MPI-IO

Escola de Verão 2020
Supercomputador Santos Dumont

MC Introdução a Programação MPI com Extensões para E/S

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Agenda

Notions
I/O for HPC
MPI-IO
Terminology

File Manipulation
Open / Create
Access Mode (amode)
Close
File Views*

Individual Operations
Collective Operations
Explicit Offsets
Individual File Pointers
Shared File Pointers

Hints
File Info
MPI-I/O Hints
Data Seiving
Collective Buffering

* This item will be revisited before learning individual file pointers for noncollective operations

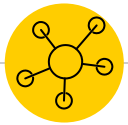
Quick Ref.

Before we start, some quick references

- OpenMPI Documentation: https://www.open-mpi.org/doc
- MPI Standard Official Documentation: https://www.mpi-forum.org/docs
- DeinoMPI (An implementation of MPI-2 for Windows): http://mpi.deino.net/mpi_functions/index.htm
- ROMIO: https://www.mcs.anl.gov/projects/romio

For many applications, ***I/O is a bottleneck*** *that limits scalability. Write operations* ***often do not perform well*** *because an application's processes do not write data to Lustre in an efficient manner, resulting in* ***file contention*** *and* ***reduced parallelism****.*

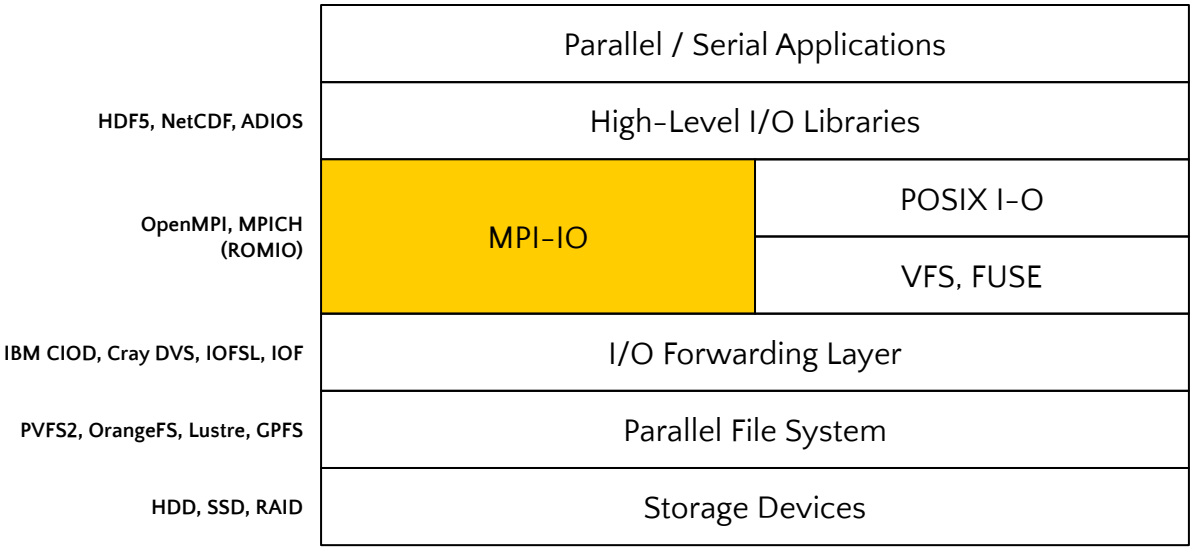
— *Getting Started on MPI I/O, Cray, 2015* —



Notions

I/O for HPC
MPI-IO
Terminology

HPC I/O Stack



Inspired by Ohta et. a. (2010)

POSIX

- POSIX (Portable Operating System Interface for Unix)
  - Set of standards
  - Define the application programming interface (API)
  - Define some shell and utility interfaces
- POSIX I/O
  - Portion of the standard that defines the IO interface for POSIX
  - `read()`, `write()`, `open()`, `close()`, ...

HPC I/O Stack

POSIX I/O

- A POSIX I/O file is simply a sequence of bytes
- POSIX I/O gives you full, low-level control of I/O operations
- There is little in the interface that inherently supports parallel I/O
- POSIX I/O does not support collective access to files
    - Programmer should coordinate access

HPC I/O Stack

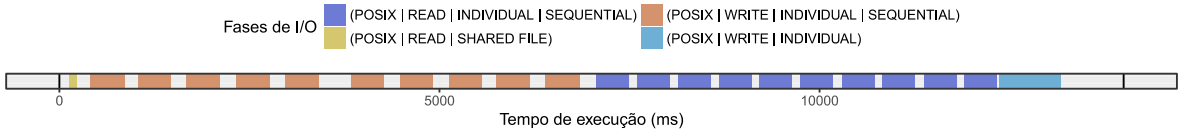
MPI-IO

- An MPI I/O file is an ordered collection of typed data items
- A higher level of data abstraction than POSIX I/O
- Define data models that are natural to your application
- You can define complex data patterns for parallel writes
- The MPI I/O interface provides independent and collective I/O calls
- Optimization of I/O functions

HPC I/O Stack

The MPI-IO Layer

- MPI-IO layer introduces an important optimization: collective I/O
- HPC programs often has distinct phases where all process:
  - Compute
  - Perform I/O (read or write checkpoint)



- Uncoordinated access is hard to serve efficiently
- Collective operations allow MPI to coordinate and optimize accesses

HPC I/O Stack

The MPI-IO Layer

Collective I/O yields four key benefits:

- “Optimizations such as data sieving and two-phase I/O rearrange the **access pattern** to be more friendly to the underlying file system”
- “If processes have overlapping requests, library can eliminate duplicate work”
- “By coalescing multiple regions, the density of the I/O request increases, making the two-phase I/O optimization more efficient”
- “The I/O request can also be aggregated down to a number of nodes more suited to the underlying file system”

MPI-IO

MPI: A Message-Passing Interface Standard

MPI-IO

Version 3.0

- This course is based on the MPI Standard Version 3.0
- The examples and exercises were created with OpenMPI 3.0.0:
- Remember to include in your C code:

```
#include <mpi.h>
```

- Remember how to compile:

```
$ mpicc code.c -o code
```

- Remember how to run:

```
$ mpirun --hostfile HOSTFILE --oversubscribe --np PROCESSES ./code
```

MPI-IO

SDumont

- You need to use Version 2.0 in SDumont Supercomputer:

```
$ module avail
$ module load openmpi/gnu/2.0.4.2
```

- Compile normally:

```
$ mpicc code.c -o code
```

- Allocate some nodes (2 nodes and 8 ranks) and run the experiment:

```
$ salloc -p treinamento -N 2 -n 8
$ mpiexec ./code
```

- Or just use `srun`

```
$ srun -p treinamento -N 2 -n 8 ./code
```

Concepts of MPI-IO

Terminology

Concepts of MPI-IO

file e *displacement*

file

An MPI file is an ordered collection of typed data items

MPI supports random or sequential access to any integral set of items

A file is opened collectively by a group of processes

All collective I/O calls on a file are collective over this group

displacement

Absolute **byte** position relative to the beginning of a file

Defines the location where a view begins

Concepts of MPI-IO

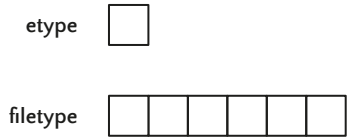
etype e *filetype*

etype

etype → elementary datatype

Unit of data access and positioning

It can be any MPI predefined or derived datatype



filetype

Basis for partitioning a file among processes

Defines a template for accessing the file

Single *etype* or derived datatype (multiple instances of same *etype*)

MPI datatype	C datatype	MPI datatype	C datatype
`MPI_SHORT`	signed short int	`MPI_CHAR`	char (printable character)
`MPI_INT`	signed int	`MPI_UNSIGNED_CHAR`	unsigned char (integral value)
`MPI_LONG_LONG_INT`	signed long long int	`MPI_UNSIGNED_SHORT`	unsigned short int
`MPI_LONG_LONG` (as a synonym)	signed long long int	`MPI_UNSIGNED`	unsigned int
`MPI_FLOAT`	float	`MPI_UNSIGNED_LONG`	unsigned long int
`MPI_DOUBLE`	double	`MPI_UNSIGNED_LONG_LONG`	unsigned long long int
`MPI_LONG_DOUBLE`	long double	`MPI_BYTE`	

