,const char*,void*);
  void       *ctx;
  PetscEH    *previous;
};
```

One can set a new error handler with the command `PetscPushErrorHandler()` which maintains a linked list of error handlers. The most recent error handler is removed via `PetscPopErrorHandler()`.

PETSc provides several default error handlers:

- `PetscTraceBackErrorHandler()`, the default,
- `PetscAbortErrorHandler()`, called with `-on_error_abort`,
- `PetscReturnErrorHandler()`, returns up the stack without printing error messages,
- `PetscEmacsClientErrorHandler()`,
- `PetscMPIAbortErrorHandler()`, call `MPI_Abort()` after printing the error message, and
- `PetscAttachDebuggerErrorHandler()`, called with `-on_error_attach_debugger`.

### 3.2.3 Error Codes

The PETSc error handler takes an error code. The generic error codes are defined in `include/petscerror.h`. The same error code is used many times in the libraries. For example, the error code `PETSC_ERR_MEM` is used whenever a requested memory allocation is not available.

### 3.2.4 Detailed Error Messages

In a modern parallel component-oriented application code, it does not always make sense to simply print error messages to the terminal (and more than likely there is no “terminal”, for example with Microsoft Windows or Apple iPad applications). PETSc provides the replaceable function pointer

```c
(*PetscErrorPrintf)("Format",...);
```

that, by default prints to standard out. Thus, error messages should not be printed with `printf()` or `fprintf()`. Rather, they should be printed with `(*PetscErrorPrintf)()`. One can direct
all error messages to `stderr`, instead of the default `stdout`, with the command line options `-error_output_stderr`.

### 3.3 Memory Management

PETSc provides a simple wrapper for the system `malloc()`, `calloc()` and `free()`. The public interface for these is provided in `petscsys.h` while the implementation code is in `src/sys/memory`. The most basic interfaces are

```c
#define PetscMalloc(a,b)  
  (*((PetscTrMalloc)((a),__LINE__,PETSC_FUNCTION_NAME,__FILE__,(void**)(b)))
#define PetscFree(a)  
  (*((PetscTrFree)((void*)(a),__LINE__,PETSC_FUNCTION_NAME,__FILE__) || ((a) = 0,0))
PetscErrorCode PetscMallocA(int n,PetscBool clear,int lineno,const char *function,const char *filename,size_t bytes0,void *ptr0,...)
PetscErrorCode PetscFreeA(int n,int lineno,const char *function,const char *filename,void *ptr0,...)
```

which allow the use of any number of profiling and error checking wrappers for `malloc()`, `calloc()` and `free()`. Both `PetscMallocA()` and `PetscFreeA()` call the function pointer values (*PetscTrMalloc) and (*PetscTrFree). `PetscMallocSet()` is used to set these function pointers. The functions are guaranteed to support requests for zero bytes of memory correctly. Freeing memory locations also sets the pointer value to zero preventing later code from accidently using memory that has been freed. All PETSc memory allocation calls are memory lined on at least double precision boundaries, the macro generated by configure `PETSC_MEMALIGN` indicates in bytes what alignment all allocations have. This can be controlled at configure time with the option `-with-memalign=<4,8,16,32,64>.

`PetscMallocA()` supports a request for up to 7 distinct memory locations of possibly different types. This serves two purposes, it reduces the number of system `malloc()` calls, thus potentially increasing performance and it clarifies in the code related memory allocations that should be freed together.

The following macros are the preferred way to obtain and release memory in the PETSc source code, they automatically manage calling `PetscMallocA()` and `PetscFreeA()` with the appropriate location information.

```c
#define PetscMalloc1(m1,r1)  
  PetscMallocA(1,PETSC_FALSE,__LINE__,PETSC_FUNCTION_NAME,__FILE__,
              (size_t)(m1)*sizeof(**(r1)),(r1))
#define PetscMalloc2(m1,r1,m2,r2)  
  PetscMallocA(2,PETSC_FALSE,__LINE__,PETSC_FUNCTION_NAME,__FILE__,
              (size_t)(m1)*sizeof(**(r1)),(r1),(size_t)(m2)*sizeof(**(r2)),(r2))
...  
#define PetscMalloc7(...)  
#define PetscMallocSet()  
#define PetscFree2(m1,m2)  
  PetscFreeA(2,__LINE__,PETSC_FUNCTION_NAME,__FILE__,&(m1),&(m2))
...  
#define PetscFree7(...)  
```
There are similar routines `PetscCalloc1()` to `PetscCalloc7()` that provide memory initialized to zero. The size requests for these macros are in number of data items requested, not in bytes. This decreases the number of errors in the code since the compiler determines from the object type their sizes instead of requiring the user to provide the correct value with `sizeof()`.

The routines `PetscTrMallocDefault()` and `PetscTrFreeDefault()` which are set with the routine `PetscSetUseTrMalloc_Private()` (and are used by default for the debug version of PETSc) provide simply logging and error checking versions of memory allocation.

### 3.4 Implementation of Profiling

This section provides details about the implementation of event logging and profiling within the PETSc kernel. The interface for profiling in PETSc is contained in the file `include/petsclog.h`. The source code for the profile logging is in `src/sys/plog/`.

#### 3.4.1 Profiling Object Creation and Destruction

The creation of objects is profiled with the command `PetscLogObjectCreate()`

```c
PetscLogObjectCreate(PetscObject h);
```

which logs the creation of any PETSc object. Just before an object is destroyed, it should be logged with with `PetscLogObjectDestroy()`

```c
PetscLogObjectDestroy(PetscObject h);
```

These are called automatically by `PetscHeaderCreate()` and `PetscHeaderDestroy()` which are used in creating all objects inherited off the basic object. Thus, these logging routines need never be called directly.

If an object has a clearly defined parent object (for instance, when a work vector is generated for use in a Krylov solver), this information is logged with the command `PetscLogObjectParent()`

```c
PetscLogObjectParent(PetscObject parent,PetscObject child);
```

It is also useful to log information about the state of an object, as can be done with the command `PetscLogObjectState()`

```c
PetscLogObjectState(PetscObject h,const char *format,...);
```

For example, for sparse matrices we usually log the matrix dimensions and number of nonzeros.

#### 3.4.2 Profiling Events

Events are logged using the pair `PetscLogEventBegin()`

