Parallel Programming with MPI

Science & Technology Support
High Performance Computing

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Table of Contents

Setting the Stage

- Overview of parallel computing
- Parallel architectures
- Parallel programming models
- Hardware
- Software

Overview of Parallel Computing

- Parallel computing is when a program uses concurrency to either
  - decrease the runtime needed to solve a problem
  - increase the size of problem that can be solved
- The direction in which high-performance computing is headed!
- Mainly this is a price/performance issue
  - Vector machines (e.g., Cray X1) very expensive to engineer and run
  - Commodity hardware/software - Clusters!

Writing a Parallel Application

- Decompose the problem into tasks
  - Ideally, these tasks can be worked on independently of the others
- Map tasks onto “threads of execution” (processors)
- Threads have shared and local data
  - Shared: used by more than one thread
  - Local: Private to each thread
- Write source code using some parallel programming environment
- Choices may depend on (among many things)
  - the hardware platform to be run on
  - the level performance needed
  - the nature of the problem

Parallel Architectures

- Distributed memory (Pentium 4 and Itanium 2 clusters)
  - Each processor has local memory
  - Cannot directly access the memory of other processors
- Shared memory (Cray X1, SGI Altix, Sun COE)
  - Processors can directly reference memory attached to other processors
  - Shared memory may be *physically* distributed
    - The cost to access remote memory may be high!
  - Several processors may sit on one memory bus (SMP)
- Combinations are very common, e.g. Itanium 2 Cluster:
  - 258 compute nodes, each with 2 CPUs sharing 4GB of memory
  - High-speed Myrinet interconnect between nodes.

Parallel Programming Models

- Distributed memory systems
  - For processors to share data, the programmer must explicitly arrange for communication - "**Message Passing"**
  - Message passing libraries:
    - MPI ("Message Passing Interface")
    - PVM ("Parallel Virtual Machine")
    - Shmem (Cray only)
- Shared memory systems
  - "Thread" based programming
  - Compiler directives (OpenMP; various proprietary systems)
  - Can also do explicit message passing, of course

Parallel Computing: Hardware

- In very good shape!
- Processors are cheap and powerful
  - Intel, AMD, IBM PowerPC, …
  - Theoretical performance approaching 10 GFLOP/sec or more.
- SMP nodes with 8-32 CPUs are common
- Clusters with tens or hundreds of nodes are common
- Affordable, high-performance interconnect technology is available - clusters!
- Systems with a few hundreds of processors and good inter-processor communication are not hard to build

Parallel Computing: Software

- Not as mature as the hardware
- The main obstacle to making use of all this power
  - Perceived difficulties with writing parallel codes outweigh the benefits
- Emergence of standards is helping enormously
  - MPI
  - OpenMP
- Programming in a shared memory environment generally easier
- Often better performance using message passing
  - Much like assembly language vs. C/Fortran

Brief History of MPI

- What is MPI
- MPI Forum
- Goals and Scope of MPI
- MPI on OSC Parallel Platforms

What Is MPI

- **M**essage **P**assing **I**nterface
- What is the message?

DATA

- Allows data to be passed between processes in a distributed memory environment

MPI Forum

- First message-passing interface standard
  - Successor to PVM
- Sixty people from forty different organizations
- International representation
- MPI 1.1 Standard developed from 92-94
- MPI 2.0 Standard developed from 95-97
- Standards documents
  - http://www.mcs.anl.gov/mpi/index.html
  - http://www.mpi-forum.org/docs/docs.html (postscript versions)

Goals and Scope of MPI

- MPI's prime goals are:
  - To provide source-code portability
  - To allow efficient implementation
- It also offers:
  - A great deal of functionality
  - Support for heterogeneous parallel architectures
- Acknowledgements
  - Edinburgh Parallel Computing Centre/University of Edinburgh for material on which this course is based
  - Dr. David Ennis of the Ohio Supercomputer Center who initially developed this course

MPI on OSC Platforms

- Itanium 2 cluster
  - MPICH/ch_gm for Myrinet from Myricom (default)
  - MPICH/ch_p4 for Gigabit Ethernet from Argonne Nat'l Lab
- Pentium 4 cluster
  - MVAPICH for InfiniBand from OSU CSE (default)
  - MPICH/ch_p4 for Gigabit Ethernet from Argonne Nat'l Lab
- Cray X1
  - Cray MPT (default)
- SGI Altix
  - MPICH/ch_p4 for shared memory from Argonne Nat'l Lab (default)
  - SGI MPT
- Sun COE
  - MPICH/ch_p4 for shared memory from Argonne Nat'l Lab (default)
  - Sun HPC Cluster Tools

MPI Program Structure

- Handles
- MPI Communicator
- MPI_Comm_world
- Header files
- MPI function format
- Initializing MPI
- Communicator Size
- Process Rank
- Exiting MPI

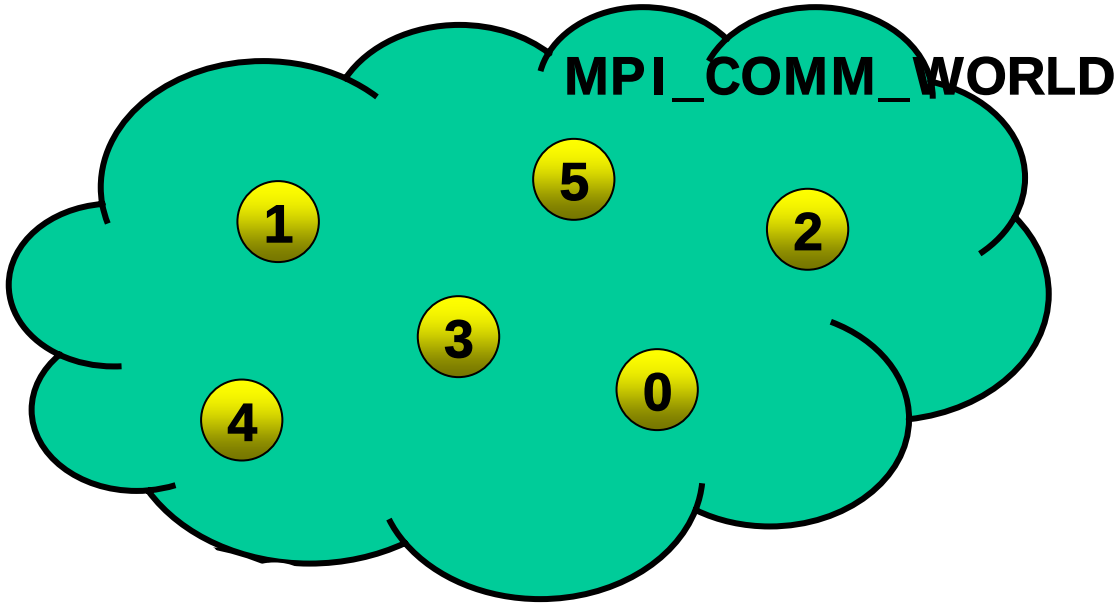
Handles

- MPI controls its own internal data structures
- MPI releases “handles” to allow programmers to refer to these
- C handles are of defined `typedefs`
- In Fortran, all handles have type `INTEGER`

MPI Communicator

- Programmer view: group of processes that are allowed to communicate with each other
- All MPI communication calls have a communicator argument
- Most often you will use `MPI_COMM_WORLD`
  - Defined when you call `MPI_Init`
  - It is all of your processors...

MPI_COMM_WORLD Communicator



Header Files

- MPI constants and handles are defined here

C:

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

Fortran:

```
include 'mpif.h'
```

MPI Function Format

C:

```
error = MPI_Xxxxx(parameter,...);
MPI_Xxxxx(parameter,...);
```

Fortran:

```
CALL MPI_XXXXX(parameter,...,IERROR)
```

Initializing MPI

- Must be the first routine called (only once)

C:

```
int MPI_Init(int *argc, char ***argv)
```

Fortran:

```
CALL MPI_INIT(IERROR)

INTEGER IERROR
```

Communicator Size

- How many processes are contained within a communicator

C:

```
MPI_Comm_size(MPI_Comm comm, int *size)
```

Fortran:

```
CALL MPI_COMM_SIZE(COMM, SIZE, IERROR)

INTEGER COMM, SIZE, IERROR
```

Process Rank

- Process ID number within the communicator
  - Starts with zero and goes to (n-1) where n is the number of processes requested

- Used to identify the source and destination of messages

C:

```
MPI_Comm_rank(MPI_Comm comm, int *rank)
```

Fortran:

```
CALL MPI_COMM_RANK(COMM, RANK, IERROR)

INTEGER COMM, RANK, IERROR
```

Exiting MPI

- Must be called last by “all” processes

C:

```
MPI_Finalize()
```

Fortran:

```
CALL MPI_FINALIZE(IERROR)
```

Bones.c

```
#include<mpi.h>

void main(int argc, char *argv[]) {
   int rank, size;
   MPI_Init(&argc, &argv);
   MPI_Comm_rank(MPI_COMM_WORLD, &rank);
   MPI_Comm_size(MPI_COMM_WORLD, &size);

/* … your code here … */

   MPI_Finalize ();
}
```

Bones.f

```
      PROGRAM skeleton
      INCLUDE ‘mpif.h’
      INTEGER ierror, rank, size
      CALL MPI_INIT(ierror)
      CALL MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierror)
      CALL MPI_COMM_SIZE(MPI_COMM_WORLD, size, ierror)

C     … your code here …

      CALL MPI_FINALIZE(ierror)
      END
```