Principal MPI Datatypes

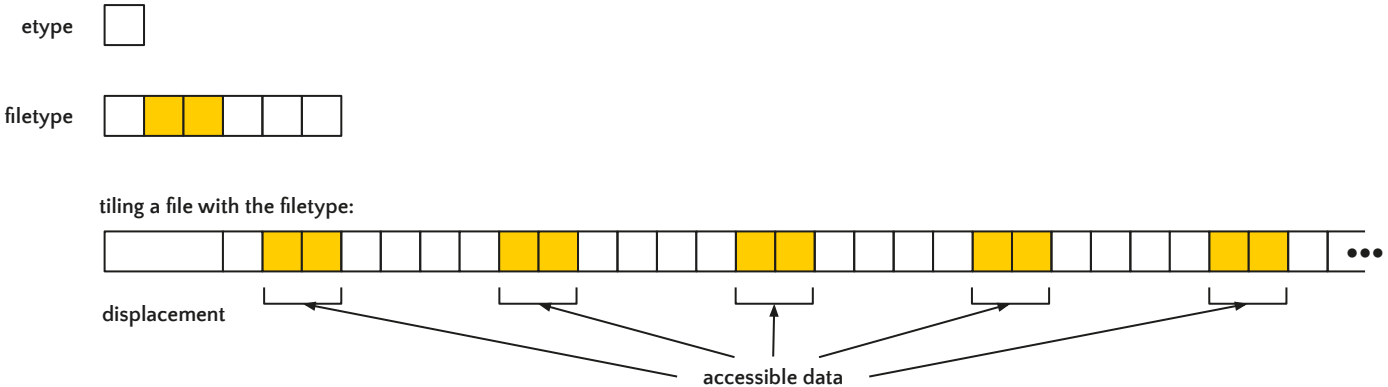
Concepts of MPI-IO

view

- Defines the current set of data visible and accessible from an open file
- Ordered set of *etypes*
- Each process has its own view, defined by:
  - a displacement
  - an *etype*
  - a filetype
- The pattern described by a filetype is repeated, beginning at the displacement, to define the view

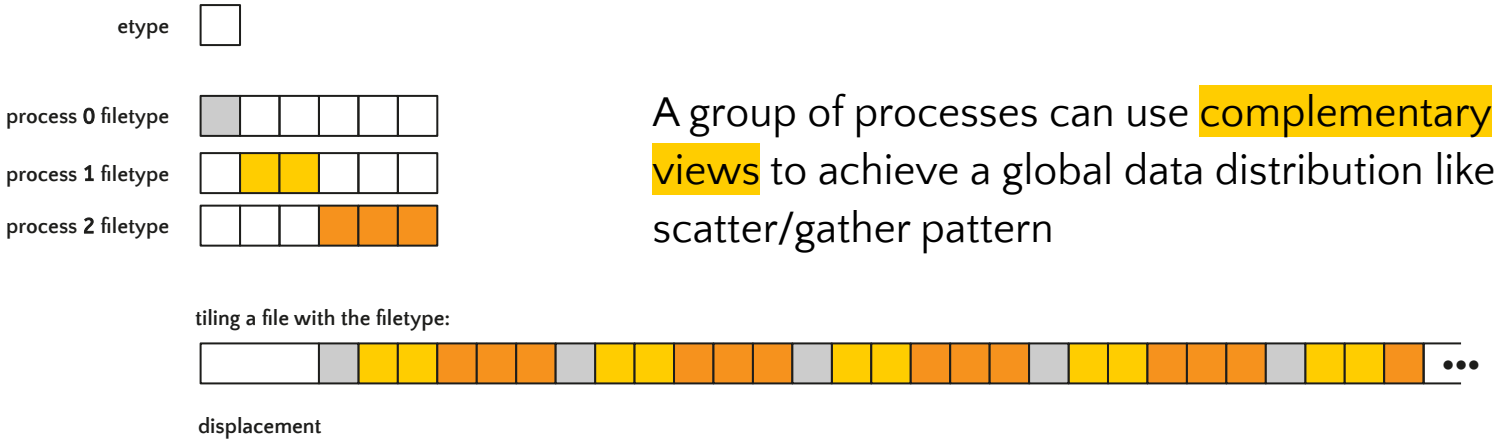
Concepts of MPI-IO

view



Concepts of MPI-IO

view



A group of processes can use complementary views to achieve a global data distribution like the scatter/gather pattern

Concepts of MPI-IO

offset e *file size*

offset

Position in the file relative to the current view

Expressed as a count of etypes

Holes in the filetype are skipped when calculating

file size

Size of MPI file is measured in bytes from the beginning of the file

Newly created files have size zero

Concepts of MPI-IO

file pointer e *file handle*

file pointer

A file pointer is an implicit offset maintained by MPI

Individual pointers are local to each process

Shared pointers is shared among the group of process

file handle

Opaque object created by `MPI_FILE_OPEN`

Freed by `MPI_FILE_CLOSE`

All operation to an open file reference the file through the file handle

File Manipulation

Opening Files
Access Mode (amode)
Closing Files

File Manipulation

Opening Files

function in C

```
int MPI_File_open(
      MPI_Comm comm,           // IN       communicator (handle)
      const char *filename,    // IN       name of file to open (string)
      int amode,               // IN       file access mode (integer)
      MPI_Info info,           // IN       info object (handle)
      MPI_File *fh             //    OUT   new file handle (handle)
)
```

- `MPI_FILE_OPEN` is a collective routine
  - All process must provide the same value for filename and amode
  - `MPI_COMM_WORLD` or `MPI_COMM_SELF` (independently)
  - User must close the file before `MPI_FINALIZE`
- Initially all processes view the file as a linear byte stream

File Manipulation

Opening Files

```
int MPI_File_open(
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      MPI_Info info,           // IN       info object (handle)
      MPI_File *fh             //    OUT   new file handle (handle)
)
```

function name
it is not code!

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File Manipulation

Opening Files

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- `MPI_FILE_OPEN` is a collective routine
  - All process must provide the same value for filename and amode
  - `MPI_COMM_WORLD` or `MPI_COMM_SELF` (independently)
  - User must close the file before `MPI_FINALIZE`
- Initially all processes view the file as a linear byte stream
- MPI_Info is used to pass hints. Pass `MPI_INFO_NULL` to use the defult

File Manipulation

Access Mode

exactly one!

- `MPI_MODE_RDONLY` → read only
- `MPI_MODE_RDWR` → reading and writing
- `MPI_MODE_WRONLY` → write only
- `MPI_MODE_CREATE` → create the file if it does not exist
- `MPI_MODE_EXCL` → error if creating file that already exists
- `MPI_MODE_DELETE_ON_CLOSE` → delete file on close
- `MPI_MODE_APPEND` → set initial position of all file pointers to end of file

```
*Combining access modes -> (MPI_MODE_CREATE|MPI_MODE_EXCL|MPI_MODE_RDWR)
```

File Manipulation

Closing Files

```
int MPI_File_close(
      MPI_File *fh            // IN       file handle (handle)
)
```

- `MPI_FILE_CLOSE` first synchronizes file state
  - Equivalent to performing an `MPI_FILE_SYNC`
  - For writes `MPI_FILE_SYNC` provides the only guarantee that data has been transferred to the storage device
- Then closes the file associated with `fh`
- `MPI_FILE_CLOSE` is a collective routine
- User is responsible for ensuring all requests have completed
- `fh` is set to `MPI_FILE_NULL`

Data Access

Positioning
Coordination
Synchronism

Data Access

Overview

- There are 3 aspects to data access:

positioning	synchronism	coordination
explicit offset	blocking	noncollective
implicit file pointer (individual)	nonblocking	collective
implicit file pointer (shared)	split collective	

- POSIX `read()/fread()` and `write()/fwrite()`
  - Blocking, noncollective operations with individual file pointers
  - `MPI_FILE_READ` and `MPI_FILE_WRITE` are the MPI equivalents

Data Access

Positioning

- We can use a mix of the three types in our code
- Routines that accept explicit offsets contain `_AT` in their name
- Inplicit Individual file pointer routines contain no positional qualifiers
- Inplicit Shared file pointer routines contain `_SHARED` or `_ORDERED` in the name
  - `_SHARED` for noncollective operations
  - `_ORDERED` for collective operations
- I/O operations leave the MPI file pointer pointing to next item
- In collective or split collective the pointer is updated by the call