```c
PetscLogEventBegin(PetscLogEvent event,PetscObject o1,...,PetscObject o4);
PetcLogEventEnd(PetscLogEvent event,PetscObject o1,...,PetscObject o4);
```

This logging is usually done in the abstract interface file for the operations, for example, `src/mat/interface/matrix.c`. 21
3.4.3 Controlling Profiling

Routines that control the default profiling available in PETSc include:

- `PetscLogDefaultBegin();`
- `PetscLogAllBegin();`
- `PetscLogDump(const char *filename);`
- `PetscLogView(PetscViewer);`

These routines are normally called by the `PetscInitialize()` and `PetscFinalize()` routines when the option `-log_view` is given.
Chapter 4

Basic Object Design and Implementation

PETSc is designed using strong data encapsulation. Hence, any collection of data (for instance, a sparse matrix) is stored in a way that is completely private from the application code. The application code can manipulate the data only through a well-defined interface, as it does not “know” how the data is stored internally.

4.1 Introduction

PETSc is designed around several classes including, for example, Vec (vectors) and Mat (matrices, both dense and sparse). Each class is implemented using a C struct that contains the data and function pointers for operations on the data (much like virtual functions in C++ classes). Each class consists of three parts:

1. A (small) common part shared by all PETSc classes (for example both KSP and PC have this same header),
2. another common part shared by all PETSc implementations of the class (for example both KSPGMRES and KSPCG have this common sub-header), and
3. a private part used by only one particular implementation written in PETSc.

For example, all matrix (Mat) classes share a function table of operations that may be performed on the matrix; all PETSc matrix implementations share some additional data fields, including matrix parallel layout, while a particular matrix implementation in PETSc (say compressed sparse row) has its own data fields for storing the actual matrix values and sparsity pattern. This will be explained in more detail in the following sections. New class implementations must use the PETSc common part.

We will use <class>_<implementation> to denote the actual source code and data structures used for a particular implementation of an object that has the <class> interface.

4.2 Organization of the Source Code

Each class has

- Its own, application public, include file include/petsc<class>.h
- Its own directory, src/<class> or src/package/<class>.
• A data structure defined in the file include/petsc/private/<class>impl.h. This data structure is shared by all the different PETSc implementations of the class. For example, for matrices it is shared by dense, sparse, parallel, and sequential formats.

• An abstract interface that defines the application-callable functions for the class. These are defined in the directory src/<class>/interface. This is how polymorphism is supported with code that implements the abstract interface to the operations on the object. Essentially, these routines do some error checking of arguments and logging of profiling information and then call the function appropriate for the particular implementation of the object. The name of the abstract function is <class>Operation, for instance, MatMult() or PCCreate(), while the name of a particular implementation is <class>Operation_<implementation>, for instance, MatMult_SeqAIJ() or PCCreate_ILU(). These naming conventions are used to simplify code maintenance (Also see Section 2.1).

• One or more actual implementations of the class (for example, sparse uniprocessor and parallel matrices implemented with the AIJ storage format). These are each in a subdirectory of src/<class>/impls. Except in rare circumstances, data structures defined here should not be referenced from outside this directory.

Each type of object, for instance a vector, is defined in its own public include file, by typedef _p_<class>* <class>; (for example, typedef _p_Vec* Vec;). This organization allows the compiler to perform type checking on all subroutine calls while at the same time completely removing the details of the implementation of _p_<class> from the application code. This capability is extremely important because it allows the library internals to be changed without altering or re-compiling the application code.

### 4.3 Common Object Header

All PETSc/PETSc objects have the following common header structures defined in include/petsc/private/petscimpl.h:

Listing 4.1: Function table common to all PETSc compatible classes

```c
typedef struct {
    PetscErrorCode (*getcomm)(PetscObject,MPI_Comm*);
    PetscErrorCode (*view)(PetscObject,Viewer);
    PetscErrorCode (*destroy)(PetscObject);
    PetscErrorCode (*query)(PetscObject,const char*,PetscObject*);
    PetscErrorCode (*compose)(PetscObject,const char*,PetscObject);
    PetscErrorCode (*composefunction)(PetscObject,const char*,void(*)(void));
    PetscErrorCode (*queryfunction)(PetscObject,const char*,void **)(void));
} PetscOps;
```

Listing 4.2: Data structure header common to all PETSc compatible classes

```c
struct _p_<class> {
    PetscClassId            classid;
    PetscOps                *bops;
    <class>Ops               *ops;
    MPI_Comm                 comm;
    PetscLogDouble           flops,time,mem;
    int                      id;
};
```
Here `<class>ops` is a function table (like the `PetscOps` above) that contains the function pointers for the operations specific to that class. For example, the PETSc vector class object operations in `include/petsc/private/vecimpl.h` include the following:

Listing 4.3: Function table common to all PETSc compatible vector objects (truncated)

```c
typedef struct _VecOps* VecOps;
struct _VecOps {
    PetscErrorCode (*duplicate)(Vec,Vec*); /* get single vector */
    PetscErrorCode (*duplicatevecs)(Vec,PetscInt,Vec**); /* get array of vectors */
    PetscErrorCode (*destroyvecs)(PetscInt,Vec[]); /* free array of vectors */
    PetscErrorCode (*dot)(Vec,Vec,PetscScalar*); /* z = x^H * y */
    PetscErrorCode (*norm)(Vec,NormType,PetscReal*); /* z = sqrt(x^H * x) */
    PetscErrorCode (*tdot)(Vec,Vec,PetscScalar*); /* x'*y */
    PetscErrorCode (*scale)(Vec,PetscScalar); /* x = alpha * x */
    PetscErrorCode (*copy)(Vec,Vec); /* y = x */
    PetscErrorCode (*set)(Vec,PetscScalar); /* y = alpha */
    PetscErrorCode (*swap)(Vec,Vec); /* exchange x and y */
    PetscErrorCode (*axpy)(Vec,PetscScalar,Vec); /* y = y + alpha * x */
    PetscErrorCode (*axpby)(Vec,PetscScalar,PetscScalar,Vec); /* y = alpha * x + beta * y */
    ... (ETC.) ...
};
```

Listing 4.4: Data structure header common to all PETSc vector classes

```c
struct _p_Vec {
    PetscClassId classid;
    PetscOps *bops;
    VecOps *ops;
    MPI_Comm comm;
};
```
Each PETSc object begins with a `PetscClassId` which is used for error checking. Each different class of objects has its value for `classid`; these are used to distinguish between classes. When a new class is created one needs to call

```
PetscClassIdRegister(const char *classname, PetscClassId *classid);
```

For example,

```
PetscClassIdRegister("index set", &IS_CLASSID);
```

One can verify that an object is valid of a particular class with `PetscValidHeaderSpecific`, for example

```
PetscValidHeaderSpecific(x, VEC_CLASSID, 1);
```

The third argument to this macro indicates the position in the calling sequence of the function the object was passed in. This is to generate more complete error messages.

To check for an object of any type use