Using MPI on the Clusters at OSC

- Compile with the MPI wrapper scripts (`mpicc`, `mpiCC`, `mpif77`, `mpif90`)
- Examples:

```
$ mpicc myprog.c
$ mpif90 myprog.f
```

- To run:

```
In batch: mpiexec ./a.out
```

Exercise #1: Hello World

- Write a minimal MPI program which prints “hello world”
- Run it on several processors in parallel
- Modify your program so that only the process ranked 2 in MPI_COMM_WORLD prints out “hello world”
- Modify your program so that each process prints out its rank and the total number of processors

What's in a Message

- Messages
- MPI Basic Datatypes - C
- MPI Basic Datatypes - Fortran
- Rules and Rationale

Messages

- A message contains an array of elements of some particular MPI datatype
- MPI Datatypes:
  - Basic types
  - Derived types
- Derived types can be build up from basic types
- C types are different from Fortran types

MPI Basic Datatypes - C

MPI Datatype	C Datatype
MPI_CHAR	Signed char
MPI_SHORT	Signed short int
MPI_INT	Signed int
MPI_LONG	Signed log int
MPI_UNSIGNED_CHAR	Unsigned char
MPI_UNSIGNED_SHORT	Unsigned short int
MPI_UNSIGNED	Unsigned int
MPI_UNSIGNED_LONG	Unsigned long int
MPI_FLOAT	Float
MPI_DOUBLE	Double
MPI_LONG_DOUBLE	Long double
MPI_BYTE	
MPI_PACKED	

MPI Basic Datatypes - Fortran

MPI Datatype	Fortran Datatype
MPI_INTEGER	INTEGER
MPI_REAL	REAL
MPI_DOUBLE_PRECISION	DOUBLE PRECISION
MPI_COMPLEX	COMPLEX
MPI_LOGICAL	LOGICAL
MPI_CHARACTER	CHARACTER(1)
MPI_BYTE	
MPI_PACKED	

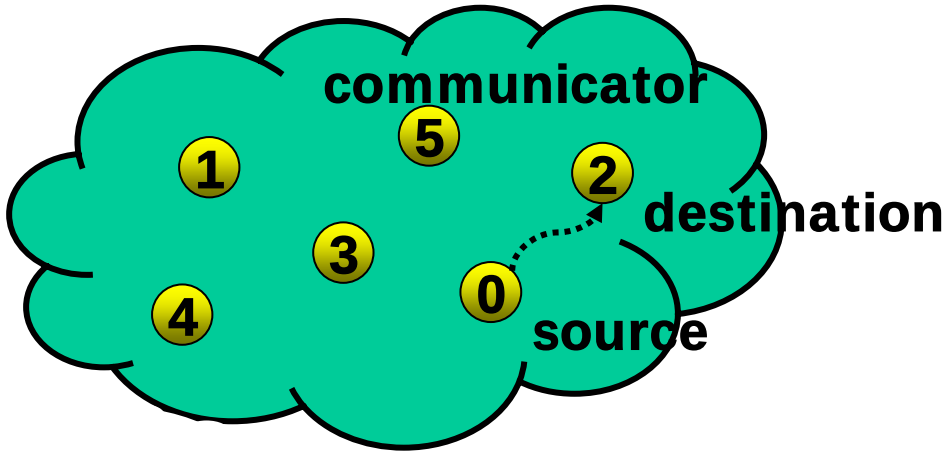
Rules and Rationale

- Programmer declares variables to have “normal” C/Fortran type, but uses matching MPI datatypes as arguments in MPI routines
- Mechanism to handle type conversion in a heterogeneous collection of machines
- General rule: MPI datatype specified in a receive must match the MPI datatype specified in the send

Point-to-Point Communications

- Definitions
- Communication Modes
- Routine Names (blocking)
- Sending a Message
- Memory Mapping
- Synchronous Send
- Buffered Send
- Standard Send
- Ready Send
- Receiving a Message
- Wildcarding
- Communication Envelope
- Received Message Count
- Message Order Preservation
- Sample Programs
- Timers
- Class Exercise: Processor Ring
- Extra Exercise 1: Ping Pong
- Extra Exercise 2: Broadcast

Point-to-Point Communication



- Communication between two processes
- Source process *sends* message to destination process
- Destination process *receives* the message
- Communication takes place within a communicator
- Destination process is identified by its rank in the communicator

Definitions

- "Completion" of the communication means that memory locations used in the message transfer can be safely accessed
  - Send: variable sent can be reused after completion
  - Receive: variable received can now be used

- MPI communication modes differ in what conditions are needed for completion

- Communication modes can be blocking or non-blocking
  - Blocking: return from routine implies completion
  - Non-blocking: routine returns immediately, user must test for completion

Communication Modes

Mode	Completion Condition
Synchronous send	Only completes when the receive has completed
Buffered send	Always completes (unless and error occurs), irrespective of receiver
Standard send	Message sent (receive state unknown)
Ready send	Always completes (unless and error occurs), irrespective of whetherr the receive has completed
Receive	Completes when a message has arrived

Routine Names (blocking)

MODE	MPI CALL
Standard send	MPI_SEND
Synchronous send	MPI_SSEND
Buffered send	MPI_BSEND
Ready send	MPI_RSEND
Receive	MPI_RECV

Sending a Message

C:

```
int MPI_Send(void *buf, int count, MPI_Datatype datatype,
             int dest, int tag, MPI_Comm comm)
```

Fortran:

```
CALL MPI_SEND(BUF, COUNT, DATATYPE, DEST, TAG, COMM, IERROR)

<type>        BUF(*)
INTEGER       COUNT, DATATYPE, DEST, TAG
INTEGER       COMM, IERROR
```

Arguments

`buf`	starting address of the data to be sent
`count`	number of elements to be sent
`datatype`	MPI datatype of each element
`dest`	rank of destination process
`tag`	message marker (set by user)
`comm`	MPI communicator of processors involved

```
MPI_SEND(data,500,MPI_REAL,6,33,MPI_COMM_WORLD,IERROR)
```

Memory Mapping

The Fortran 2-D array

1,1	1,2	1,3
2,1	2,2	2,3
3,1	3,2	3,3

Is stored in memory

1,1
2,1
3,1
1,2
2,2
3,2
1,3
2,3
3,3

Synchronous Send

- Completion criteria:
  Completes when message has been received
- Use if need to know that message has been received
- Sending & receiving processes synchronize
  - regardless of who is faster
  - processor idle time is probable
- Safest communication method

Buffered Send

- Completion criteria:
  Completes when message copied to buffer
- Advantage: Completes immediately
- Disadvantage: User cannot assume there is a pre-allocated buffer
- Control your own buffer space using MPI routines
  `MPI_Buffer_attach`
  `MPI_Buffer_detach`

Standard Send

- Completion criteria:
  Unknown!

- May or may not imply that message has arrived at destination

- Don’t make any assumptions (implementation dependent)

Ready Send

- Completion criteria:
  Completes immediately, but only successful if matching receive already posted
- Advantage: Completes immediately
- Disadvantage: User must synchronize processors so that receiver is ready
- Potential for good performance

Receiving a Message

C:

```
int MPI_Recv(void *buf, int count, MPI_Datatype datatype, \
     int source, int tag, MPI_Comm comm, MPI_Status *status)
```

Fortran:

```
CALL MPI_RECV(BUF, COUNT, DATATYPE, SOURCE, TAG, COMM,
              STATUS, IERROR)

<type>        BUF(*)
INTEGER       COUNT, DATATYPE, DEST, TAG
INTEGER       COMM, STATUS(MPI_STATUS_SIZE), IERROR
```

For a communication to succeed

- Sender must specify a valid destination rank
- Receiver must specify a valid source rank
- The communicator must be the same
- Tags must match
- Receiver's buffer must be large enough

Wildcarding

- Receiver can wildcard
- To receive from any source

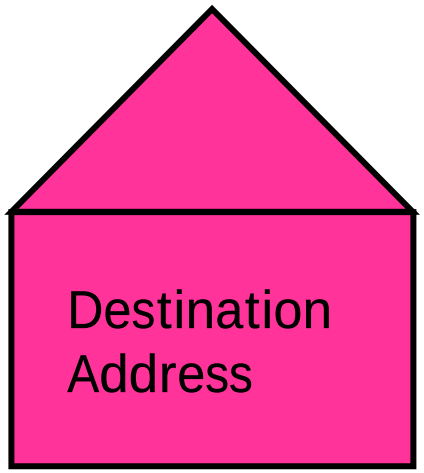
```
MPI_ANY_SOURCE
```

To receive with any tag

```
MPI_ANY_TAG
```

- Actual source and tag are returned in the receiver's `status` parameter

Communication Envelope



Sender's Address

For the attention of:

Data
Item 1
Item 2
Item 3

Communication Envelope Information

- Envelope information is returned from `MPI_RECV` as `status`

- Information includes:
  - Source: `status.MPI_SOURCE` or `status(MPI_SOURCE)`
  - Tag: `status.MPI_TAG` or `status(MPI_TAG)`
  - Count: `MPI_Get_count` or `MPI_GET_COUNT`

Received Message Count

- Message received may not fill receive buffer
- `count` is number of elements actually received