Data Access

Synchronism

- Blocking calls
  - Will not return until the I/O request is completed
- Nonblocking calls
  - Initiates an I/O operation
  - Does not wait for it to complete
  - Need to send a request complete call (`MPI_WAIT` or `MPI_TEST`)
- Nonblocking calls are named `MPI_FILE_I...` with an `I` (immediate)
- We should not access the buffer until the operation is complete

Data Access

Coordination

- Every noncollective routine has a collective counterpart:
  - `MPI_FILE_...` is `MPI_FILE_..._ALL`
  - `MPI_FILE_..._SHARED` is `MPI_FILE_..._ORDERED`
- We also have a pair `MPI_FILE_..._BEGIN` and `MPI_FILE_..._END`
  - Split Collectvie routines
- Collective routines may perform much better
- Global data access have potential for automatic optimization

positioning	synchronism	coordination	
		noncollective	collective
explicit offsets	blocking	`MPI_File_read_at` `MPI_File_write_at`	`MPI_File_read_at_all` `MPI_File_write_at_all`
	nonblocking	`MPI_File_iread_at` `MPI_File_iwrite_at`	`MPI_File_iread_at_all` `MPI_File_iwrite_at_all`
	split collective	`N/A`	`MPI_File_read_at_all_begin/end` `MPI_File_write_at_all_begin/end`
individual file pointers	blocking	`MPI_File_read` `MPI_File_write`	`MPI_File_read_all` `MPI_File_write_all`
	nonblocking	`MPI_File_iread` `MPI_File_iwrite`	`MPI_File_iread_all` `MPI_File_iwrite_all`
	split collective	`N/A`	`MPI_File_read_all_begin/end` `MPI_File_write_all_begin/end`
shared file pointer	blocking	`MPI_File_read_shared` `MPI_File_write_shared`	`MPI_File_read_ordered` `MPI_File_write_ordered`
	nonblocking	`MPI_File_iread_shared` `MPI_File_iwrite_shared`	`N/A`
	split collective	`N/A`	`MPI_File_read_ordered_begin/end` `MPI_File_write_ordered_begin/end`

Classification of ***MPI-IO Functions*** *in C*

Data Access

Noncollective I/O

Explicit Offsets

positioning	synchronism	coordination	
		noncollective	collective
explicit offsets	blocking	`MPI_File_read_at` `MPI_File_write_at`	`MPI_File_read_at_all` `MPI_File_write_at_all`
	nonblocking	`MPI_File_iread_at` `MPI_File_iwrite_at`	`MPI_File_iread_at_all` `MPI_File_iwrite_at_all`
	split collective	`N/A`	`MPI_File_read_at_all_begin/end` `MPI_File_write_at_all_begin/end`
individual file pointers	blocking	`MPI_File_read` `MPI_File_write`	`MPI_File_read_all` `MPI_File_write_all`
	nonblocking	`MPI_File_iread` `MPI_File_iwrite`	`MPI_File_iread_all` `MPI_File_iwrite_all`
	split collective	`N/A`	`MPI_File_read_all_begin/end` `MPI_File_write_all_begin/end`
shared file pointer	blocking	`MPI_File_read_shared` `MPI_File_write_shared`	`MPI_File_read_ordered` `MPI_File_write_ordered`
	nonblocking	`MPI_File_iread_shared` `MPI_File_iwrite_shared`	`N/A`
	split collective	`N/A`	`MPI_File_read_ordered_begin/end` `MPI_File_write_ordered_begin/end`

Classification of ***MPI-IO Functions*** *in C*

Data Access - Noncollective

Explicit Offsets

```
int MPI_File_write_at(
      MPI_File fh,             // IN OUT   file handle (handle)
      MPI_Offset offset,       // IN       file offset (integer)
      const void *buf,         // IN       initial address of buffer (choice)
      int count,               // IN       number of elements in buffer (integer)
      MPI_Datatype datatype,   // IN       datatype of each buffer element (handle)
      MPI_Status *status       //    OUT   status object (Status)
)
```

```
int MPI_File_read_at(
      MPI_File fh,             // IN OUT   file handle (handle)
      MPI_Offset offset,       // IN       file offset (integer)
      void *buf,               //    OUT   initial address of buffer (choice)
      int count,               // IN       number of elements in buffer (integer)
      MPI_Datatype datatype,   // IN       datatype of each buffer element (handle)
      MPI_Status *status       //    OUT   status object (Status)
)
```

exercise or experiment

Hands-on!

WRITE - Explicit Offsets

SOLUTION FILE

write-i-offsets-character.c

Using explicit offsets (and default view) write a program where each process will print its rank, as a character, 10 times.

If we ran with 4 processes the file (you should create it) should contain:

```
$ cat my-rank.txt
01230123012301230123012301230123012301230123
```

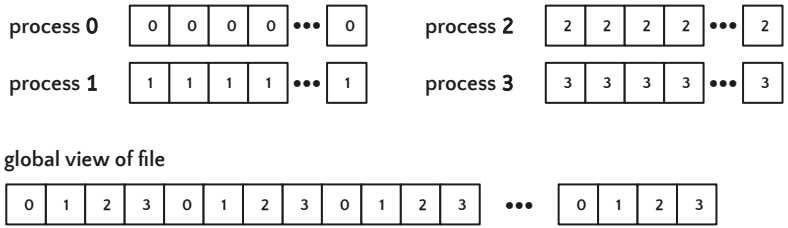
SOLUTION FILE

`write-i-offsets-character.c`

Hands-on!

WRITE - Explicit Offsets

Using explicit offsets (and default view) write a program where each process will print its rank, as a character, 10 times.



If we ran with 4 processes the file (you should create it) should contain:

```
$ cat my-rank.txt
01230123012301230123012301230123012301230123
```

Hands-on!

READ - Explicit Offsets

SOLUTION FILE

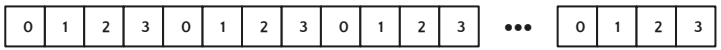
`read-i-offsets-character.c`

Modify your program so that each process will read the printed ranks, as a character, 10 times using explicit offsets (and default view).

Remember to open the file to read only!

Each process should print to `stdout` the values.

global view of file




```
rank: 2, offset: 120, read: 2
rank: 1, offset: 004, read: 1
rank: 2, offset: 136, read: 2
rank: 2, offset: 152, read: 2
rank: 0, offset: 000, read: 0
...
```

Revisiting...

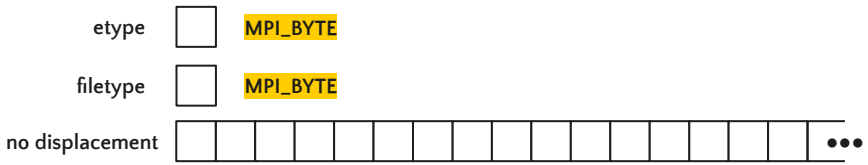
File Manipulation

File View
Data Types
Data Representation

File Manipulation

Default File View

- Unless explicitly specified, the default file view is:
  - A linear byte steam
  - `displacement` is set to zero
  - `etype` is set to `MPI_BYTE`
  - `filetype` is set to `MPI_BYTE`
  - This is the same for all the processes that opened the file
  - i.e. each process initially sees the whole file



File Manipulation

File Views

```
int MPI_File_set_view(
      MPI_File fh,              // IN OUT   file handle (handle)
      MPI_Offset disp,          // IN       displacement (integer)
      MPI_Datatype etype,       // IN       elementary datatype (handle)
      MPI_Datatype filetype,    // IN       filetype (handle)
      const char *datarep,      // IN       data representation (string)
      MPI_Info info             // IN       info object (handle)
)
```

- `MPI_FILE_SET_VIEW` changes the process's view of the data
- This is a collective operation
- Values for `disp`, `filetype` and `info` may vary
- `disp` is the absolute offset in bytes from where the view begins
- Multiple file views is possible

File Manipulation

Datatypes

- A general datatype is an opaque object that specifies two things:
  - A sequence of basic datatypes
  - A sequence of integer (byte) displacements
- e.g. `MPI_INT` is a predefined handle to a datatype with:
  - One entry of type `int`
  - Displacement equals to zero
- The other basic MPI datatypes are similar
- We can also create derived datatypes