```
PetscValidHeader(x, 1);
```

### 4.4 Common Object Functions

Several routines are provided for manipulating data within the header. These include the specific functions in the PETSc common function table. The function pointers are not called directly, rather one calls `lstinlinePetscObjectFunctionName()` where `lstinlineFunctionName` is one of the functions listed below with the first letter of each word capitalized.

- `getcomm(PetscObject, MPI_Comm*)` obtains the MPI communicator associated with this object.
- `view(PetscObject, Viewer)` allows one to store or visualize the data inside an object. If the Viewer is NULL than should cause the object to print information on the object to `lstinlinestdout`. 

---

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• destroy(PetscObject) causes the reference count of the object to be decreased by one or the object to be destroyed and all memory used by the object to be freed when the reference count drops to zero. If the object has any other objects composed with it then they are each sent a destroy(), i.e. the destroy() function is called on them also.

• compose(PetscObject, const char *name, PetscObject) associates the second object with the first object and increases the reference count of the second object. If an object with the same name was previously composed, that object is dereferenced and replaced with the new object. If the second object is NULL and an object with the same name has already been composed that object is dereferenced (the destroy() function is called on it, and that object is removed from the first object); i.e. this is a way to remove, by name, an object that was previously composed.

• query(PetscObject, const char *name, PetscObject*) retrieves an object that was previously composed with the first object via PetscObjectCompose(). Retrieves a NULL if no object with that name was previously composed.

• composefunction(PetscObject, const char *name, const char *fname, void *func) associates a function pointer to an object. If the object already had a composed function with the same name, the old one is replaced. If func is NULL the existing function is removed from the object. The string fname is the character string name of the function; it may include the path name or URL of the dynamic library where the function is located. The argument name is a “short” name of the function to be used with the queryfunction() call. On systems that support dynamic libraries the func argument is ignored; otherwise func is the actual function pointer.

  For example, fname may be libpetscksp:PCCreate_LU or http://www.mcs.anl.gov/petsc/libpetscksp:PCCreate_LU.

• queryfunction(PetscObject, const char *name, void **func) retrieves a function pointer that was associated with the object via PetscObjectComposeFunction(). If dynamic libraries are used, the function is loaded into memory at this time (if it has not been previously loaded), not when the composefunction() routine was called.

Since the object composition allows one to only compose PETSc objects with PETSc objects rather than any arbitrary pointer, PETSc provides the convenience object PetscContainer, created with the routine PetscContainerCreate(MPI_Comm, PetscContainer*) to allow one to wrap any kind of data into a PETSc object that can then be composed with a PETSc object.

4.5 Object Function Implementation

This section discusses how PETSc implements the compose(), query(), composefunction(), and queryfunction() functions for its object implementations. Other PETSc compatible class implementations are free to manage these functions in any manner; but, unless there is a specific reason, they should use the PETSc defaults so that the library writer does not have to “reinvent the wheel.”

4.5.1 Compose and Query Objects

In src/sys/objects/olist.c, PETSc defines a C struct

```c
typedef struct _PetscObjectList* PetscObjectList;
struct _PetscObjectList {
    char           name[128];
    PetscObject    obj;
};
```
from which linked lists of composed objects may be constructed. The routines to manipulate these elementary objects are

```c
int PetscObjectListAdd(PetscObjectList *fl, const char *name, PetscObject obj);
int PetscObjectListDestroy(PetscObjectList fl);
int PetscObjectListFind(PetscObjectList fl, const char *name, PetscObject *obj);
int PetscObjectListDuplicate(PetscObjectList fl, PetscObjectList *nl);
```

The function `PetscObjectListAdd()` will create the initial `PetscObjectList` if the argument `fl` points to a NULL.

The PETSc object `compose()` and `query()` functions are (defined in `src/sys/objects/inherit.c`)

```c
PetscErrorCode PetscObjectCompose_Petsc(PetscObject obj, const char *name, PetscObject *ptr)
{
    PetscErrorCode ierr;

    PetscFunctionBegin;
    PetscObjectListAdd(&obj->olist, name, ptr);
    PetscFunctionReturn(0);
}

PetscErrorCode PetscObjectQuery_Petsc(PetscObject obj, const char *name, PetscObject *ptr)
{
    PetscErrorCode ierr;

    PetscFunctionBegin;
    PetscObjectListFind(obj->olist, name, ptr);
    PetscFunctionReturn(0);
}
```

### 4.5.2 Compose and Query Functions

PETSc allows one to compose functions by specifying a name and function pointer. In `src/sys/dll/reg.c`, PETSc defines the linked list structure

```c
struct _n_PetscFunctionList {
    void (*routine)(void); /* the routine */
    char *name; /* string to identify routine */
    PetscFunctionList next; /* next pointer */
    PetscFunctionList next_list; /* used to maintain list of all lists for freeing */
};
```

Each PETSc object contains a `PetscFunctionList` object. The `composefunction()` and `queryfunction()` are given by
PetscErrorCode PetscObjectComposeFunction_Petsc(PetscObject obj, const char *name, void *ptr)
{
    PetscErrorCode ierr;

    PetscFunctionBegin;
    PetscFunctionListAdd(&obj->qlist, name, fname, ptr);
    PetscFunctionReturn(0);
}

PetscErrorCode PetscObjectQueryFunction_Petsc(PetscObject obj, const char *name, void (**ptr)(void))
{
    PetscErrorCode ierr;

    PetscFunctionBegin;
    PetscFunctionListFind(obj->qlist, name, ptr);
    PetscFunctionReturn(0);
}

In addition to using the PetscFunctionList mechanism to compose functions into PETSc objects, it is also used to allow registration of new class implementations; for example, new preconditioners - see Section ??.

4.5.3 Simple PETSc Objects

There are some simple PETSc objects that do not need PETSCHEADER and the associated functionality. These objects are internally named as _n_<class> as opposed to _p_<class>. For example, _n_PetscTable vs _p_Vec.

4.6 PETSc Packages

The PETSc source code is divided into the following library level packages: sys, Vec, Mat, DM, KSP, SNES, TS, TAO. Each of these has a directory under the src directory in the PETSc tree and, optionally, can be compiled into separate libraries. Each package defines one or more classes, for example the KSP package defines the KSP and PC classes, as well as several utility classes. In addition each library level package may contain several class level packages associated with individual classes in the library level package. In general most “important” classes in PETSc have their own class level package. Each package provides a registration function XXXInitializePackage(), for example KSPInitializePackage(), which registers all the classes and events for that package. They also register a finalization routine, XXXFinalizePackage() that releases all the resources used in registering the package, using PetscRegisterFinalize(). The registration for each package is performed “on demand” the first time a class in the package is utilized. This is handled, for example, with the code such as

PetscErrorCode VecCreate(MPI_Comm comm, Vec *vec)
{
    Vec v;
PetscFunctionBegin;
PetscValidPointer(vec,2);
*vec = NULL;
VecInitializePackage();
Chapter 5

How the Solvers Handle User Provided Callbacks

The solver objects in PETSc, KSP (optionally), SNES, and TS require user provided callback functions (and contexts for the functions) that define the problem to be solved. These functions are supplied by the user with calls such as `SNESetFunction(SNES,...)` and `TSSetRHSFunction(TS,...)`. One would naturally think that the functions provided would be attached to the appropriate solver object, that is the SNES callbacks would be attached to the SNES object and TS callbacks to the TS object. This is not the case. Or possibly one might think the callbacks would be attached to the DM object associated with the solver object. This is also not the case. Rather the callback functions are attached to an inner nonpublic DMXXX object (XXX is KSP, SNES, or TS) that is attached to the DM that is attached to the XXX solver object. This convoluted design is to support multilevel and multidomain solvers where different levels and different domains may (or may not) share the same callback function or call back context. One can control exactly what XXX/DM objects share a common DMXXX object.

In Figure 1 we depict how three levels of KSP objects share a common DMKSP object. The code to access the inner DMKSP object is