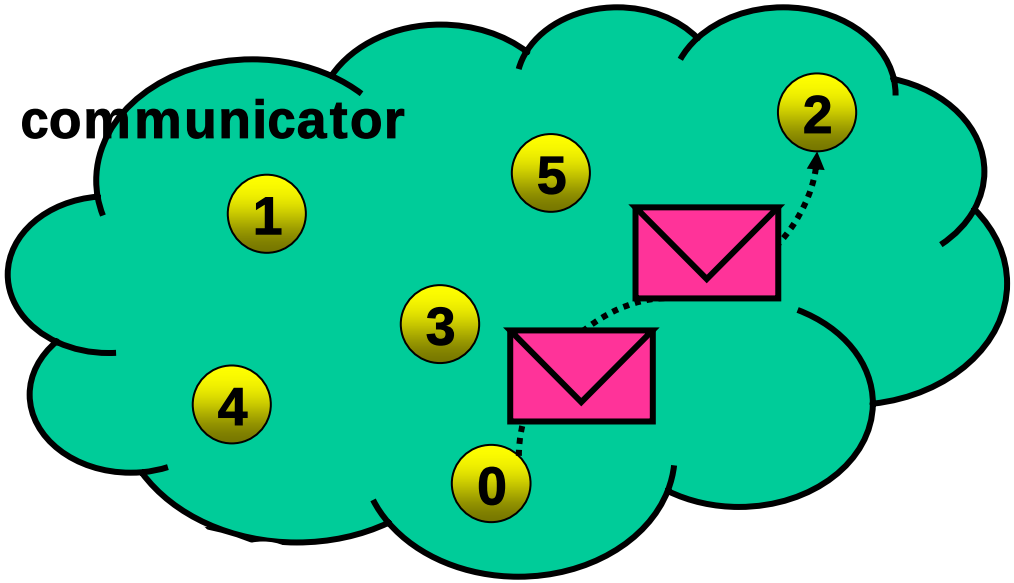
C:

```
int MPI_Get_count (MPI_Status *status,
                   MPI_Datatype datatype, int *count)
```

Fortran:

```
CALL MPI_GET_COUNT(STATUS,DATATYPE,COUNT,IERROR)

INTEGER        STATUS(MPI_STATUS_SIZE), DATATYPE
INTEGER        COUNT,IERROR
```

Message Order Preservation



- Messages do no overtake each other
- Example: Process 0 sends two messages
  Process 2 posts two receives that match either message
  Order preserved

Sample Program #1 - C

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

/* Run with two processes */

 void main(int argc, char *argv[]) {
    int rank, i, count;
    float data[100],value[200];
    MPI_Status status;

    MPI_Init(&argc,&argv);
    MPI_Comm_rank(MPI_COMM_WORLD,&rank);

    if(rank==1) {
       for(i=0;i<100;++i) data[i]=i;
       MPI_Send(data,100,MPI_FLOAT,0,55,MPI_COMM_WORLD);
    } else {
       MPI_Recv(value,200,MPI_FLOAT,MPI_ANY_SOURCE,55,MPI_COMM_WORLD,&status);
       printf("P:%d Got data from processor %d \n",rank, status.MPI_SOURCE);
       MPI_Get_count(&status,MPI_FLOAT,&count);
       printf("P:%d Got %d elements \n",rank,count);
       printf("P:%d value[5]=%f \n",rank,value[5]);
    }
    MPI_Finalize();
 }
```

Program Output

```
P: 0 Got data from processor 1
P: 0 Got 100 elements
P: 0 value[5]=5.000000
```

Sample Program #1 - Fortran

```
      PROGRAM p2p
C Run with two processes
      INCLUDE 'mpif.h'
      INTEGER err, rank, size
      real data(100)
      real value(200)
      integer status(MPI_STATUS_SIZE)
      integer count
      CALL MPI_INIT(err)
      CALL MPI_COMM_RANK(MPI_COMM_WORLD,rank,err)
      CALL MPI_COMM_SIZE(MPI_COMM_WORLD,size,err)
      if (rank.eq.1) then
         data=3.0
         call MPI_SEND(data,100,MPI_REAL,0,55,MPI_COMM_WORLD,err)
       else
         call MPI_RECV(value,200,MPI_REAL,MPI_ANY_SOURCE,55,
     &                 MPI_COMM_WORLD,status,err)
         print *, "P:",rank," got data from processor ",
     &                 status(MPI_SOURCE)
         call MPI_GET_COUNT(status,MPI_REAL,count,err)
         print *, "P:",rank," got ",count," elements"
         print *, "P:",rank," value(5)=",value(5)
       end if
      CALL MPI_FINALIZE(err)
      END
```

```
          Program Output
P: 0 Got data from processor 1
P: 0 Got 100 elements
P: 0 value[5]=3.
```

Timers

- Time is measured in seconds
- Time to perform a task is measured by consulting the timer before and after

C:

```
double MPI_Wtime(void);
```

Fortran:

```
DOUBLE PRECISION MPI_WTIME()
```

Class Exercise: Processor Ring

- A set of processes are arranged in a ring
- Each process stores its rank in `MPI_COMM_WORLD` in an integer
- Each process passes this on to its neighbor on the right
- Each processor keeps passing until it receives its rank back

Extra Exercise 1: Ping Pong

- Write a program in which two processes repeatedly pass a message back and forth
- Insert timing calls to measure the time taken for one message
- Investigate how the time taken varies with the size of the message

Extra Exercise 2: Broadcast

- Have processor 1 send the same message to all the other processors and then receive messages of the same length from all the other processors
- How does the time taken vary with the size of the messages and the number of processors?

Non-Blocking Communication

- Non-Blocking Communications
- Non-Blocking Send
- Non-Blocking Receive
- Handles
- Non-Blocking Synchronous Send
- Non-Blocking Receive
- Blocking and Non-Blocking
- Routine Names
- Completion Tests
- Wait/Test Routines
- Multiple Communications
- Testing Multiple Non-Blocking Communications
- Class Exercise: Calculating Ring

Non-Blocking Communications

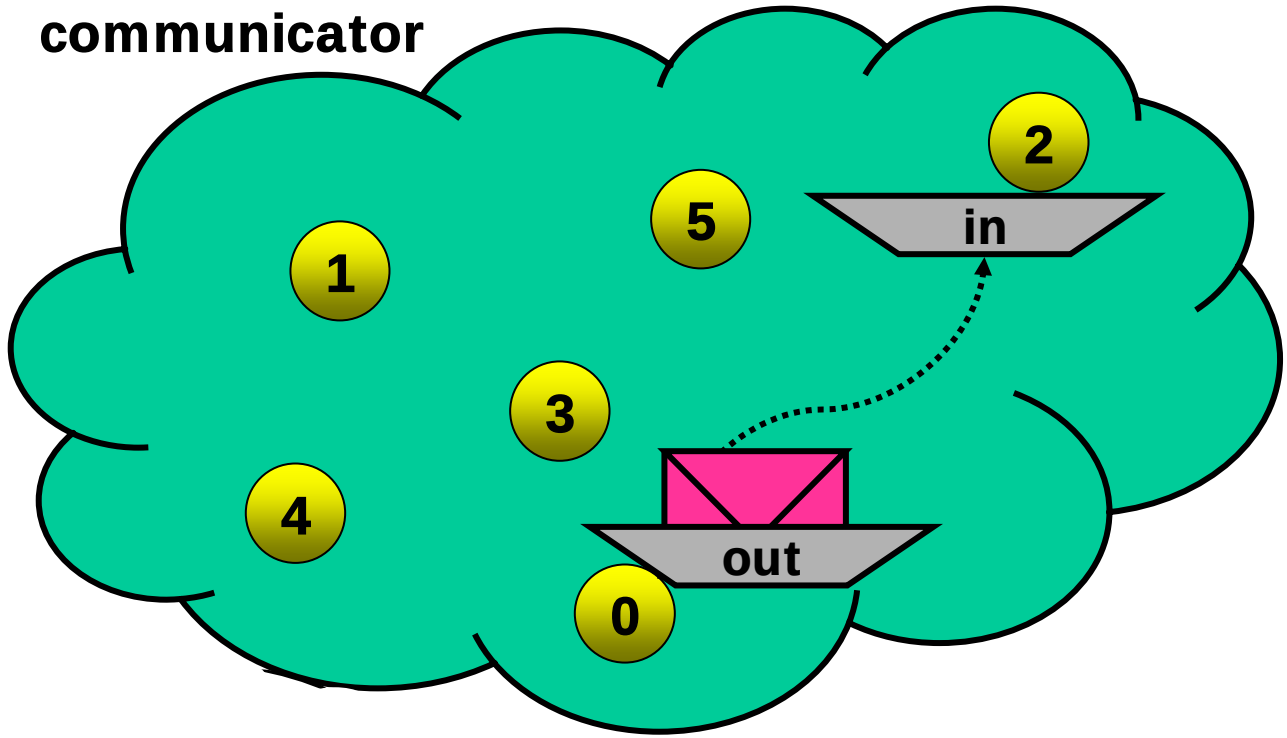
Separate communication into three phases:

1. Initiate non-blocking communication ("post" a send or receive)

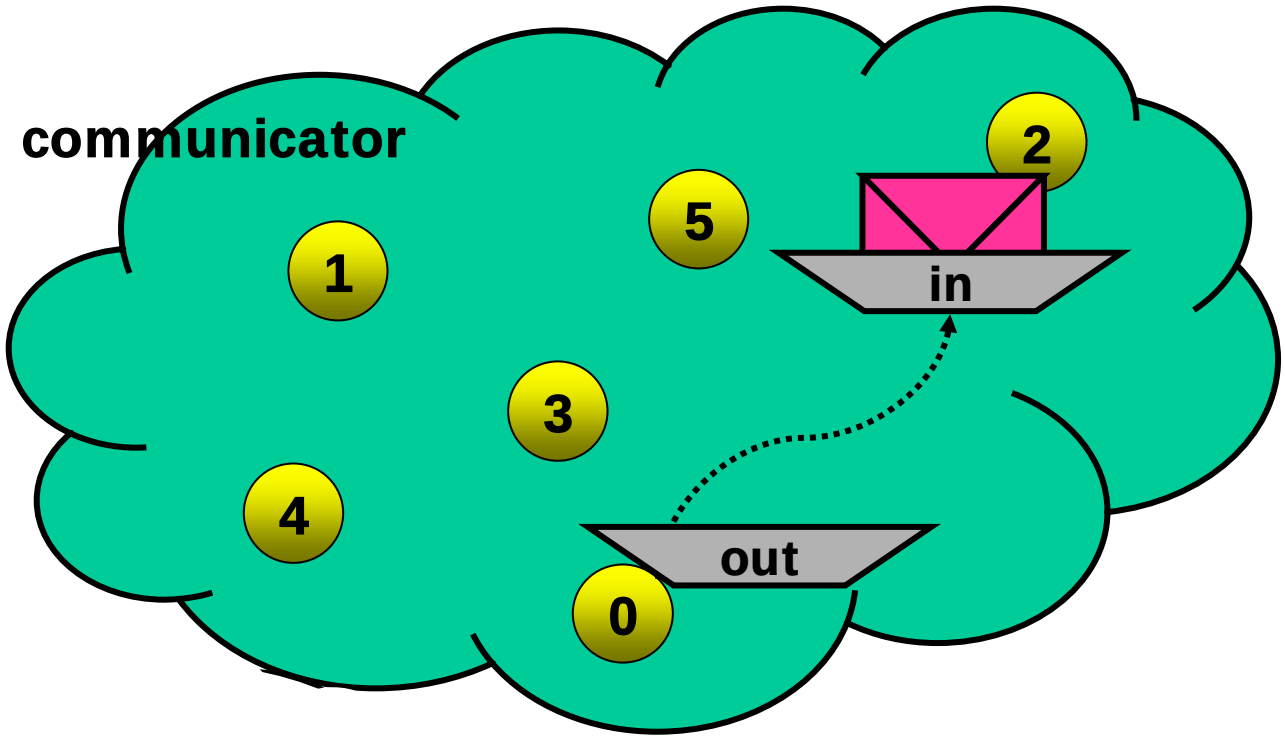
2. Do some other work not involving the data in transfer
   - Overlap calculation and communication
   - Latency hiding

3. Wait for non-blocking communication to complete

Non-Blocking Send



Non-Blocking Receive



Handles Used For Non-Blocking Communication

Datatype	Same as for blocking (MPI_Datatype or INTEGER)
Communicator	Same as for blocking (MPI_Comm or INTEGER)
Request	MPI_Request or INTEGER

- A request handle is allocated when a non-blocking communication is initiated
- The request handle is used for testing if a specific communication has completed

Non-Blocking Synchronous Send

C:

```
int MPI_Issend(void *buf, int count, MPI_Datatype datatype,
    int dest, int tag, MPI_Comm comm, MPI_Request *request)
```

Fortran:

```
CALL MPI_ISSEND(BUF,COUNT,DATATYPE,DEST,TAG,COMM,REQUEST,IERROR)

<type>       BUF(*)
INTEGER      COUNT,DATATYPE,DEST,TAG,COMM
INTEGER      REQUEST,IERROR
```

Non-Blocking Receive

C:

```
int MPI_Irecv(void *buf, int count, MPI_Datatype datatype,
    int source, int tag, MPI_Comm comm, MPI_Request *request)
```

Fortran:

```
CALL MPI_IRECV(BUF,COUNT,DATATYPE,SOURCE,TAG,COMM,REQUEST,IERROR)

<type>       BUF(*)
INTEGER      COUNT,DATATYPE,SOURCE,TAG,COMM
INTEGER      REQUEST,IERROR
```

Note: no STATUS argument

Blocking and Non-Blocking

- Send and receive can be blocking or non-blocking
- A blocking send can be used with a non-blocking receive, and vice-versa
- Non-blocking sends can use any mode -- synchronous, buffered, standard, or ready

  Note: there is no advantage for buffered or ready modes

Routine Names

Non-Blocking Operation	MPI Call
Standard send	MPI_ISEND
Synchronous send	MPI_ISSEND
Buffered send	MPI_IBSEND
Ready send	MPI_IRSEND
Receive	MPI_IRECV

Completion Tests

- Waiting vs. Testing
- Wait --> routine does not return until completion finished
- Test --> routine returns a TRUE or FALSE value depending on whether or not the communication has completed

Wait/Test Routines

C:

```
int MPI_Wait(MPI_Request *request,MPI_Status *status)
int MPI_Test(MPI_Request *request,int *flag,MPI_Status *status)
```

Fortran:

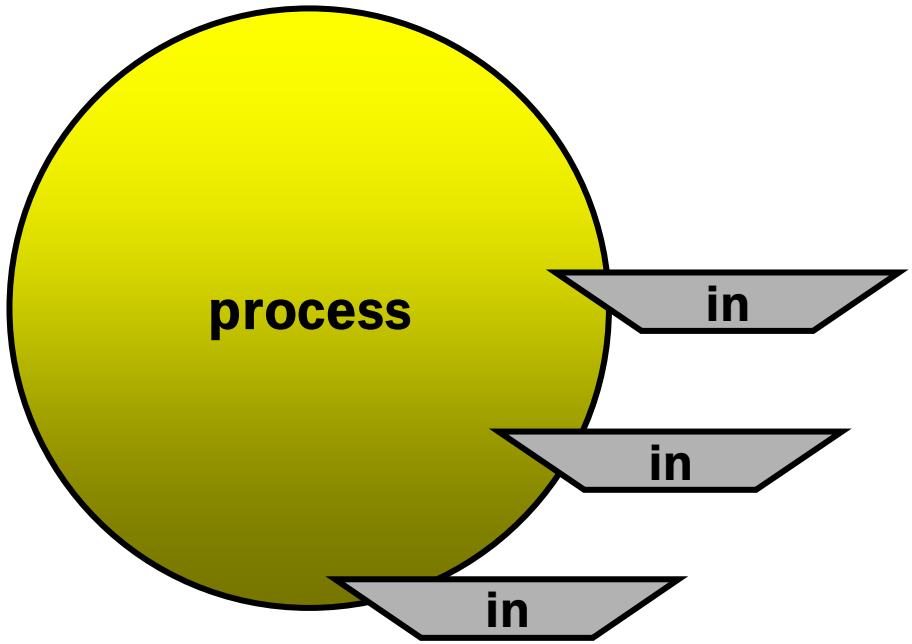
```
CALL MPI_WAIT(REQUEST,STATUS,IERR)
INTEGER REQUEST,STATUS(MPI_STATUS_SIZE),IERR

CALL MPI_TEST(REQUEST,FLAG,STATUS,IERR)
LOGICAL FLAG
INTEGER REQUEST,STATUS(MPI_STATUS_SIZE),IERR
```

Here is where STATUS appears.

Multiple Communications

- Test or wait for completion of one (and only one) message
  - `MPI_Waitany`
  - `MPI_Testany`
- Test or wait for completion of all messages
  - `MPI_Waitall`
  - `MPI_Testall`
- Test or wait for completion of as many messages as possible
  - `MPI_Waitsome`
  - `MPI_Testsome`

Testing Multiple Non-Blocking Communications



Class Exercise: Calculating Ring

- Repeat the Processor Ring exercise this time using non-blocking communication routines
- In addition, each processor should calculate the sum of all the ranks as it receives them

Derived Datatypes

- MPI Datatypes
- Procedure
- Datatype Construction
- Type Maps
- Contiguous Datatype*
- Vector Datatype*
- Extent of a Datatype
- Structure Datatype*
- Committing a Datatype
- Exercises

*includes sample C and Fortran programs

MPI Datatypes

- Basic types
- Derived types
  - Constructed from existing types (basic and derived)
  - Used in MPI communication routines to transfer high-level, extensive data entities
- Examples:
  - Sub-arrays or “unatural” array memory striding
  - C structures and Fortran common blocks
  - Large set of general variables
- Alternative to repeated sends of varied basic types
  - Slow, clumsy, and error prone

Procedure

- *Construct* the new datatype using appropriate MPI routines
  - `MPI_Type_contiguous, MPI_Type_vector, MPI_Type_struct, MPI_Type_indexed, MPI_Type_hvector, MPI_Type_hindexed`
- *Commit* the new datatype
  - `MPI_Type_Commit`
- *Use* the new datatype in sends/receives, etc.

Datatype Construction

- Datatype specified by its *type map*
  - Stencil laid over memory

- Displacements are offsets (in bytes) from the starting memory address of the desired data
  - `MPI_Type_extent` function can be used to get size (in bytes) of datatypes

Type Maps

Basic datatype 0	Displacement of datatype 0
Basic datatype 1	Displacement of datatype 1
…	…
Basic datatype n-1	Displacement of datatype n-1

Contiguous Datatype

- The simplest derived datatype consists of a number of contiguous items of the same datatype

C:

```
int MPI_Type_contiguous (int count,
          MPI_datatype oldtype,MPI_Datatype *newtype)
```

Fortran:

```
CALL MPI_TYPE_CONTIGUOUS(COUNT,OLDTYPE,NEWTYPE,IERROR)