File Manipulation

Datatypes

- A datatype object has to be committed before it can be used

```
int MPI_Type_commit(
      MPI_Datatype *datatype  // IN OUT   datatype that is committed (handle)
)
```

- There is no need to commit basic datatypes!
- To free a datatype we should use:

```
int MPI_Type_free(
      MPI_Datatype *datatype  // IN OUT   datatype that is freed (handle)
)
```

File Manipulation

Datatypes

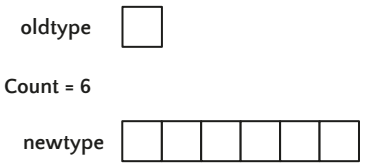
MPI Function	To create a...
`MPI_Type_contiguous`	contiguous datatype
`MPI_Type_vector`	vector (strided) datatype
`MPI_Type_create_indexed`	indexed datatype
`MPI_Type_create_indexed_block`	indexed datatype w/uniform block length
`MPI_Type_create_struct`	structured datatype
`MPI_Type_create_resized`	type with new extent and bounds
`MPI_Type_create_darray`	distributed array datatype
`MPI_Type_create_subarray`	n-dim subarray of an n-dim array

File Manipulation

Datatype Constructors

```
int MPI_Type_contiguous(
      int count,              // IN       replication count (non-negative integer)
      MPI_Datatype oldtype,   // IN       old datatype (handle)
      MPI_Datatype *newtype   //    OUT   new datatype (handle)
)
```

- `MPI_TYPE_CONTIGUOUS` is the simplest datatype constructor
- Allows replication of a datatype into contiguous locations
- `newtype` is the concatenation of `count` copies of `oldtype`

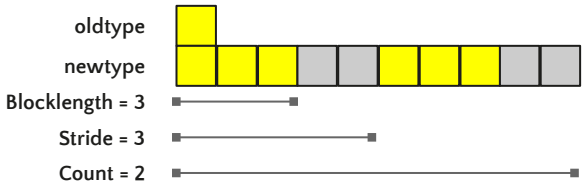


File Manipulation

Datatype Constructors

```
int MPI_Type_vector(
      int count,              // IN      number of blocks (non-negative integer)
      int blocklength,        // IN      number of elements in each block (non-negative integer)
      int stride,             // IN      number of elements between start of each block (integer)
      MPI_Datatype oldtype,   // IN      old datatype (handle)
      MPI_Datatype *newtype   //    OUT  new datatype (handle)
)
```

- `MPI_TYPE_VECTOR` replication into locations of equally spaced blocks
- Each block is the concatenation of copies of `oldtype`
- Spacing between blocks is multiple of `oldtype`



File Manipulation

Datatype Constructors

```
int MPI_Type_create_subarray(
      int ndims,                    // IN       number of array dimensions (positive integer)
      const int array_sizes[],      // IN       number of elements of in each dimension
      const int array_subsizes[],   // IN       number of elements of oldtype in each dimension
      const int array_starts[],     // IN       start coordinates of subarray in each dimension
      int order,                    // IN       array storage order flag (state)
      MPI_Datatype oldtype,         // IN       array element datatype (handle)
      MPI_Datatype *newtype         //     OUT  new datatype (handle)
)
```

- Describes an *n*-dimensional subarray of an *n*-dimensional array
- Facilitates access to arrays distributed in blocks among processes to a single shared file that contains the global array (I/O)
- The order in C is `MPI_ORDER_C` (row-major order)

File Manipulation

Data Representation

- MPI supports multiple data representations (***datarep***):
  - `“native”`
  - `“internal”`
  - `“external32”`
- `“native”` and `“internal”` are implementation dependent
- `“external32”` is common to all MPI implementations
  - Intended to facilitate file interoperability

File Manipulation

Data Representation

`“native”`

- Data in this representation is stored in a file exactly as it is in memory
- Homogeneous systems:
  - No loss in precision or I/O performance due to type conversions
- On heterogeneous systems
  - Loss of interoperability

`“internal”`

- Data stored in implementation specific format
- Can be used with homogeneous or heterogeneous environments
- Implementation will perform type conversions if necessary

File Manipulation

Data Representation

`“external32”`

- Follows standardized representation (IEEE)
- All input/output operations are converted from/to the `“external32”`
- Files can be exported/imported between different MPI environments
- I/O performance may be lost due to type conversions
- `“internal”` may be implemented as equal to `“external32”`
- Can be read/written also by non-MPI programs

positioning	synchronism	coordination	
		noncollective	collective
explicit offsets	blocking	`MPI_File_read_at` `MPI_File_write_at`	`MPI_File_read_at_all` `MPI_File_write_at_all`
	nonblocking	`MPI_File_iread_at` `MPI_File_iwrite_at`	`MPI_File_iread_at_all` `MPI_File_iwrite_at_all`
	split collective	`N/A`	`MPI_File_read_at_all_begin/end` `MPI_File_write_at_all_begin/end`
individual file pointers	blocking	`MPI_File_read` `MPI_File_write`	`MPI_File_read_all` `MPI_File_write_all`
	nonblocking	`MPI_File_iread` `MPI_File_iwrite`	`MPI_File_iread_all` `MPI_File_iwrite_all`
	split collective	`N/A`	`MPI_File_read_all_begin/end` `MPI_File_write_all_begin/end`
shared file pointer	blocking	`MPI_File_read_shared` `MPI_File_write_shared`	`MPI_File_read_ordered` `MPI_File_write_ordered`
	nonblocking	`MPI_File_iread_shared` `MPI_File_iwrite_shared`	`N/A`
	split collective	`N/A`	`MPI_File_read_ordered_begin/end` `MPI_File_write_ordered_begin/end`

Classification of ***MPI-IO Functions*** *in C*

Data Access

Noncollective I/O

Individual File Pointers
Shared File Pointers

Data Access - Noncollective

Individual File Pointers

- MPI maintains one individual file pointer per process per file handle
- Implicitly specifies the offset
- Same semantics of the explicit offset routines
- Relative to the current view of the file

"After an individual file pointer operation is initiated, the individual file pointer is updated to point to the next `etype` after the last one that will be accessed"

Data Access - Noncollective

Individual File Pointers

```
int MPI_File_write(
      MPI_File fh,             // IN OUT   file handle (handle)
      const void *buf,         // IN       initial address of buffer (choice)
      int count,               // IN       number of elements in buffer (integer)
      MPI_Datatype datatype,   // IN       datatype of each buffer element (handle)
      MPI_Status *status       //    OUT   status object (Status)
)
```

```
int MPI_File_read(
      MPI_File fh,             // IN OUT   file handle (handle)
      void *buf,               //    OUT   initial address of buffer (choice)
      int count,               // IN       number of elements in buffer (integer)
      MPI_Datatype datatype,   // IN       datatype of each buffer element (handle)
      MPI_Status *status       //    OUT   status object (Status)
)
```

Hands-on!

WRITE – Individual Pointers

SOLUTION FILE

`write-i-ifp-double-buffer.c`

Using individual file points (and a view) write 100 double precision values `rank + (i / 100)`, one per line, per process. Write the entire buffer at once!

Remember to view the file you should use `hexdump` or similar!