```c
DM dm_2;
DMKSP dmksp;
KSPGetDM(ksp_2,&dm_2);
DMGetDKMSP(dm_2,&dmksp);
```

To obtain a new DMKSP object for which one can change the callback functions (or their contexts) without affecting the original DMKSP one calls
DM dm_2;
DMKSP dmksp;
KSPGetDM(ksp_2,&dm_2);
DMGetDMKSPWrite(dm_2,&dmksp_2);

This results in the object organization as indicated in Figure 2

```
KSP1  KSP2  KSP3
   |     |     |
DM1  |     |     | DM3
   |     |
DMKSP  DMKSP2
```

Figure 2: Two levels of KSP/DM share the same DMKSP, one has its own private copy

The DMKSP object is essentially the list of callback functions and their contexts.

```c
typedef struct _p_DMKSP *DMKSP;
typedef struct _DMKSPOps *DMKSPOps;
struct _DMKSPOps {
    PetscErrorCode (*computeoperators)(KSP,Mat,Mat,void*);
    PetscErrorCode (*computerhs)(KSP,Vec,void*);
    PetscErrorCode (*computeinitialguess)(KSP,Vec,void*);
    PetscErrorCode (*destroy)(DMKSP*);
    PetscErrorCode (*duplicate)(DMKSP,DMKSP);
};
struct _p_DMKSP {
    PETSCHEADER(struct _DMKSPOps);
    void *operatorsctx;
    void *rhsctx;
    void *initialguessctx;
    void *data;
    DM originaldm;

    void (*fortran_func_pointers[3])(void); /* Store our own function pointers so
    they are associated with the DMKSP instead of the DM */
};
```

We now explore in more detail exactly how the solver calls set by the user are passed down to the inner DMKSP object. For each user level solver routine for setting a callback there exists a similar routine at the DM level, thus XXXSetY(XXX,...) has a routine DMXXXSetY(DM,...).

```c
PetscErrorCode KSPSetComputeOperators(KSP ksp,PetscErrorCode (*func)(KSP,Mat,Mat,void*),void *ctx)
{
    PetscErrorCode ierr;
```
The implementation of `DMXXXSetY(DM,...)` gets a “writable” version of the `DMXXX` object via `DMGetDMXXXWrite(DM,DMXXX*)` and sets the function callback and its context into the `DMXXX` object.

```
PetscErrorCode DMKSPSetComputeOperators(DM dm,PetscErrorCode (*func)(KSP,Mat,Mat,void*),void *ctx)
{
    PetscErrorCode ierr;
    DMKSP kdm;

    PetscFunctionBegin;
    PetscValidHeaderSpecific(dm,DM_CLASSID,1);
    ierr = DMGetDMKSP(dm,&kdm);CHKERRQ(ierr);
    if (func) kdm->ops->computeoperators = func;
    if (ctx) kdm->operatorsctx = ctx;
    PetscFunctionReturn(0);
}
```

The routine for `DMGetDMXXXWrite(DM,DMXXX*)` entails a duplication of the object unless the `DM` associated with the `DMXXX` object is the original `DM` that the `DMXXX` object was created with. This can be seen in the following code.

```
PetscErrorCode DMGetDMKSPWrite(DM dm,DMKSP *kspdm)
{
    PetscErrorCode ierr;
    DMKSP kdm;

    PetscFunctionBegin;
    PetscValidHeaderSpecific(dm,DM_CLASSID,1);
    ierr = DMGetDMKSP(dm,&kdm);CHKERRQ(ierr);
    if (!kdm->originaldm) kdm->originaldm = dm;
    if (kdm->originaldm != dm) { /* Copy on write */
        DMKSP oldkdm = kdm;
        ierr = PetscInfo(dm,"Copying DMKSP due to write\n");CHKERRQ(ierr);
        ierr = DMKSPCreate(PetscObjectComm((PetscObject)dm),&kdm);CHKERRQ(ierr);
        ierr = DMKSCPongy(oldkdm,kdm);CHKERRQ(ierr);
        ierr = DMKSPCopy(oldkdm,kdm);CHKERRQ(ierr);
        ierr = DMKSPDestroy((DMKSP*)&dm->dmksp);CHKERRQ(ierr);
        dm->dmksp = (PetscObject)kdm;
    }
    *kspdm = kdm;
    PetscFunctionReturn(0);
}
```
The routine `DMGetDMXXX(DM,DMXXX*)` has the form
```
PetscErrorCode DMGetDMKSP(DM dm,DMKSP *kspdm)
{
    PetscErrorCode ierr;

    PetscFunctionBegin;
    PetscValidHeaderSpecific(dm,DM_CLASSID,1);
    *kspdm = (DMKSP) dm->dmksp;
    if (!*kspdm) {
        ierr = PetscInfo(dm,"Creating new DMKSP\n");CHKERRQ(ierr);
        ierr = DMKSPCreate(PetscObjectComm((PetscObject)dm),kspdm);CHKERRQ(ierr);
        dm->dmksp = (PetscObject) *kspdm;
        ierr = DMCoarsenHookAdd(dm,DMCoarsenHook_DMKSP,NULL,NULL);CHKERRQ(ierr);
        ierr = DMRefineHookAdd(dm,DMRefineHook_DMKSP,NULL,NULL);CHKERRQ(ierr);
    }
    PetscFunctionReturn(0);
}
```

This routine uses `DMCoarsenHookAdd()` and `DMCoarsenHookAdd()` to attach to the `DM` object two functions that are automatically called when the object is coarsened or refined. The hooks `DMCoarsenHook_DMXXX()` and `DMCoarsenHook_DMXXX()` have the form.
```
static PetscErrorCode DMRefineHook_DMKSP(DM dm,DM dmc,void *ctx)
{
    PetscErrorCode ierr;

    PetscFunctionBegin;
    ierr = DMCopyDMKSP(dm,dmc);CHKERRQ(ierr);
    PetscFunctionReturn(0);
}
```

where
```
PetscErrorCode DMCopyDMKSP(DM dmsrc,DM dmdest)
{
    PetscErrorCode ierr;