INTEGER COUNT, OLDTYPE, NEWTYPE, IERROR
```

Sample Program #2 - C

```
#include <stdio.h>
#include<mpi.h>
/* Run with four processes */
 void main(int argc, char *argv[]) {
    int rank;
    MPI_Status status;
    struct {
     int x;
     int y;
     int z;
    } point;
    MPI_Datatype ptype;
    MPI_Init(&argc,&argv);
    MPI_Comm_rank(MPI_COMM_WORLD,&rank);
    MPI_Type_contiguous(3,MPI_INT,&ptype);
    MPI_Type_commit(&ptype);
    if(rank==3){
       point.x=15; point.y=23; point.z=6;
       MPI_Send(&point,1,ptype,1,52,MPI_COMM_WORLD);
    } else if(rank==1) {
       MPI_Recv(&point,1,ptype,3,52,MPI_COMM_WORLD,&status);
       printf("P:%d received coords are (%d,%d,%d) \n",rank,point.x,point.y,point.z);
    }
    MPI_Finalize();
 }
```

```
Program Output:
P:1 received coords are (15,23,6)
```

Sample Program #2 - Fortran

```
      PROGRAM contiguous
C Run with four processes
      INCLUDE 'mpif.h'
      INTEGER err, rank, size
      integer status(MPI_STATUS_SIZE)
      integer x,y,z
      common/point/x,y,z
      integer ptype
      CALL MPI_INIT(err)
      CALL MPI_COMM_RANK(MPI_COMM_WORLD,rank,err)
      CALL MPI_COMM_SIZE(MPI_COMM_WORLD,size,err)
      call MPI_TYPE_CONTIGUOUS(3,MPI_INTEGER,ptype,err)
      call MPI_TYPE_COMMIT(ptype,err)
      print *,rank,size
      if(rank.eq.3) then
         x=15
         y=23
         z=6
         call MPI_SEND(x,1,ptype,1,30,MPI_COMM_WORLD,err)
        else if(rank.eq.1)then
         call MPI_RECV(x,1,ptype,3,30,MPI_COMM_WORLD,status,err)
         print *,'P:',rank,' coords are ',x,y,z
        end if
      CALL MPI_FINALIZE(err)
      END
```

```
Program Output
P:1 coords are 15, 23, 6
```

Vector Datatype

- User completely specifies memory locations defining the **vector**

C:

```
int MPI_Type_vector(int count, int blocklength, int stride,
MPI_Datatype oldtype, MPI_Datatype *newtype)
```

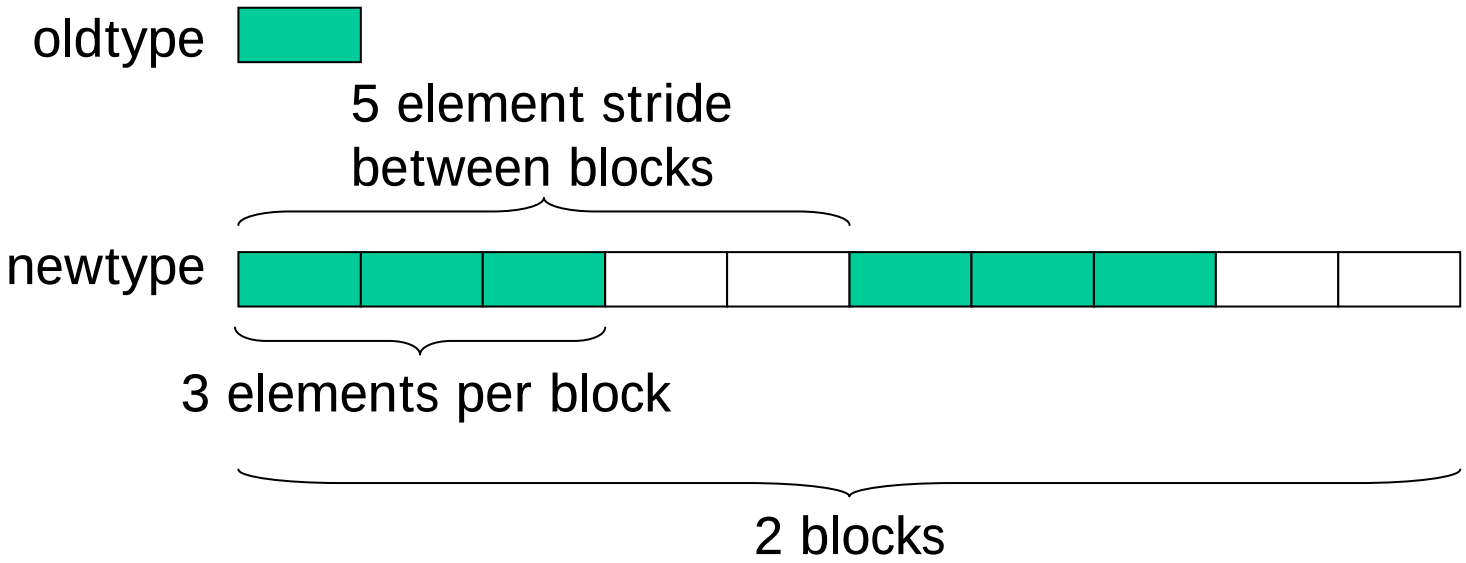
Fortran:

```
CALL MPI_TYPE_VECTOR(COUNT, BLOCKLENGTH, STRIDE,
                     OLDTYPE, NEWTYPE, IERROR)
```

- *newtype* has *count* blocks each consisting of *blocklength* copies of *oldtype*

- Displacement between blocks is set by *stride*

Vector Datatype Example



- count = 2
- stride = 5
- blocklength = 3

Sample Program #3 - C

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

 void main(int argc, char *argv[]) {
    int rank,i,j;
    MPI_Status status;
    double x[4][8];
    MPI_Datatype coltype;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD,&rank);
    MPI_Type_vector(4,1,8,MPI_DOUBLE,&coltype);
    MPI_Type_commit(&coltype);
    if(rank==3){
      for(i=0;i<4;++i)
       for(j=0;j<8;++j) x[i][j]=pow(10.0,i+1)+j;
      MPI_Send(&x[0][7],1,coltype,1,52,MPI_COMM_WORLD);
    } else if(rank==1) {
       MPI_Recv(&x[0][2],1,coltype,3,52,MPI_COMM_WORLD,&status);
       for(i=0;i<4;++i)printf("P:%d my x[%d][2]=%1f\n",rank,i,x[i][2]);
    }
    MPI_Finalize();
 }
```

```
      Program Output
P:1 my x[0][2]=17.000000
P:1 my x[1][2]=107.000000
P:1 my x[2][2]=1007.000000
P:1 my x[3][2]=10007.000000
```

Sample Program #3 - Fortran

```
      PROGRAM vector
C Run with four processes
      INCLUDE 'mpif.h'
      INTEGER err, rank, size
      integer status(MPI_STATUS_SIZE)
      real x(4,8)
      integer rowtype
      CALL MPI_INIT(err)
      CALL MPI_COMM_RANK(MPI_COMM_WORLD,rank,err)
      CALL MPI_COMM_SIZE(MPI_COMM_WORLD,size,err)
      call MPI_TYPE_VECTOR(8,1,4,MPI_REAL,rowtype,err)
      call MPI_TYPE_COMMIT(rowtype,err)
      if(rank.eq.3) then
        do i=1,4
         do j=1,8
          x(i,j)=10.0**i+j
         end do
        enddo
         call MPI_SEND(x(2,1),1,rowtype,1,30,MPI_COMM_WORLD,err)
        else if(rank.eq.1)then
         call MPI_RECV(x(4,1),1,rowtype,3,30,MPI_COMM_WORLD,status,err)
         print *,'P:',rank,' the 4th row of x is'
         do i=1,8
          print*,x(4,i)
         end do
        end if
      CALL MPI_FINALIZE(err)
      END
```

```
      Program Output
P:1 the 4th row of x is
101.
102.
103.
104.
105.
106.
107.
108.
```

Extent of a Datatype

- Handy utility function for datatype construction
- Extent defined to be the memory span (in bytes) of a datatype

C:

```
MPI_Type_extent (MPI_Datatype datatype, MPI_Aint* extent)
```

Fortran:

```
CALL MPI_TYPE_EXTENT (DATATYPE, EXTENT, IERROR)

INTEGER       DATATYPE, EXTENT, IERROR
```

Structure Datatype

- Use for variables comprised of heterogeneous datatypes
  - C structures
  - Fortran common blocks
- This is the most general derived data type

C:

```
int MPI_Type_struct (int count, int *array_of_blocklengths,
                     MPI_Aint *array_of_displacements,
                     MPI_Datatype *array_of_types,
                     MPI_Datatype *newtype)
```