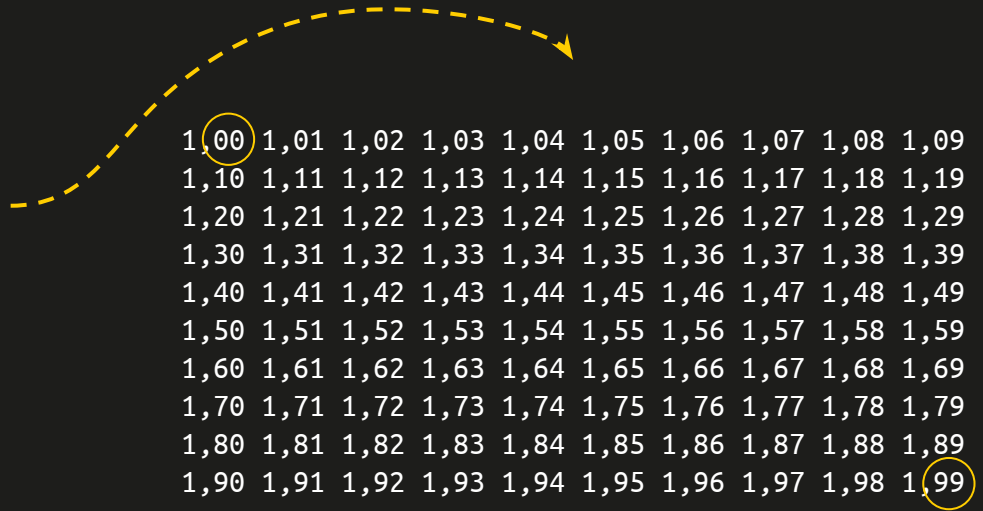
```
$ mpirun -np 4 write-i-ifp-double-buffer
$ hexdump -v -e '10 "%f "' -e '"\n"' write-i-ifp-double-buffer.data
0,000000 0,010000 0,020000 0,030000 0,040000 0,050000 0,060000 0,070000 0,080000 0,090000
0,100000 0,110000 0,120000 0,130000 0,140000 0,150000 0,160000 0,170000 0,180000 0,190000
0,200000 0,210000 0,220000 0,230000 0,240000 0,250000 0,260000 0,270000 0,280000 0,290000
...
0,900000 0,910000 0,920000 0,930000 0,940000 0,950000 0,960000 0,970000 0,980000 0,990000
1,000000 1,010000 1,020000 1,030000 1,040000 1,050000 1,060000 1,070000 1,080000 1,090000
```

rank

i / 100

```
$ hexdump -v -e '10 "%.2f "' -e '"\n"' write-i-ifp-double-buffer.data
```

```
0,00 0,01 0,02 0,03 0,04 0,05 0,06 0,07 0,08 0,09
0,10 0,11 0,12 0,13 0,14 0,15 0,16 0,17 0,18 0,19
0,20 0,21 0,22 0,23 0,24 0,25 0,26 0,27 0,28 0,29
0,30 0,31 0,32 0,33 0,34 0,35 0,36 0,37 0,38 0,39
0,40 0,41 0,42 0,43 0,44 0,45 0,46 0,47 0,48 0,49
0,50 0,51 0,52 0,53 0,54 0,55 0,56 0,57 0,58 0,59
0,60 0,61 0,62 0,63 0,64 0,65 0,66 0,67 0,68 0,69
0,70 0,71 0,72 0,73 0,74 0,75 0,76 0,77 0,78 0,79
0,80 0,81 0,82 0,83 0,84 0,85 0,86 0,87 0,88 0,89
0,90 0,91 0,92 0,93 0,94 0,95 0,96 0,97 0,98 0,99
1,00 1,01 1,02 1,03 1,04 1,05 1,06 1,07 1,08 1,09
1,10 1,11 1,12 1,13 1,14 1,15 1,16 1,17 1,18 1,19
1,20 1,21 1,22 1,23 1,24 1,25 1,26 1,27 1,28 1,29
1,30 1,31 1,32 1,33 1,34 1,35 1,36 1,37 1,38 1,39
1,40 1,41 1,42 1,43 1,44 1,45 1,46 1,47 1,48 1,49
1,50 1,51 1,52 1,53 1,54 1,55 1,56 1,57 1,58 1,59
1,60 1,61 1,62 1,63 1,64 1,65 1,66 1,67 1,68 1,69
1,70 1,71 1,72 1,73 1,74 1,75 1,76 1,77 1,78 1,79
1,80 1,81 1,82 1,83 1,84 1,85 1,86 1,87 1,88 1,89
1,90 1,91 1,92 1,93 1,94 1,95 1,96 1,97 1,98 1,99
2,00 2,01 2,02 2,03 2,04 2,05 2,06 2,07 2,08 2,09
2,10 2,11 2,12 2,13 2,14 2,15 2,16 2,17 2,18 2,19
2,20 2,21 2,22 2,23 2,24 2,25 2,26 2,27 2,28 2,29
2,30 2,31 2,32 2,33 2,34 2,35 2,36 2,37 2,38 2,39
2,40 2,41 2,42 2,43 2,44 2,45 2,46 2,47 2,48 2,49
2,50 2,51 2,52 2,53 2,54 2,55 2,56 2,57 2,58 2,59
2,60 2,61 2,62 2,63 2,64 2,65 2,66 2,67 2,68 2,69
2,70 2,71 2,72 2,73 2,74 2,75 2,76 2,77 2,78 2,79
2,80 2,81 2,82 2,83 2,84 2,85 2,86 2,87 2,88 2,89
2,90 2,91 2,92 2,93 2,94 2,95 2,96 2,97 2,98 2,99
3,00 3,01 3,02 3,03 3,04 3,05 3,06 3,07 3,08 3,09
3,10 3,11 3,12 3,13 3,14 3,15 3,16 3,17 3,18 3,19
3,20 3,21 3,22 3,23 3,24 3,25 3,26 3,27 3,28 3,29
3,30 3,31 3,32 3,33 3,34 3,35 3,36 3,37 3,38 3,39
3,40 3,41 3,42 3,43 3,44 3,45 3,46 3,47 3,48 3,49
3,50 3,51 3,52 3,53 3,54 3,55 3,56 3,57 3,58 3,59
3,60 3,61 3,62 3,63 3,64 3,65 3,66 3,67 3,68 3,69
3,70 3,71 3,72 3,73 3,74 3,75 3,76 3,77 3,78 3,79
3,80 3,81 3,82 3,83 3,84 3,85 3,86 3,87 3,88 3,89
3,90 3,91 3,92 3,93 3,94 3,95 3,96 3,97 3,98 3,99
```



Data Access - Noncollective

Shared File Pointers

- MPI maintains exactly one shared file pointer per collective open
- Shared among processes in the communicator group
- Same semantics of the explicit offset routines
- Multiple calls to the shared pointer behaves as if they were serialized
- All processes must have the same view
- For noncollective operations order is not deterministic

Data Access - Noncollective

Shared File Pointers

```
int MPI_File_write_shared(
      MPI_File fh,             // IN OUT   file handle (handle)
      const void *buf,         // IN       initial address of buffer (choice)
      int count,               // IN       number of elements in buffer (integer)
      MPI_Datatype datatype,   // IN       datatype of each buffer element (handle)
      MPI_Status *status       //    OUT   status object (Status)
)
```

```
int MPI_File_read_shared(
      MPI_File fh,             // IN OUT   file handle (handle)
      void *buf,               //    OUT   initial address of buffer (choice)
      int count,               // IN       number of elements in buffer (integer)
      MPI_Datatype datatype,   // IN       datatype of each buffer element (handle)
      MPI_Status *status       //    OUT   status object (Status)
)
```

Data Access

Collective I/O

Explicit Offsets
Individual File Pointers
Shared File Pointers

positioning	synchronism	coordination	
		noncollective	collective
explicit offsets	blocking	`MPI_File_read_at` `MPI_File_write_at`	`MPI_File_read_at_all` `MPI_File_write_at_all`
	nonblocking	`MPI_File_iread_at` `MPI_File_iwrite_at`	`MPI_File_iread_at_all` `MPI_File_iwrite_at_all`
	split collective	`N/A`	`MPI_File_read_at_all_begin/end` `MPI_File_write_at_all_begin/end`
individual file pointers	blocking	`MPI_File_read` `MPI_File_write`	`MPI_File_read_all` `MPI_File_write_all`
	nonblocking	`MPI_File_iread` `MPI_File_iwrite`	`MPI_File_iread_all` `MPI_File_iwrite_all`
	split collective	`N/A`	`MPI_File_read_all_begin/end` `MPI_File_write_all_begin/end`
shared file pointer	blocking	`MPI_File_read_shared` `MPI_File_write_shared`	`MPI_File_read_ordered` `MPI_File_write_ordered`
	nonblocking	`MPI_File_iread_shared` `MPI_File_iwrite_shared`	`N/A`
	split collective	`N/A`	`MPI_File_read_ordered_begin/end` `MPI_File_write_ordered_begin/end`