    PetscFunctionBegin;
    PetscValidHeaderSpecific(dmsrc,DM_CLASSID,1);
    PetscValidHeaderSpecific(dmdest,DM_CLASSID,2);
    ierr = DMKSPDestroy((DMKSP*)&dmdest->dmksp);CHKERRQ(ierr);
    dmdest->dmksp = dmsrc->dmksp;
    ierr = PetscObjectReference(dmdest->dmksp);CHKERRQ(ierr);
    ierr = DMCoarsenHookAdd(dmdest,DMCoarsenHook_DMKSP,NULL,NULL);CHKERRQ(ierr);
    ierr = DMRefineHookAdd(dmdest,DMRefineHook_DMKSP,NULL,NULL);CHKERRQ(ierr);
    PetscFunctionReturn(0);
}
```
insures that the new \texttt{DM} shares the same \texttt{DMXXX} as the parent \texttt{DM} and also inherits the hooks if it is refined or coarsened.

If you provide callbacks to a solver \textit{after} the \texttt{DM} associated with a solver has been refined or coarsened those child \texttt{DM}’s will not share a common \texttt{DMXXX}.

The \texttt{TS} object manages its callback functions in a way similar to \texttt{KSP} and \texttt{SNES} though there are no multi-level \texttt{TS} implementations so in theory the \texttt{DMTS} object is currently unneeded.
Chapter 6

The Various Matrix Classes

PETSc provides a variety of matrix implementations, since no single matrix format is appropriate for all problems. This section first discusses various matrix blocking strategies, and then describes the assortment of matrix types within PETSc.

6.1 Matrix Blocking Strategies

In today’s computers, the time to perform an arithmetic operation is dominated by the time to move the data into position, not the time to compute the arithmetic result. For example, the time to perform a multiplication operation may be one clock cycle, while the time to move the floating point number from memory to the arithmetic unit may take 10 or more cycles. To help manage this difference in time scales, most processors have at least three levels of memory: registers, cache, and random access memory, RAM. (In addition, some processors have external caches, and the complications of paging introduce another level to the hierarchy.)

Thus, to achieve high performance, a code should first move data into cache, and from there move it into registers and use it repeatedly while it remains in the cache or registers before returning it to main memory. If one reuses a floating point number 50 times while it is in registers, then the “hit” of 10 clock cycles to bring it into the register is not important. But if the floating point number is used only once, the “hit” of 10 clock cycles becomes very noticeable, resulting in disappointing flop rates.

Unfortunately, the compiler controls the use of the registers, and the hardware controls the use of the cache. Since the user has essentially no direct control, code must be written in such a way that the compiler and hardware cache system can perform well. Good quality code is then be said to respect the memory hierarchy.

The standard approach to improving the hardware utilization is to use blocking. That is, rather than working with individual elements in the matrices, one employs blocks of elements. Since the use of implicit methods in PDE-based simulations leads to matrices with a naturally blocked structure (with a block size equal to the number of degrees of freedom per cell), blocking is extremely advantageous. The PETSc sparse matrix representations use a variety of techniques for blocking, including

- storing the matrices using a generic sparse matrix format, but storing additional information about adjacent rows with identical nonzero structure (so called I-nodes); this I-node information is used in the key computational routines to improve performance (the default for the MATSEQAIJ and MATMPIAIJ formats); and
• storing the matrices using a fixed (problem dependent) block size (via the MATSEQBAIJ and MATMPIBAIJ formats);

The advantage of the first approach is that it is a minimal change from a standard sparse matrix format and brings a large percent of the improvement one obtains via blocking. Using a fixed block size gives the best performance, since the code can be hardwired with that particular size (for example, in some problems the size may be 3, in others 5, etc.), so that the compiler will then optimize for that size, removing the overhead of small loops entirely.

The following table presents the floating point performance for a basic matrix-vector product using these three approaches: a basic compressed row storage format (using the PETSc runtime options -mat_seqaij -mat_no_unroll); the same compressed row format using I-nodes (with the option -mat_seqaij); and a fixed block size code, with a block size of three for these problems (using the option -mat_seqbaij). The rates were computed on one node of an older IBM SP, using two test matrices. The first matrix (ARCO1), courtesy of Rick Dean of Arco, arises in multiphase flow simulation; it has 1501 degrees of freedom, 26,131 matrix nonzeros, a natural block size of 3, and a small number of well terms. The second matrix (CFD), arises in a three-dimensional Euler flow simulation and has 15,360 degrees of freedom, 496,000 nonzeros, and a natural block size of 5. In addition to displaying the flop rates for matrix-vector products, we also display them for triangular solve obtained from an ILU(0) factorization.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Block size</th>
<th>Basic</th>
<th>I-node version</th>
<th>Fixed block size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiphase</td>
<td>3</td>
<td>27</td>
<td>43</td>
<td>70</td>
</tr>
<tr>
<td>Euler</td>
<td>5</td>
<td>28</td>
<td>58</td>
<td>90</td>
</tr>
<tr>
<td>Triangular Solves from ILU(0) (Mflop/sec)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiphase</td>
<td>3</td>
<td>22</td>
<td>31</td>
<td>49</td>
</tr>
<tr>
<td>Euler</td>
<td>5</td>
<td>22</td>
<td>39</td>
<td>65</td>
</tr>
</tbody>
</table>

These examples demonstrate that careful implementations of the basic sequential kernels in PETSc can dramatically improve overall floating point performance, and users can immediately benefit from such enhancements without altering a single line of their application codes. Note that the speeds of the I-node and fixed block operations are several times that of the basic sparse implementations. The disappointing rates for the variable block size code occur because even on a sequential computer, the code performs the matrix-vector products and triangular solves using the coloring introduced above and thus does not utilize the cache particularly efficiently. This is an example of improving the parallelization capability at the expense of using each processor less efficiently.

### 6.1.1 Sequential AIJ Sparse Matrices

The default matrix representation within PETSc is the general sparse AIJ format (also called the Yale sparse matrix format or compressed sparse row format, CSR).

### 6.1.2 Parallel AIJ Sparse Matrices

This matrix type, which is the default parallel matrix format; additional implementation details are given in [3].

### 6.1.3 Sequential Block AIJ Sparse Matrices

The sequential and parallel block AIJ formats, which are extensions of the AIJ formats described above, are intended especially for use with multiclass PDEs. The block variants store matrix
elements by fixed-sized dense \( nb \times nb \) blocks. The stored row and column indices begin at zero.

The routine for creating a sequential block AIJ matrix with \( m \) rows, \( n \) columns, and a block size of \( nb \) is

\[
\text{MatCreateSeqBAIJ}(\text{MPI Comm} \ comm, \text{int} \ nb, \text{int} \ m, \text{int} \ n, \text{int} \ nz, \text{int} \ *nnz, \text{Mat} \ *A)
\]

The arguments \( nz \) and \( nnz \) can be used to preallocate matrix memory by indicating the number of block nonzeros per row. For good performance during matrix assembly, preallocation is crucial; however, the user can set \( nz=0 \) and \( nnz=NULL \) for PETSc to dynamically allocate matrix memory as needed. The PETSc users manual discusses preallocation for the AIJ format; extension to the block AIJ format is straightforward.

Note that the routine \( \text{MatSetValuesBlocked()} \) can be used for more efficient matrix assembly when using the block AIJ format.

### 6.1.4 Parallel Block AIJ Sparse Matrices

Parallel block AIJ matrices with block size \( nb \) can be created with the command \( \text{MatCreateBAIJ()} \)

\[
\text{MatCreateBAIJ}(\text{MPI Comm} \ comm, \text{int} \ nb, \text{int} \ m, \text{int} \ n, \text{int} \ M, \text{int} \ N, \text{int} \ d_nz, \text{int} \ *d_nnz, \text{int} \ o_nz, \text{int} \ *o_nnz, \text{Mat} \ *A);
\]

\( A \) is the newly created matrix, while the arguments \( m, n, M, \) and \( N \), indicate the number of local rows and columns and the number of global rows and columns, respectively. Either the local or global parameters can be replaced with \( \text{PETSC_DECIDE} \), so that PETSc will determine \( \text{PETSC_DECIDE} \) them. The matrix is stored with a fixed number of rows on each processor, given by \( m \), or determined by PETSc if \( m \) is \( \text{PETSC_DECIDE} \).

If \( \text{PETSC_DECIDE} \) is not used for \( m \) and \( n \) then the user must ensure that they are chosen to be compatible with the vectors. To do this, one first considers the product \( y = Ax \). The \( m \) that one uses in \( \text{MatCreateBAIJ()} \) must match the local size used in the \( \text{VecCreateMPI()} \) for \( y \). The \( n \) used must match that used as the local size in \( \text{VecCreateMPI()} \) for \( x \).

The user must set \( d_nz=0, o_nz=0, d_nnz=NULL, \) and \( o_nnz=NULL \) for PETSc to control dynamic allocation of matrix memory space. Analogous to \( nz \) and \( nnz \) for the routine \( \text{MatCreateSeqBAIJ()} \), these arguments optionally specify block nonzero information for the diagonal (\( d_nz \) and \( d_nnz \)) and off-diagonal (\( o_nz \) and \( o_nnz \)) parts of the matrix. For a square global matrix, we define each processor’s diagonal portion to be its local rows and the corresponding columns (a square submatrix); each processor’s off-diagonal portion encompasses the remainder of the local matrix (a rectangular submatrix). The PETSc users manual gives an example of preallocation for the parallel AIJ matrix format; extension to the block parallel AIJ case is straightforward.

### 6.1.5 Sequential Dense Matrices

PETSc provides both sequential and parallel dense matrix formats, where each processor stores its entries in a column-major array in the usual Fortran77 style.

### 6.1.6 Parallel Dense Matrices

The parallel dense matrices are partitioned by rows across the processors, so that each local rectangular submatrix is stored in the dense format described above.
Chapter 7

PETSc Testing System

The PETSc test system consists of:

1. A language contained within the source files that describes the tests to be run
2. The test generator (config/gmakegentest.py) that at the make step parses
   the source files and generates the makefiles and shell scripts that compose:
3. The petsc test harness: a harness consisting of makefile and shell scripts that
   runs the executables with several logging and reporting features.

Details on using the harness may be found in the main PETSc manual.

7.1 PETSc Test description language

PETSc tests and tutorials contain within their file a simple language to describe tests and subtests
required to run executables associated with compilation of that file. The general skeleton of the
file is:

```c
static char help[] = "A simple MOAB example\n
...
<source code>
...

/*TEST
   build:
   requires: moab
testset:
   suffix: 1
   requires: !complex
testset:
   suffix: 2
   args: -debug -fields v1,v2,v3
test:
test:
   args: -foo bar
TEST*/
```

For our language, a test is associated with:
• A single shell script
• A single makefile
• A single output file that represents the *expected results*.
• Two or more command tests. Usually, one (or more) mpiexec test that runs the executable, and one (or more) diff tests to compare output with the expected result.

Our language also supports a *testset* that specifies either a new test entirely, or multiple executable/diff tests within a single test. At the core, the executable/diff test combination will look something like this:

```
mpiexec -n 1 ../ex1 1> ex1.tmp 2> ex1.err
diff ex1.tmp output/ex1.out 1> diff-ex1.tmp 2> diff-ex1.err
```

In practice, we want to do various logging and counting by the test harness, but this is explained further below. The input language supports simple, yet flexible, test control and we begin by describing this language.

### 7.1.1 Runtime language options

At the end of each test file, a marked comment block, using YAML, is inserted to describe the test(s) to be run. The elements of the test are done with a set of supported key words that sets up the test.

**The goals of the language are to:**

1. Be as minimal as possible with the simplest test requiring only one keyword
2. Be independent of the filename such that a file can be renamed without rewriting the tests
3. Be intuitive

To enable the second bullet, the *basestring* of the filename is defined as the filename without the extension; e.g., if the filename is *ex1.c* then *basestring=ex1.f*

With this background, these keywords are are:

**testset** or **test**: *(Required)*

At the top level, either a single test, or a testset must be specified. All other keywords are sub-entries of this keyword.

**suffix**: *(Optional; Default: suffix="")*

- The testname is given by: *testname = basestring* if suffix is set to an empty string, and by *testname = basestring + "." + suffix*
- This can only be specified for top level test nodes

**output_file**: *(Optional; Default: output_file = "output/" + testname + ".out")*

- The output of the test is to be compared to an *expected result* whose name is given by *output_file*.
- This file is described relative to the source directory of the source file and should be in the output subdirectory (e.g., *output/ex1.out*)
The integer that is passed to mpiexec; i.e., mpiexec -n nsize

- The arguments to pass to the executable

- Setting this boolean to True will tell the test to appear in the test harness, but report only TODO per the TAP standard.
- A runscript will be generated and can easily be modified by hand to run

- Sometimes only a subset of the output is meant to be tested against the expected result. If this keyword is used, it processes the executable output and puts it into the file to be actually compared with output_file.
- The value of this is the command to be run; e.g., grep foo or sort -nr
- A skeleton example of the resultant commands to be run is:

```
mpiexec -n 1 ..ex1 | grep residual 1> ex1.tmp 2> ex1.err
diff ex1.tmp output/ex1.out 1> diff-ex1.tmp 2> diff-ex1.err
```
- If the filter begins with Error:, then the test is assumed to be testing the error output, and the error code and output is set up to be tested.

- Sometimes filtering the output is useful for standardizing tests; for example, to handle the issues related to parallel output. This works the same as filter to implement this feature

- The tests are run under PETSC_ARCH/tests, but some tests require runtime files that are maintained in the source tree. Files in this (space-delimited) list will be copied over. If you list a directory instead of files it will copy the entire directory (this is limited currently to a single directory)
- The copying is done by the file generator and not by creating makefile dependencies.
- Instead of a list of files one may also provide a single directory name.

- A space-delimited list of run requirements (not build requirements. See Build requirements below)
- In general, the language supports and and not constructs using ! => not and , => and
- MPIUNI should work for all -n 1 examples so this need not be in the requirements list
7.1. PETSC TEST DESCRIPTION LANGUAGE

- Inputs sometimes include external matrices that are found in the DATAFILES path.
  requires: DATAFILES can be specified for these tests.
- Packages are specified with lower case specification; e.g., requires: superlu_dist
- Any defined variable in petscconf.h can be specified with the defined(...) syntax; e.g.,
  defined(PETSC_USE_INFO)
- Any define of the form PETSC_HAVE_FOO can just use requires: foo similar to how
  third-party packages are handled.

timeoutfactor: (Optional; Default: "1")

- Tests are limited to a set time that is found at the top of "config/petsc_harness.sh".
  and can be overwritten by passing in the TIMEOUT argument to gmakefile (see make
  -f gmakefile help).
- This parameters allows one to extend the default timeout for an individual test such
  that the new timeout time is timeout=(default timeout) x (timeoutfactor).

7.1.2 Additional specifications

In addition to the above keywords, other language features are supported:

- for loops: Specifying {{ ... }shared output} or {{ ... }separate output} will create for loops over enclosed space-delimited list. If the loop causes a different output, then separate output would be used. If the loop does not cause separate output, then the shared (or {{ ... }}) syntax must be used.
  For loops are supported within nsize and args. An example would be:

  ```
  args: -matload_block_size {{2 3}}
  ```

  In this case, two execution lines would be added with two different arguments. Associated diff lines would be added as well automatically.
  In this case, it assumed that the output for each matload_block_size will give the same output so that only one diff file is needed. If the variables produced different output, then the separate output option would be added. In this case, each loop variable and value become a separate script.
  See examples below for how it works in practice.

7.1.3 Test block examples

This is the simplest test block:

```
/*TESTS
test:
TESTS*/
```

which is equivalent to:

```
/*TESTS
testset:
test:
TESTS*/
```

which is equivalent to:
/*TESTS
testset:
TESTS*/

If this block is in src/a/b/examples/tutorials/ex1.c, then it will create a_b_tutorials-ex1 test that requires only one processor/thread, with no arguments, and diff the resultant output with src/a/b/examples/tutorials/output/ex1.out.

For Fortran, the equivalent is:

!/*TESTS
! test:
!TESTS*/

A fuller example would be:

/*TESTS
test:
test:
suffix: 1
nsize: 2
args: -t 2 -pc_type jacobi -ksp_monitor_short -ksp_type gmres
args: -ksp_gmres_cgs_refinement_type refine_always -s2_ksp_type bcgs
args: -s2_pc_type jacobi -s2_ksp_monitor_short
requires: x
*/TESTS

This creates two tests. Assuming that this is src/a/b/examples/tutorials/ex1.c, the tests would be a_b_tutorials-ex1 and a_b_tutorials-ex1_1.

An example of how one tests a permutation of arguments against the same output file:

/*TESTS
testset:
suffix: 19
requires: datafilespath
args: -f0 ${DATAFILESPATH}/matrices/poisson1
args: -ksp_type cg -pc_type icc -pc_factor_levels 2
test:
test:
args: -mat_type seqsbaij
*/TESTS

Assuming that this is ex10.c, there would be two mpiexec/diff invocations in runex10_19.sh.

Here is a similar example, but the permutation of arguments create different output:

/*TESTS
testset:
requires: datafilespath
args: -f0 ${DATAFILESPATH}/matrices/medium
args: -ksp_type bicg
test:
suffix: 4
args: -pc_type lu
test:
suffix: 5
*/TESTS

Assuming that this is ex10.c, there would be two shell scripts created: runex10_4.sh and runex10_5.sh.

An example using a for loop would be:
7.1. **PETSC TEST DESCRIPTION LANGUAGE**

In this example, `ex138_2` will invoke `runex138_2.sh` twice with two different arguments, but both are diffed with the same file.

Here is a more complex example using for loops:

```plaintext
/*TESTS
  testset:
    suffix: 1
    args: -f ${DATAFILESPATH}/matrices/small -mat_type aij
    requires: datafilespath
  testset:
    suffix: 2
    output_file: output/ex138_1.out
    args: -f ${DATAFILESPATH}/matrices/small -mat_type baij
      test:
        args: -matload_block_size 2
      test:
        args: -matload_block_size 3
  */TESTS
```

This is functionally equivalent to the for loop shown above.

If this is in `ex10.c`, then the shell scripts generated would be:

```plaintext
runex10_19_pc_factor_levels-0.sh
runex10_19_pc_factor_levels-2.sh
runex10_19_pc_factor_levels-4.sh
```

Each shell script would invoke `mpiexec` twice.

### 7.1.4 Build language options

It is possible to specify issues related to the compilation of the source file with the `build:` block. The language is:

- **requires:** *(Optional; Default: "")*
  - Same as the runtime requirements (e.g., can include `requires: fftw`) but also requirements related to types:
    1. Precision types: `single`, `double`, `quad`, `int32`
    2. Scalar types: `complex` (and `!complex`)
• In addition, TODO is available to allow one to skip the build of this file but still maintain it in the source tree.

• **depends:** *(Optional; Default: "")*
  
  • List any dependencies required to compile the file

A typical example for compiling for real/double only is:

```
/*T
build:
  requires: !complex
T*/
```

### 7.2 PETSC Test Harness

The goals of the PETSc Test Harness are to:

• Provide standard output used by other testing tools
• Lightweight as possible and easily fit within the PETSc build chain
• Provide information on all tests, even those that are not built or run because they do not meet the configuration requirements

Before understanding the test harness, it is first important to understand the desired requirements for reporting and logging.

#### 7.2.1 Testing the parsing

After inserting the language into the file, one can test the parsing by executing:

```bash
${PETSC_DIR}/lib/petsc/bin/maint/testparse.py -t <test src file>
```

A dictionary will be pretty-printed out. From this dictionary print-out, it is usually obvious if there is a problem in the parsing. This python file is used by

```bash
${PETSC_DIR}/config/gmakegentest.py
```

in generating the test harness.

### 7.3 Test output standards: TAP

The PETSc test system is designed to be compliant with the Test Anything Protocol (TAP): See [https://testanything.org/tap-specification.html](https://testanything.org/tap-specification.html)

This is a very simple standard designed to allow testing tools to work together easily. There are libraries to enable the output to be used easily including sharness, which is used by the git team. However, the simplicity of the petsc tests and TAP specification means that we use our own simple harness given by a single shell script that each file sources: `petsc_harness.sh`.

As an example, consider this test input:

```sh
test:
suffix: 2
output_file: output/ex138.out
args: -f ${DATAFILESPATH}/matrices/small -mat_type {{aij baij sbaij}} -matload_block_size {{2 3}}
requires: datafilespath
```
A sample output would be:

```
ok 1 In mat...tests: "./ex138 -f $(DATAFILESPATH)/matrices/small -mat_type aij -matload_block_size 2"
ok 2 In mat...tests: "Diff of ./ex138 -f $(DATAFILESPATH)/matrices/small -mat_type aij -matload_block_size 2"
ok 3 In mat...tests: "./ex138 -f $(DATAFILESPATH)/matrices/small -mat_type aij -matload_block_size 3"
ok 4 In mat...tests: "Diff of ./ex138 -f $(DATAFILESPATH)/matrices/small -mat_type aij -matload_block_size 3"
ok 5 In mat...tests: "./ex138 -f $(DATAFILESPATH)/matrices/small -mat_type baij -matload_block_size 2"
ok 6 In mat...tests: "Diff of ./ex138 -f $(DATAFILESPATH)/matrices/small -mat_type baij -matload_block_size 2"
... 
ok 11 In mat...tests: "./ex138 -f $(DATAFILESPATH)/matrices/small -mat_type saij -matload_block_size 2"
ok 12 In mat...tests: "Diff of ./ex138 -f $(DATAFILESPATH)/matrices/small -mat_type aij -matload_block_size 2"
```

### 7.4 Test harness implementation

Most of the requirements for being TAP-compliant lie in the shell scripts so we focus on that description.

A sample shell script is given by:

```
#!/bin/sh
. petsc_harness.sh

petsc_testrun ./ex1 ex1.tmp ex1.err
petsc_testrun 'diff ex1.tmp output/ex1.out' diff-ex1.tmp diff-ex1.err

petsc_testend
```

`petsc_harness.sh` is a small shell script that provides the logging and reporting functions
`petsc_testrun` and `petsc_testend`.

A small sample of the output from the test harness would be:

```
ok 1 ./ex1
ok 2 diff ex1.tmp output/ex1.out
not ok 4 ./ex2
  #ex2: Error: cannot read file
not ok 5 diff ex2.tmp output/ex2.out
ok 7 ./ex3 -f /matrices/small -mat_type aij -matload_block_size 2
ok 8 diff ex3.tmp output/ex3.out
ok 9 ./ex3 -f /matrices/small -mat_type aij -matload_block_size 3
ok 10 diff ex3.tmp output/ex3.out
ok 11 ./ex3 -f /matrices/small -mat_type baij -matload_block_size 2
ok 12 diff ex3.tmp output/ex3.out
ok 13 ./ex3 -f /matrices/small -mat_type baij -matload_block_size 3
ok 14 diff ex3.tmp output/ex3.out
ok 15 ./ex3 -f /matrices/small -mat_type sbaij -matload_block_size 2
ok 16 diff ex3.tmp output/ex3.out
ok 17 ./ex3 -f /matrices/small -mat_type sbaij -matload_block_size 3
ok 18 diff ex3.tmp output/ex3.out
  # FAILED 4 5
# failed 2/16 tests; 87.500% ok
```

For developers, modifying the lines that get written to the file can be done by modifying:

```
${PETSC_DIR}/config/example_template.py
```

To modify the test harness, one can modify this file

```
${PETSC_DIR}/config/petsc_harness.sh
```
7.5 Using the Test Harness for Regression Testing

The test system is primarily designed to provide user-facing information and to be used in automated testing. However, it can also be helpful for contributing developers in regression testing, if one is willing to do a little investigation into the files that the test harness generates. A typical workflow might proceed as follows. Note that the exact syntax of all input and output in this section is subject to change.

1. Make changes to the code base, and prepare a branch to submit upstream.

2. To protect against unintended regressions, run the full test suite on your branch. (For information on how to run a subset of tests, consult the Users Manual and other sources referenced therein).

   ```make -f gmakefile.test test```

3. Examine the output for any failed tests, for example

   ```
   # ------------
   # Summary
   # ------------
   # FAILED ts_tutorials-ex11_adv_2d_quad_0 diff-sys_classes_viewer_tests-ex4_4 ts_tutorials-
   # ex11_adv_2d_quad_1
   # success 3051/3915 tests (77.9%)
   # failed 3/3915 tests (0.1%)
   # todo 91/3915 tests (2.3%)
   # skip 770/3915 tests (19.7%)
   #
   # Approximate time (not incl. build time): 429 sec
   #
   # To rerun failed tests:
   #   /opt/local/bin/gmake -f gmakefile test search='ts_tutorials-ex11_adv_2d_quad_0
   # sys_classes_viewer_tests-ex4_4 ts_tutorials-ex11_adv_2d_quad'
   ```

   The above indicates that three tests have failed and should be investigated. One would also probably check beforehand that no tests fail with an unmodified version of PETSc on the development machine.

4. Rerun one of the failed tests, with additional verbosity.

   ```
   /opt/local/bin/gmake V=1 -f gmakefile test
   search='sys_classes_viewer_tests-ex4_4'
   ```

5. Examine the output

   ```
   arch-darwin-master-double-debug/tests/sys/classes/viewer/examples/tests/runex4_4.sh -v
   ok sys_classes_viewer_tests-ex4_4 cat ex4_4.tmp | > /dev/null; cat ex4a1.tmp > ex4_4.tmp.tmp
   2>> runex4_4.err && mv ex4_4.tmp.tmp ex4_4.tmp
   not ok diff-sys_classes_viewer_tests-ex4_4 /Users/patrick/petsc-master/lib/petsc/bin/
   out ex4_4.tmp > diff-runex4_4.out 2> diff-runex4_4.err
   #2a3,14
   #> Testing PetscViewerASCIIPrintf 0
   #> Testing PetscViewerASCIIPrintf 1
   #> Testing PetscViewerASCIIPrintf 0
   #> Testing PetscViewerASCIIPrintf 1
   ```
7.5. USING THE TEST HARNESS FOR REGRESSION TESTING

| #> Testing PetscViewerASCIIPrintf 0   |   #> Testing PetscViewerASCIIPrintf 1   |
| #> Testing PetscViewerASCIIPrintf 0   |   #> Testing PetscViewerASCIIPrintf 1   |
| #> Testing PetscViewerASCIIPrintf 0   |   #> Testing PetscViewerASCIIPrintf 1   |
| #> Testing PetscViewerASCIIPrintf 0   |   #> Testing PetscViewerASCIIPrintf 1   |

This suggests that the output does not match the reference output.

6. Take a look in the directory where the test was run from.

```bash
cd arch-darwin-master-double-debug/tests/sys/classes/viewer/examples/tests/
```

7. Examine the scripts and output files there. In this example, these are `runex4_4.sh` and `runex4_4/`, which contains `sys_classes_viewer_tests-ex4_4.sh` along with various output files.

8. By examining these files, one can determine that
   
   - The command to run the test was
     ```bash
     /Users/patrick/petsc-master/arch-darwin-master-double-debug/bin/mpiexec -n 1 ../ex4 -myviewer ascii:ex4a1.tmp::append
     ```

   - The reference output is in
     ```bash
     /Users/patrick/petsc-master/src/sys/classes/viewer/examples/tests/output/ex4a.out
     ```

9. This should provide enough information to iteratively debug the problem by making changes, recompiling, and re-running this example directly.

10. Repeat with other errors.

To rerun just the reporting,

```bash
config/report_tests.py
```

To see the full options:

```bash
config/report_tests.py -h
```

To see the full timing information for the 5 most expensive tests:

```bash
config/report_tests.py -t 5
```
Bibliography