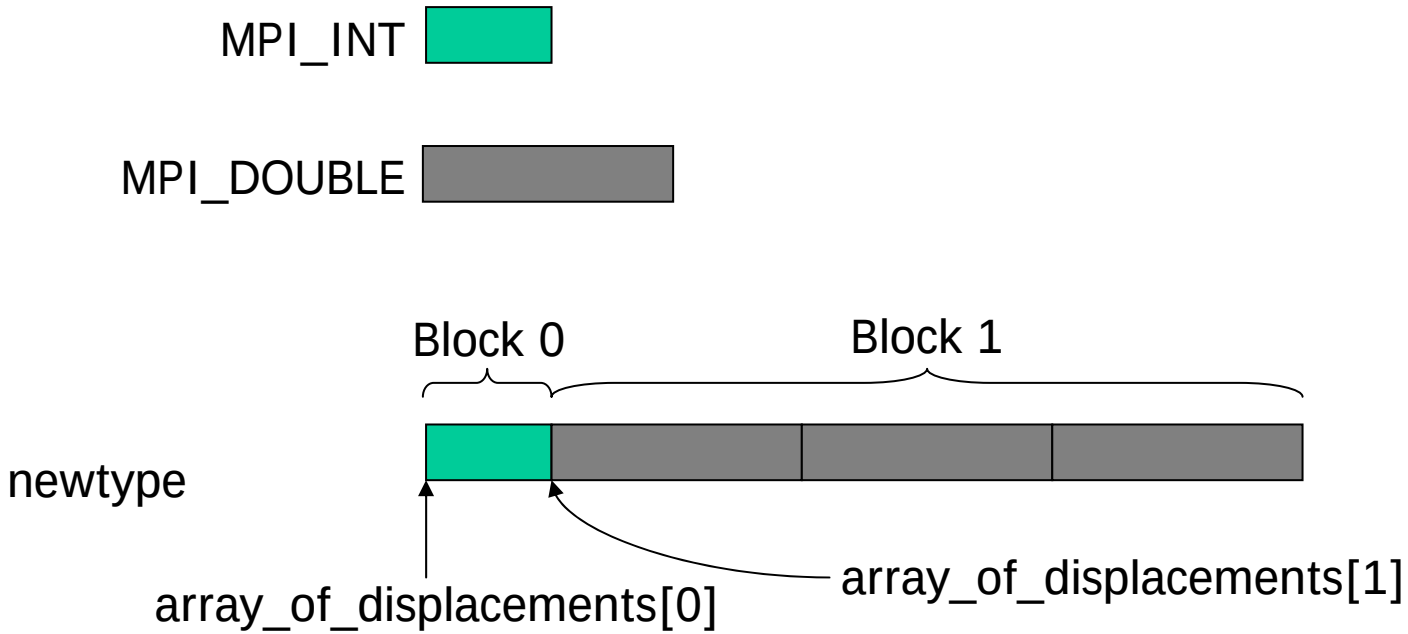
Fortran:

```
CALL MPI_TYPE_STRUCT(COUNT,ARRAY_OF_BLOCKLENGTHS,
                     ARRAY_OF_DISPLACEMENTS,ARRAY_OF_TYPES,
                     NEWTYPE,IERROR)
```

Structure Datatype (cont)

- *Newtype* consists of `count` blocks where the ith block is `array_of_blocklengths[i]` copies of the type `array_of_types[i]`. The displacement of the ith block (in bytes) is given by `array_of_displacements[i]`.

Struct Datatype Example



- `count = 2`
- `array_of_blocklengths = {1,3}`
- `array_of_types = {MPI_INT, MPI_DOUBLE}`
- `array_of_displacements = {0, extent(MPI_INT)}`

Sample Program #4 - C

```
#include <stdio.h>
#include<mpi.h>
void main(int argc, char *argv[]) {
 int rank,i;
 MPI_Status status;
 struct {
    int num;
    float x;
    double data[4];
   } a;
   int blocklengths[3]={1,1,4};
   MPI_Datatype types[3]={MPI_INT,MPI_FLOAT,MPI_DOUBLE};
   MPI_Aint displacements[3];
   MPI_Datatype restype;
   MPI_Aint intex,floatex;
   MPI_Init(&argc,&argv);
   MPI_Comm_rank(MPI_COMM_WORLD,&rank);
   MPI_Type_extent(MPI_INT,&intex);MPI_Type_extent(MPI_FLOAT,&floatex);
   displacements[0]= (MPI_Aint) 0; displacemtnts[1]=intex;
   displacements[2]=intex+floatex;
   MPI_Type_struct(3,blocklengths,displacements,types,&restype);
```

Sample Program #4 - C (cont.)

```
...
   MPI_Type_commit(&restype);
   if (rank==3){
      a.num=6; a.x=3.14; for(i=0;i 4;++i) a.data[i]=(double) i;
      MPI_Send(&a,1,restype,1,52,MPI_COMM_WORLD);
   } else if(rank==1) {
      MPI_Recv(&a,1,restype,3,52,MPI_COMM_WORLD,&status);
      printf("P:%d my a is %d %f %lf %lf %lf %lf\n",
             rank,a.num,a.x,a.data[0],a.data[1],a.data[2],a.data[3]);
    }
    MPI_Finalize();
}
```

Program output

```
P:1 my a is 6 3.140000 0.000000 1.000000 2.000000 3.000002
```

Sample Program #4 - Fortran

```
PROGRAM structure
INCLUDE 'mpif.h'
INTEGER err, rank, size
integer status(MPI_STATUS_SIZE)
integer num
real x
complex data(4)
common /result/num,x,data
integer blocklengths(3)
data blocklengths/1,1,4/
integer displacements(3)
integer types(3),restype
data types/MPI_INTEGER,MPI_REAL,MPI_COMPLEX/
integer intex,realex
CALL MPI_INIT(err)
CALL MPI_COMM_RANK(MPI_COMM_WORLD,rank,err)
CALL MPI_COMM_SIZE(MPI_COMM_WORLD,size,err)
call MPI_TYPE_EXTENT(MPI_INTEGER,intex,err)
call MPI_TYPE_EXTENT(MPI_REAL,realex,err)
displacements(1)=0
displacements(2)=intex
displacements(3)=intex+realex
```

Sample Program #4 - Fortran (cont.)

```
 call MPI_TYPE_STRUCT(3,blocklengths, displacements,types,
&                     restype,err)
 call MPI_TYPE_COMMIT(restype,err)
 if(rank.eq.3) then
   num=6
   x=3.14
   do i=1,4
    data(i)=cmplx(i,i)
   end do
   call MPI_SEND(num,1,restype,1,30,MPI_COMM_WORLD,err)
  else if(rank.eq.1)then
   call MPI_RECV(num,1,restype,3,30,MPI_COMM_WORLD,status,err)
   print*,'P:',rank,' I got'
   print*,num
   print*,x
   print*,data
  end if
 CALL MPI_FINALIZE(err)
 END
```

```
          Program Output
P:1 I got
6
3.1400001
(1.,1.), (2.,2.), (3.,3.), (4.,4.)
```

Committing a Datatype

- Once a datatype has been constructed, it needs to be committed before it is used.
- This is done using `MPI_TYPE_COMMIT`

C:

```
int MPI_Type_commit (MPI_Datatype *datatype)
```

Fortran:

```
CALL MPI_TYPE_COMMIT (DATATYPE, IERROR)
```

Class Exercise: “Structured” Ring

- Modify the calculating ring exercise
- Calculate two separate sums:
  - rank integer sum, as before
  - rank floating point sum
- Use and MPI structure datatype in this problem

Extra Exercise: Matrix Block

- Write and MPI program where two processes exchange a sub-array (corner, boundary, etc) of a two-dimensional array. How does the time taken for one message vary as a function of sub-array size?

Collective Communication

- Collective Communication
- Barrier Synchronization
- Broadcast*
- Scatter*
- Gather
- Gather/Scatter Variations
- Summary Illustration
- Global Reduction Operations
- Predefined Reduction Operations
- MPI_Reduce
- Minloc and Maxloc*
- User-defined Reduction Operators
- Reduction Operator Functions
- Registering a User-defined Reduction Operator*
- Variants of MPI_Reduce
- Class Exercise: Last Ring

*includes sample C and Fortran programs

Collective Communication

- Communications involving a group of processes
- Called by *all* processes in a communicator
- Examples:
  - Broadcast, scatter, gather (Data Distribution)
  - Global sum, global maximum, etc. (Collective Operations)
  - Barrier synchronization

Characteristics of Collective Communication

- Collective communication will not interfere with point-to-point communication and vice-versa
- All processes must call the collective routine
- Synchronization not guaranteed (except for barrier)
- No non-blocking collective communication
- No tags
- Receive buffers must be exactly the right size

Barrier Synchronization

- Red light for each processor: turns green when all processors have arrived
- Slower than hardware barriers (example: SGI/Cray T3E)

C:

```
int MPI_Barrier (MPI_Comm comm)
```

Fortran:

```
CALL MPI_BARRIER (COMM,IERROR)
INTEGER COMM,IERROR
```

Broadcast

- One-to-all communication: same data sent from root process to all the others in the communicator

- C:

```
int MPI_Bcast (void *buffer, int, count,
  MPI_Datatype datatype,int root, MPI_Comm comm)
```

- Fortran:

```
MPI_BCAST(BUFFER, COUNT, DATATYPE, ROOT, COMM IERROR)

<type> BUFFER (*)
INTEGER COUNT, DATATYPE, ROOT, COMM, IERROR
```

- All processes must specify same root rank and communicator

Sample Program #5 - C

```
#include<mpi.h>
void main (int argc, char *argv[]) {
  int rank;
  double param;
  MPI_Init(&argc, &argv);
  MPI_Comm_rank(MPI_COMM_WORLD,&rank);
  if(rank==5) param=23.0;
  MPI_Bcast(&param,1,MPI_DOUBLE,5,MPI_COMM_WORLD);
  printf("P:%d after broadcast parameter is %f\n",rank,param);
  MPI_Finalize();
}
```

```
                Program Output
P:0 after broadcast parameter is 23.000000
P:6 after broadcast parameter is 23.000000
P:5 after broadcast parameter is 23.000000
P:2 after broadcast parameter is 23.000000
P:3 after broadcast parameter is 23.000000
P:7 after broadcast parameter is 23.000000
P:1 after broadcast parameter is 23.000000
P:4 after broadcast parameter is 23.000000
```