Classification of ***MPI-IO Functions*** *in C*

Data Access - Collective

Explicit Offsets

```
int MPI_File_write_at_all(
      MPI_File fh,             // IN OUT   file handle (handle)
      MPI_Offset offset,       // IN       file offset (integer)
      const void *buf,         // IN       initial address of buffer (choice)
      int count,               // IN       number of elements in buffer (integer)
      MPI_Datatype datatype,   // IN       datatype of each buffer element (handle)
      MPI_Status *status       //    OUT   status object (Status)
)
```

```
int MPI_File_read_at_all(
      MPI_File fh,             // IN OUT   file handle (handle)
      MPI_Offset offset,       // IN       file offset (integer)
      void *buf,               // OUT      initial address of buffer (choice)
      int count,               // IN       number of elements in buffer (integer)
      MPI_Datatype datatype,   // IN       datatype of each buffer element (handle)
      MPI_Status *status       //    OUT   status object (Status)
)
```

Data Access - Collective

Individual File Pointers

```
int MPI_File_write_all(
      MPI_File fh,             // IN OUT   file handle (handle)
      const void *buf,         // IN       initial address of buffer (choice)
      int count,               // IN       number of elements in buffer (integer)
      MPI_Datatype datatype,   // IN       datatype of each buffer element (handle)
      MPI_Status *status       //    OUT   status object (Status)
)
```

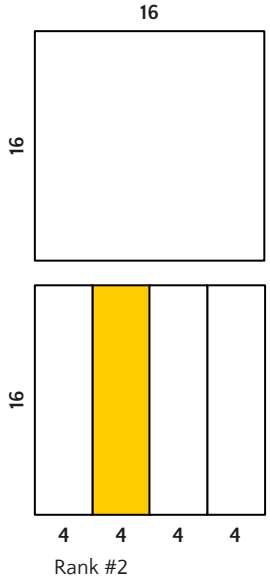
```
int MPI_File_read_all(
      MPI_File fh,             // IN OUT   file handle (handle)
      void *buf,               //    OUT   initial address of buffer (choice)
      int count,               // IN       number of elements in buffer (integer)
      MPI_Datatype datatype,   // IN       datatype of each buffer element (handle)
      MPI_Status *status       //    OUT   status object (Status)
)
```

Hands-on!

WRITE - Subarray Datatype

SOLUTION FILE

`write-c-ifp-view-subarray-datatype-double.c`



- Consider a global matrix of 16 X 16 and 4 processes (easy to visualize)
- Divide the domain into 4 parts of 16 X 4 (local matrix)
- Make each process fill its local matrix with `(rank + (count / 100.0))`
- Where `count` is a counter of cells when iterating
- Create a new filetype to write the subarray of doubles
- Define a view based on the subarray filetype you created
- Each process should write its subarray in a collective operation
- Make sure you are using `MPI_ORDER_C` to store in row-major order
- Use `hexdump` to view your file and make sure it is correct!

```
hexdump -v -e '16 "%f "' -e '"\n"' write-c-ifp-view-subarray-datatype-double.data

0,000000 0,010000 0,020000 0,030000 1,000000 1,010000 1,020000 1,030000 2,000000 2,010000 2,020000 2,030000 3,000000 3,010000 3,020000 3,030000
0,040000 0,050000 0,060000 0,070000 1,040000 1,050000 1,060000 1,070000 2,040000 2,050000 2,060000 2,070000 3,040000 3,050000 3,060000 3,070000
0,080000 0,090000 0,100000 0,110000 1,080000 1,090000 1,100000 1,110000 2,080000 2,090000 2,100000 2,110000 3,080000 3,090000 3,100000 3,110000
0,120000 0,130000 0,140000 0,150000 1,120000 1,130000 1,140000 1,150000 2,120000 2,130000 2,140000 2,150000 3,120000 3,130000 3,140000 3,150000
0,160000 0,170000 0,180000 0,190000 1,160000 1,170000 1,180000 1,190000 2,160000 2,170000 2,180000 2,190000 3,160000 3,170000 3,180000 3,190000
0,200000 0,210000 0,220000 0,230000 1,200000 1,210000 1,220000 1,230000 2,200000 2,210000 2,220000 2,230000 3,200000 3,210000 3,220000 3,230000
0,240000 0,250000 0,260000 0,270000 1,240000 1,250000 1,260000 1,270000 2,240000 2,250000 2,260000 2,270000 3,240000 3,250000 3,260000 3,270000
0,280000 0,290000 0,300000 0,310000 1,280000 1,290000 1,300000 1,310000 2,280000 2,290000 2,300000 2,310000 3,280000 3,290000 3,300000 3,310000
0,320000 0,330000 0,340000 0,350000 1,320000 1,330000 1,340000 1,350000 2,320000 2,330000 2,340000 2,350000 3,320000 3,330000 3,340000 3,350000
0,360000 0,370000 0,380000 0,390000 1,360000 1,370000 1,380000 1,390000 2,360000 2,370000 2,380000 2,390000 3,360000 3,370000 3,380000 3,390000
0,400000 0,410000 0,420000 0,430000 1,400000 1,410000 1,420000 1,430000 2,400000 2,410000 2,420000 2,430000 3,400000 3,410000 3,420000 3,430000
0,440000 0,450000 0,460000 0,470000 1,440000 1,450000 1,460000 1,470000 2,440000 2,450000 2,460000 2,470000 3,440000 3,450000 3,460000 3,470000
0,480000 0,490000 0,500000 0,510000 1,480000 1,490000 1,500000 1,510000 2,480000 2,490000 2,500000 2,510000 3,480000 3,490000 3,500000 3,510000
0,520000 0,530000 0,540000 0,550000 1,520000 1,530000 1,540000 1,550000 2,520000 2,530000 2,540000 2,550000 3,520000 3,530000 3,540000 3,550000
0,560000 0,570000 0,580000 0,590000 1,560000 1,570000 1,580000 1,590000 2,560000 2,570000 2,580000 2,590000 3,560000 3,570000 3,580000 3,590000
0,600000 0,610000 0,620000 0,630000 1,600000 1,610000 1,620000 1,630000 2,600000 2,610000 2,620000 2,630000 3,600000 3,610000 3,620000 3,630000
```

Output for 16 x 16 matrix and 4 processes

Data Access - Collective

Shared File Pointers

- MPI maintains exactly one shared file pointer per collective open (`MPI_FILE_OPEN`)
- Shared among processes in the communicator group
- Same semantics of the explicit offset routines
- Multiple calls to the shared pointer behaves as if they were serialized
- Order is deterministic
- Accesses to the file will be in the order determined by the ranks

Data Access - Collective

Shared File Pointers

```
int MPI_File_write_ordered(
      MPI_File fh,             // IN OUT   file handle (handle)
      const void *buf,         // IN       initial address of buffer (choice)
      int count,               // IN       number of elements in buffer (integer)
      MPI_Datatype datatype,   // IN       datatype of each buffer element (handle)
      MPI_Status *status       //    OUT   status object (Status)
)
```

```
int MPI_File_read_ordered(
      MPI_File fh,             // IN OUT   file handle (handle)
      void *buf,               //    OUT   initial address of buffer (choice)
      int count,               // IN       number of elements in buffer (integer)
      MPI_Datatype datatype,   // IN       datatype of each buffer element (handle)
      MPI_Status *status       //    OUT   status object (Status)
)
```

positioning	synchronism	coordination	
		noncollective	collective
explicit offsets	blocking	`MPI_File_read_at` `MPI_File_write_at`	`MPI_File_read_at_all` `MPI_File_write_at_all`
	nonblocking	`MPI_File_iread_at` `MPI_File_iwrite_at`	`MPI_File_iread_at_all` `MPI_File_iwrite_at_all`
	split collective	`N/A`	`MPI_File_read_at_all_begin/end` `MPI_File_write_at_all_begin/end`
individual file pointers	blocking	`MPI_File_read` `MPI_File_write`	`MPI_File_read_all` `MPI_File_write_all`
	nonblocking	`MPI_File_iread` `MPI_File_iwrite`	`MPI_File_iread_all` `MPI_File_iwrite_all`
	split collective	`N/A`	`MPI_File_read_all_begin/end` `MPI_File_write_all_begin/end`
shared file pointer	blocking	`MPI_File_read_shared` `MPI_File_write_shared`	`MPI_File_read_ordered` `MPI_File_write_ordered`
	nonblocking	`MPI_File_iread_shared` `MPI_File_iwrite_shared`	`N/A`
	split collective	`N/A`	`MPI_File_read_ordered_begin/end` `MPI_File_write_ordered_begin/end`