Sample Program #5 - Fortran

```
PROGRAM broadcast
INCLUDE 'mpif.h'
INTEGER err, rank, size
real param
CALL MPI_INIT(err)
CALL MPI_COMM_RANK(MPI_WORLD_COMM,rank,err)
CALL MPI_COMM_SIZE(MPI_WORLD_COMM,size,err)
if(rank.eq.5) param=23.0
call MPI_BCAST(param,1,MPI_REAL,5,MPI_COMM_WORLD,err)
print *,"P:",rank," after broadcast param is ",param
CALL MPI_FINALIZE(err)
END
```

```
            Program Output
P:1 after broadcast parameter is 23.
P:3 after broadcast parameter is 23.
P:4 after broadcast parameter is 23
P:0 after broadcast parameter is 23
P:5 after broadcast parameter is 23.
P:6 after broadcast parameter is 23.
P:7 after broadcast parameter is 23.
P:2 after broadcast parameter is 23.
```

Scatter

- One-to-all communication: different data sent to each process in the communicator (in rank order)

C:

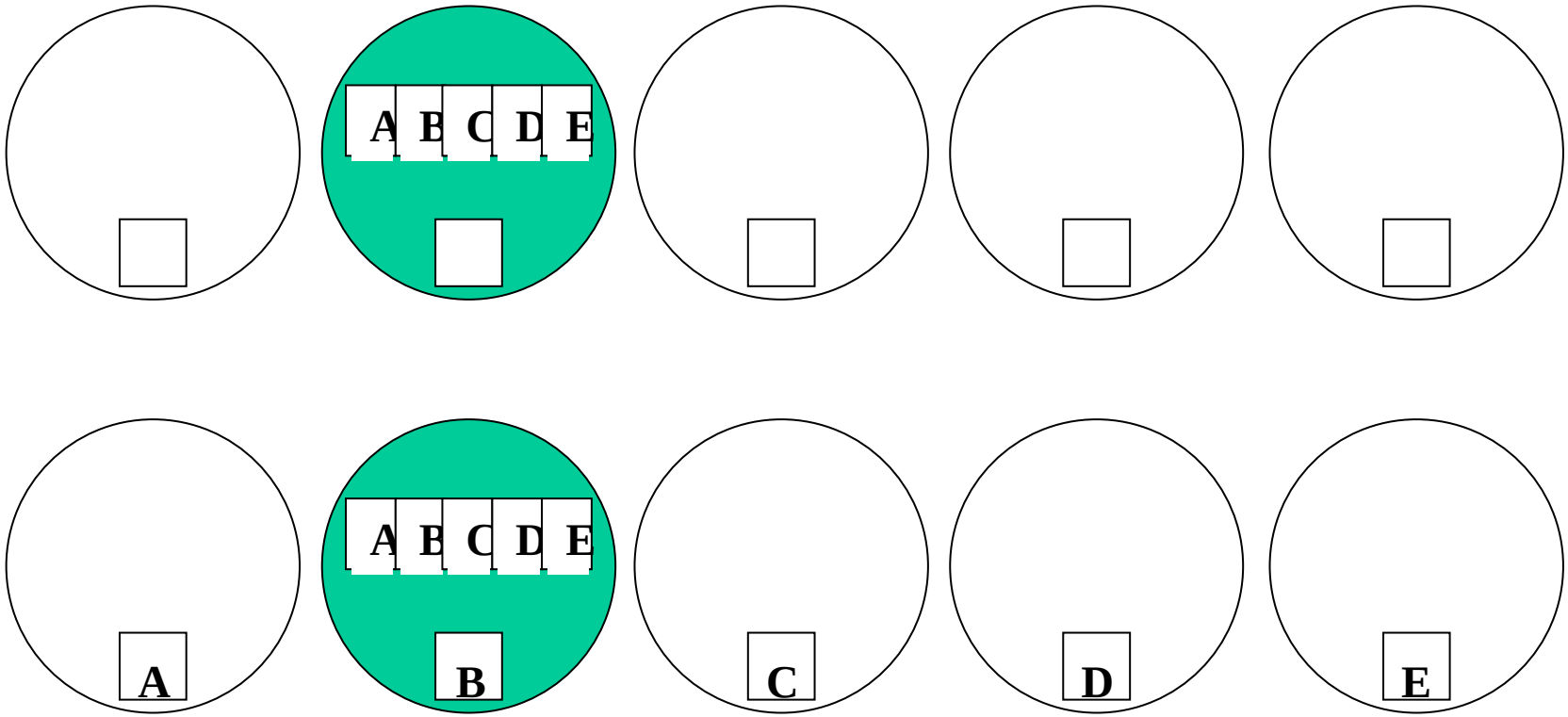
```
int MPI_Scatter(void* sendbuf, int sendcount,
        MPI_Datatype sendtype, void* recvbuf, int recvcount,
        MPI_Datatype recvtype, int root, MPI_Comm comm)
```

Fortran:

```
CALL MPI_SCATTER(SENDBUF, SENDCOUNT, SENDTYPE, RECVBUF,
        RECVCOUNT, RECVTYPE, ROOT, COMM, IERROR)
<type> SENDBUF(*), RECVBUF(*)
```

- `sendcount` is the number of elements sent to each process, not the "total" number sent
  - send arguments are significant only at the root process

Scatter Example



Sample Program #6 - C

```
#include <mpi.h>
 void main (int argc, char *argv[]) {
    int rank,size,i,j;
    double param[4],mine;
    int sndcnt,revcnt;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD,&rank);
    MPI_Comm_size(MPI_COMM_WORLD,&size);
    revcnt=1;
    if(rank==3){
       for(i=0;i<4;i++) param[i]=23.0+i;
       sndcnt=1;
    }
    MPI_Scatter(param,sndcnt,MPI_DOUBLE,&mine,revcnt,MPI_DOUBLE,3,MPI_COMM_WORLD);
    printf("P:%d mine is %f\n",rank,mine);
    MPI_Finalize();
 }
```

```
      Program Output
P:0 mine is 23.000000
P:1 mine is 24.000000
P:2 mine is 25.000000
P:3 mine is 26.000000
```

Sample Program #6 - Fortran

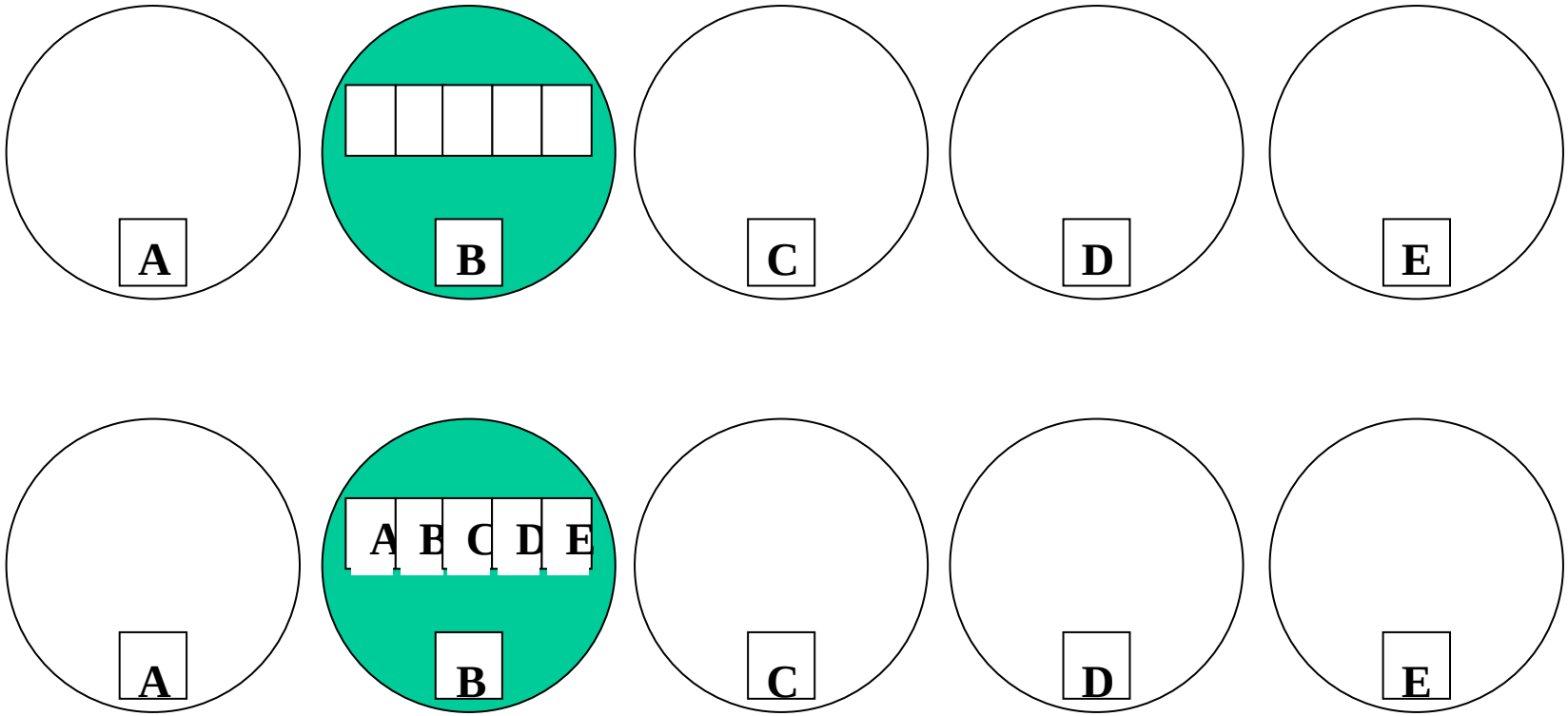
```
 PROGRAM scatter
 INCLUDE 'mpif.h'
 INTEGER err, rank, size
 real param(4), mine
 integer sndcnt,rcvcnt
 CALL MPI_INIT(err)
 CALL MPI_COMM_RANK(MPI_WORLD_COMM,rank,err)
 CALL MPI_COMM_SIZE(MPI_WORLD_COMM,size,err)
 rcvcnt=1
 if(rank.eq.3) then
    do i=1,4
       param(i)=23.0+i
    end do
    sndcnt=1
 end if
 call MPI_SCATTER(param,sndcnt,MPI_REAL,mine,rcvcnt,MPI_REAL,
&            3,MPI_COMM_WORLD,err)
 print *,"P:",rank," mine is ",mine
 CALL MPI_FINALIZE(err)
 END
```

```
   Program Output
P:1 mine is 25.
P:3 mine is 27.
P:0 mine is 24.
P:2 mine is 26.
```