Classification of ***MPI-IO Functions*** *in C*

Hints

File Info
Setting and Getting Hints
MPI-I/O Hints
Data Seiving
Collective Buffering

MPI-IO

Hints (ROMIO)

- Hints are `(key,value)` pairs
- Hints allow users to provide information on:
  - The access pattern to the files
  - Details about the file system
- The goal is to direct possible optimizations
- Applications may choose to ignore this hints

MPI-IO

Hints

- Hints are provided via `MPI_INFO` objects
- When no hint is provided you should use `MPI_INFO_NULL`
- Hints are informed, per file, in operations such as:

  `MPI_FILE_OPEN`, `MPI_FILE_DELETE`, `MPI_FILE_SET_VIEW` and `MPI_FILE_SET_INFO`

- Some hints cannot be overridden in operations such as:

  `MPI_FILE_SET_VIEW` and `MPI_FILE_SET_INFO`

Hints

Procedure

1. Create an info object with `MPI_INFO_CREATE`
2. Set the hint(s) with `MPI_INFO_SET`
3. Pass the info object to the I/O layer

   → through `MPI_FILE_OPEN`, `MPI_FILE_SET_VIEW` or `MPI_FILE_SET_INFO`
4. Free the info object with `MPI_INFO_FREE`

   → can be freed as soon as passed!
5. Issue the I/O operations

   → `MPI_FILE_WRITE_ALL` ...

Hints - Info

Creating and Freeing

```
int MPI_Info_create(
      MPI_Info *info          // OUT      info object created (handle)
)
```

- `MPI_INFO_CREATE` creates a new info object
- The info object may be different on each process
- Hints that are required to be the same must be the same

```
int MPI_Info_free(
      MPI_Info *info          // IN OUT   info object (handle)
)
```

- `MPI_INFO_FREE` frees info and sets it to `MPI_INFO_NULL`

Hints - Info

Setting and Removing

```
int MPI_Info_set(
      MPI_Info info,          // IN OUT   info object (handle)
      const char *key,        // IN       key (string)
      const char *value       // IN       value (string)
)
```

- `MPI_INFO_SET` adds `(key,value)` pair to `info`
- This will override existing values for that key

```
int MPI_Info_delete(
      MPI_Info info,          // IN OUT   info object (handle)
      const char *key         // IN       key (string)
)
```

- Deletes a `(key,value)` pair or raises `MPI_ERR_INFO_NOKEY`

Hints - Info

Fetching Information

```
int MPI_Info_get_nkeys(
      MPI_Info info,          // IN       info object (handle)
      int *nkeys              //    OUT   number of defined keys (integer)
)
```

- Retrieves the number of keys sets in the `info` object
- We can also get each of those keys, i.e. the n^{th} key, using:

```
MPI_Info_get_nthkey(
      MPI_Info info,          // IN       info object (handle)
      int n,                  // IN       key number (integer)
      char *key               //    OUT   key (string)
)
```

Hints - Info

Fetching Information

```
int MPI_Info_get(
      MPI_Info info,          // IN       info object (handle)
      const char *key,        // IN       key (string)
      int length,             // IN       length of value arg (integer)
      char *value,            // OUT      value (string)
      int *flag               // OUT      true if key defined, false if not (boolean)
)
```

- Retrieves the value set in key in a previous call to `MPI_INFO_SET`
- `length` is the number of characters available in `value`

```
int MPI_Info_get_valuelen(
      MPI_Info info,          // IN       info object (handle)
      const char *key,        // IN       key (string)
      int *length,            // OUT      length of value arg (integer)
      int *flag               // OUT      true if key defined, false if not (boolean)
)
```

Hints

Setting Hints

```
int MPI_File_set_info(
      MPI_File fh,            // IN OUT   file handle (handle)
      MPI_Info info           // IN       info object (handle)
)
```

- `MPI_FILE_SET_INFO` define new values for the hints of `fh`
- It is a collective routine
- The info object may be different on each process
- Hints that are required to be the same must be the same

Hints

Reading Hints

```
int MPI_File_get_info(
      MPI_File fh,            // IN       file handle (handle)
      MPI_Info *info_used     // OUT      new info object (handle)
)
```

- `MPI_FILE_GET_INFO` return a new `info` object
- Contain hints associated by `fh`
- Lists the actually used hints
  - Remember that some of them may be ignored!
- Only returns active hints

Hands-on!

Which Hints?

SOLUTION FILE

`get-all-hints.c`

Create a very simple code to:

- Open a file (you should create new empty file)
- Read all the default hints
  - Get the `info` object associated with the `fh` you just opened
  - Get the total number of keys sets
  - Iterate and get each of the keys
  - Get the value of the keys
  - Print these hints and its flag to the standard output
- Run your solution on your machine or on SDumont!
- CHALLENGE: modify/create some hints and get the values again!

Hands-on!
Which Hints?

SOLUTION FILE
`get-all-hints.c`

- If you run on your machine, you need to use **ROMIO**!
- To find the version use:

```
$ ompi_info | grep romio

MCA io: romio314 (MCA v2.1.0, API v2.0.0, Component v3.0.0)
```

- Then you can run with ROMIO:

```
$ mpirun -np 1 --oversubscribe --mca io romio314 ./get-all-hints
```

- Try to run using the ROMIO_HINTS variable. What is the difference?

```
$ ROMIO_HINTS=$PWD/hints.txt mpirun -np 1 --oversubscribe --mca io romio314 ./get-all-hints
```

```
there are 25 hints set:
  direct_read: false (true)
  direct_write: false (true)
  romio_lustre_co_ratio: 1 (true)
  romio_lustre_coll_threshold: 0 (true)
  romio_lustre_ds_in_coll: enable (true)
  cb_buffer_size: 16777216 (true)
  romio_cb_read: automatic (true)
  romio_cb_write: automatic (true)
  cb_nodes: 1 (true)
  romio_no_indep_rw: false (true)
  romio_cb_pfr: disable (true)
  romio_cb_fr_types: aar (true)
  romio_cb_fr_alignment: 1 (true)
  romio_cb_ds_threshold: 0 (true)
  romio_cb_alltoall: automatic (true)
  ind_rd_buffer_size: 4194304 (true)
  ind_wr_buffer_size: 524288 (true)
  romio_ds_read: automatic (true)
  romio_ds_write: automatic (true)
  cb_config_list: *:1 (true)
  romio_filesystem_type: LUSTRE: (true)
  romio_aggregator_list: 0  (true)
  striping_unit: 1048576 (true)
  striping_factor: 1 (true)
  romio_lustre_start_iodevice: 0 (true)
```

Output of the exercise on SDumont

Hands-on!
Stripes!

SOLUTION FILE
NOT AVAILABLE

Take one of the codes from the previous exercises and:

- Make sure you are writing something
- Increase the total generated file size
- Define the `striping_factor` and/or `striping_unit` hints
- Measure the performance of your code on SDumont!
- You can use `lfs getstripe filename` to make sure of the striping data you used

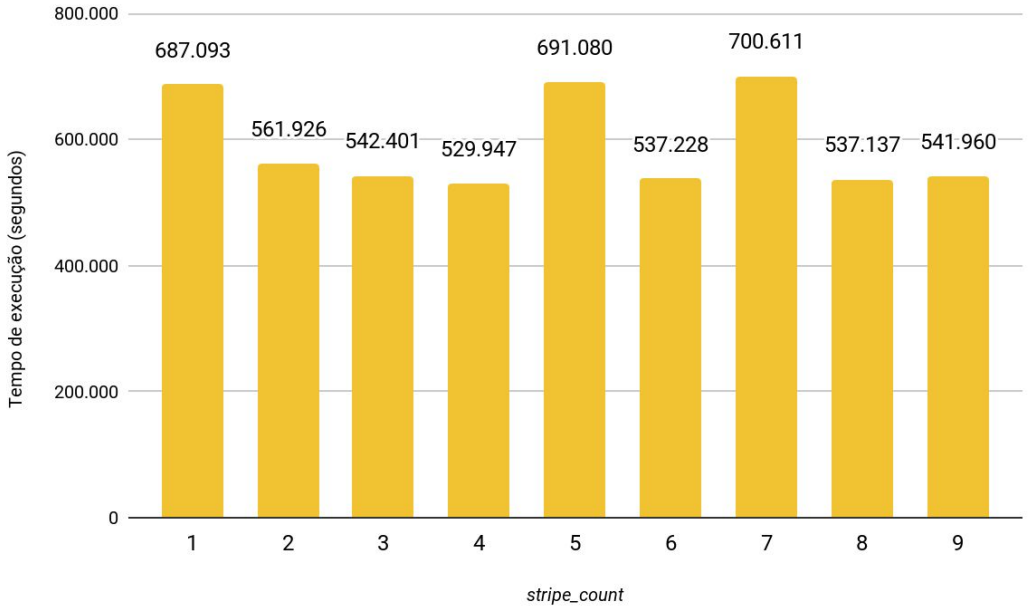
```
$ lfs getstripe striping-factor-1.txt
striping-factor-1.txt
lmm_stripe_count:   1
lmm_stripe_size:    1048576
lmm_layout_gen:     0
lmm_stripe_offset:  8
        obdidx             objid             objid             group
             8         627435435       0x2565e7ab                 0
```

```
$ lfs getstripe striping-factor-2.txt
striping-factor-2.txt
lmm_stripe_count:   2
lmm_stripe_size:    1048576
lmm_layout_gen:     0
lmm_stripe_offset:  7
        obdidx             objid             objid             group
             7         627456996       0x25663be4                 0
             5         626079511       0x25513717                 0
```

```
$ lfs getstripe striping-factor-4.txt
striping-factor-4.txt
lmm_stripe_count:   4
lmm_stripe_size:    1048576
lmm_layout_gen:     0
lmm_stripe_offset:  8
        obdidx             objid             objid             group
             8         627435439       0x2565e7af                 0
             2         626779178       0x255be42a                 0
             9         627429489       0x2565d071                 0
             1         627009698       0x255f68a2                 0
```

```
$ lfs getstripe striping-factor-8.txt
striping-factor-8.txt
lmm_stripe_count:   8
lmm_stripe_size:    1048576
lmm_layout_gen:     0
lmm_stripe_offset:  6
        obdidx             objid             objid             group
             6         627172680       0x2561e548                 0
             4         627663700       0x25696354                 0
             0         627437154       0x2565ee62                 0
             8         627435440       0x2565e7b0                 0
             2         626779179       0x255be42b                 0
             9         627429490       0x2565d072                 0
             1         627009699       0x255f68a3                 0
             7         627456999       0x25663be7                 0
```

Checking the output of the exercise on SDumont



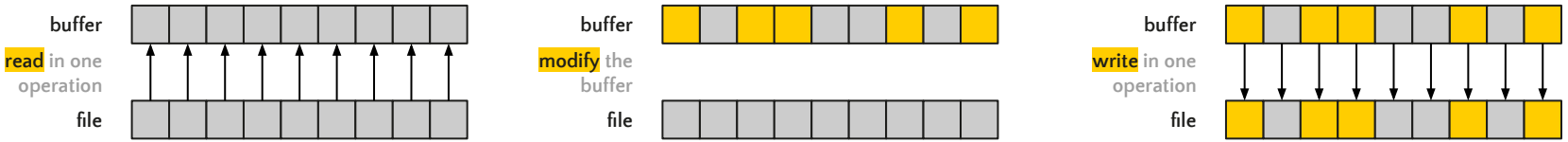
Output of the exercise on SDumont

Time is presented as the average of 10 repetitions

Optimization

Data Sieving

- I/O performance suffers when making many small I/O requests
- Access on small, non-contiguous regions of data can be optimized:
  - Group requests
  - Use temporary buffers
- This optimisation is local to each process (non-collective operation)



Hints

Data Sieving

`ind_rd_buffer_size` → size (in bytes) of the intermediate buffer used during read

Default is 4194304 (4 Mbytes)

`ind_wr_buffer_size` → size (in bytes) of the intermediate buffer used during write

Default is 524288 (512 Kbytes)

`romio_ds_read` → determines when ROMIO will choose to perform data sieving

enable, disable, or **automatic** (ROMIO uses heuristics)

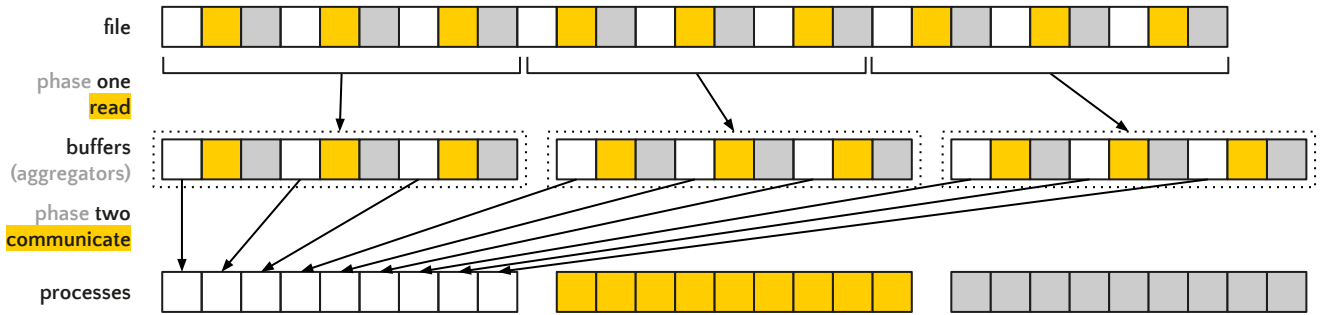
`romio_ds_write` → determines when ROMIO will choose to perform data sieving

enable, disable, or **automatic** (ROMIO uses heuristics)

Optimization

Collective Buffering

- Collective buffering, a.k.a. two-phase collective I/O
- Re-organises data across processes to match data layout in file
- Involves communication between processes
- Only the aggregators perform the I/O operation



Hints

Collective Buffering

`cb_buffer_size` → size (in bytes) of the buffer used in two-phase collective I/O

Default is 4194304 (4 Mbytes)

Multiple operations could be used if size is greater than this value

`cb_nodes` → maximum number of aggregators to be used

Default is the number of unique hosts in the communicator used when opening the file

`romio_cb_read` → controls when collective buffering is applied to collective read

enable, disable, or **automatic** (ROMIO uses heuristics)

`romio_cb_write` → controls when collective buffering is applied to collective write

enable, disable, or **automatic** (ROMIO uses heuristics)

Conclusion

Review
Final Thoughts

Conclusion

- MPI-IO is powerful to express complex data patterns
- Library can automatically optimize I/O requests
- But there is no “magic”
- There is also no “best solution” for all situations
- Modifying an existing application or writing a new application to use collective I/O optimization techniques is not necessarily easy, but the payoff can be substantial
- Prefer using MPI collective I/O with collective buffering

Thank You!

Any questions?

Get in touch!

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References

Cray Inc. **Getting Started on MPI I/O**, report, 2009; Illinois. (docs.cray.com/books/S-2490-40/S-2490-40.pdf: accessed February 17, 2018).

Message Passing Interface Forum. **MPI: A Message-Passing Interface Standard Version 3.0**, report, September 21, 2012; (mpi-forum.org/docs/mpi-3.0/mpi30-report.pdf: accessed February 17, 2018), University of Tennessee, Knoxville, Tennessee.

Robert Latham, Robert Ross. (2013) **Parallel I/O Basics**. In: Earth System Modelling - Volume 4. SpringerBriefs in Earth System Sciences. Springer, Berlin, Heidelberg,

Thakur, R.; Lusk, E. & Gropp, W. **Users guide for ROMIO: A high-performance, portable MPI-IO implementation**, report, October 1, 1997; Illinois. (digital.library.unt.edu/ark:/67531/metadc695943/: accessed February 17, 2018), University of North Texas Libraries, Digital Library, digital.library.unt.edu; crediting UNT Libraries Government Documents Department.

William Gropp; Torsten Hoefler; Rajeev Thakur; Ewing Lusk, **Parallel I/O**, in Using Advanced MPI: Modern Features of the Message-Passing Interface, 1, MIT Press, 2014, pp.392.

TEMPLATES

http://www.lncc.br/~andrerc/mpi-io-lncc-2020-templates.tar.gz

SOLUTIONS

http://www.lncc.br/~andrerc/mpi-io-lncc-2020-solutions.tar.gz