Gather

- All-to-one communication: different data collected by root process
  - Collection done in rank order
- `MPI_GATHER` & `MPI_Gather` have same arguments as matching scatter routines
- Receive arguments only meaningful at the root process

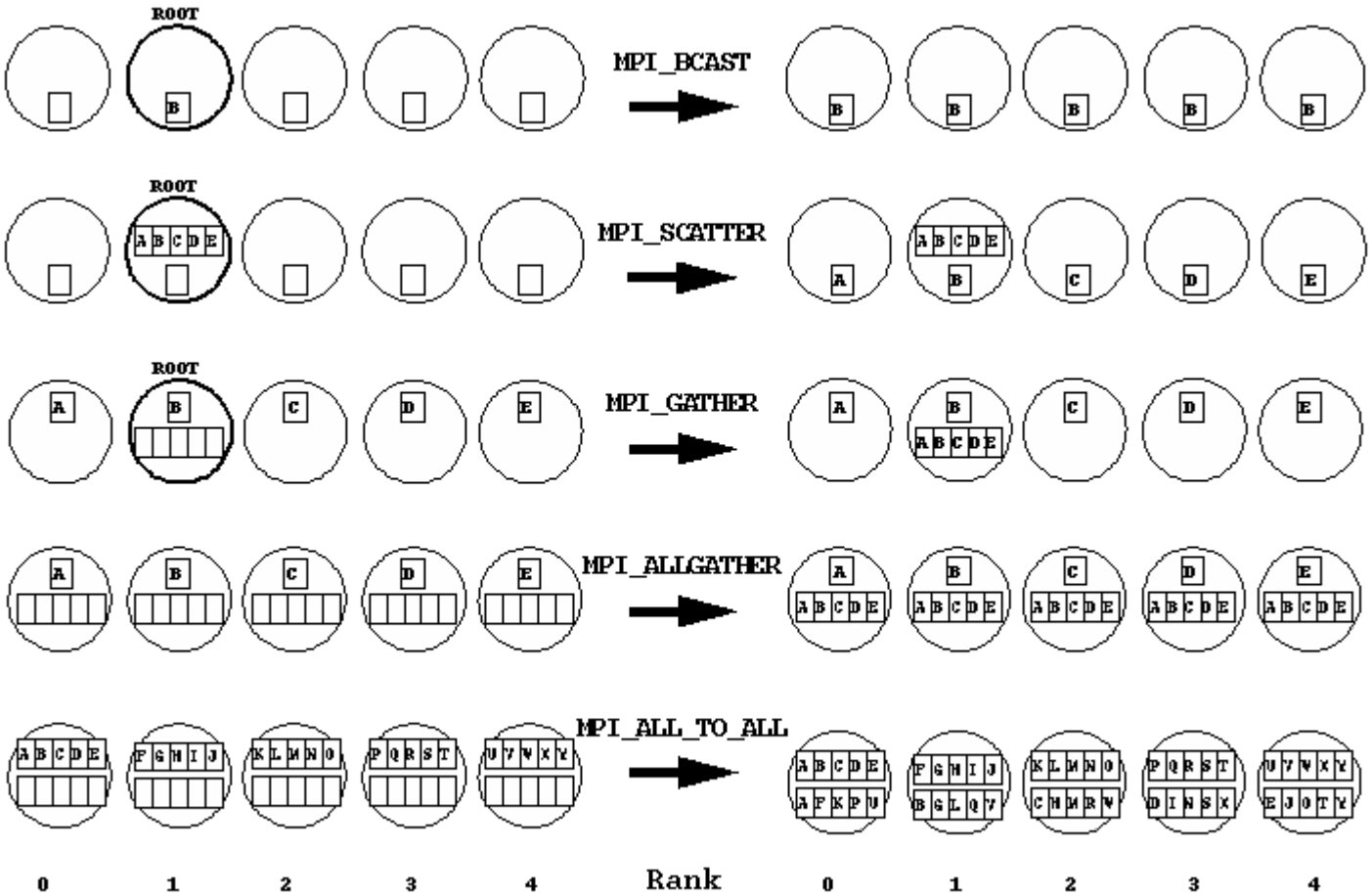
Gather Example



Gather/Scatter Variations

- `MPI_Allgather`
- `MPI_Alltoall`
- No root process specified: all processes get gathered or scattered data
- Send and receive arguments significant for all processes

Summary


ROOT
MPI_BCAST
ROOT
MPI_SCATTER
ROOT
MPI_GATHER
MPI_ALLGATHER
MPI_ALL_TO_ALL
Rank
0
1
2
3
4

Global Reduction Operations

- Used to compute a result involving data distributed over a group of processes
- Examples:
  - Global sum or product
  - Global maximum or minimum
  - Global user-defined operation

Example of Global Reduction

- Sum of all the `x` values is placed in `result` only on processor 0

C:

```
int MPI_Barrier (MPI_Comm comm)
```

Fortran:

```
CALL MPI_BARRIER (COMM,IERROR)
INTEGER COMM,IERROR
```

Predefined Reduction Operations

MPI Name	Function
MPI_MAX	Maximum
MPI_MIN	Minimum
MPI_SUM	Sum
MPI_PROD	Product
MPI_LAND	Logical AND
MPI_BAND	Bitwise AND
MPI_LOR	Logical OR
MPI_BOR	Bitwise OR
MPI_LXOR	Logical exclusive OR
MPI_BXOR	Bitwise exclusive OR
MPI_MAXLOC	Maximum and location
MPI_MINLOC	Minimum and location

General Form

- `count` is the number of "*ops*" done on consecutive elements of `sendbuf` (it is also size of `recvbuf`)

- `op` is an associative operator that takes two operands of type `datatype` and returns a result of the same type

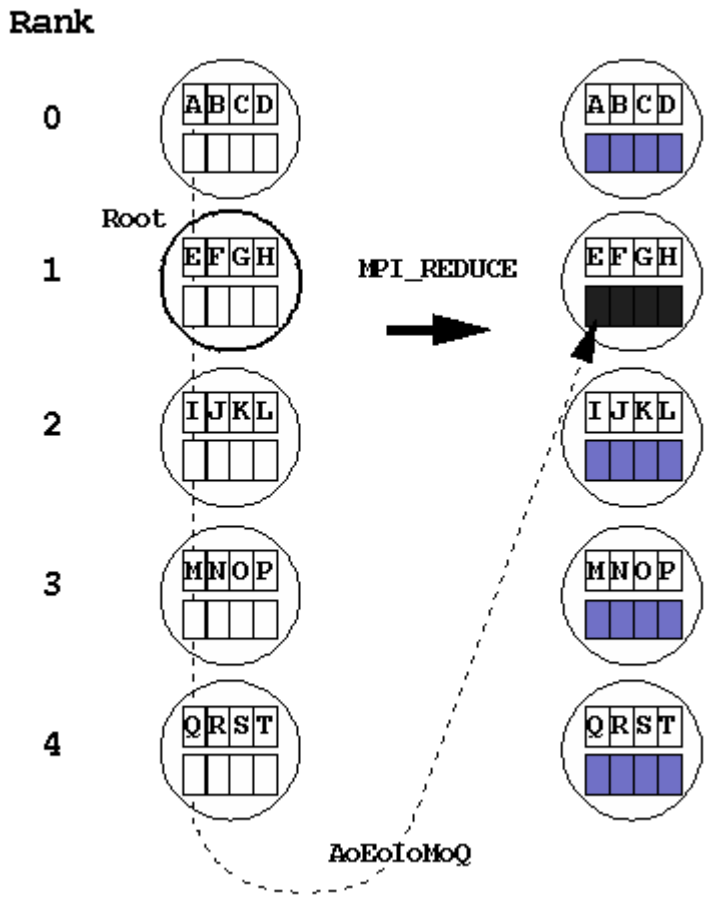
C:

```
int MPI_Reduce(void* sendbuf, void* recvbuf, int count,
               MPI_Datatype datatype, MPI_Op op, int root,
               MPI_Comm comm)
```

Fortran:

```
CALL MPI_REDUCE(SENDBUF,RECVBUF,COUNT,DATATYPE,OP,ROOT,COMM,IERROR)
<type> SENDBUF(*), RECVBUF(*)
```

MPI_Reduce


Rank
0
1
2
3
4
Root
A B C D
E F G H
I J K L
M N O P
Q R S T
MPI_REDUCE
A B C D
E F G H
I J K L
M N O P
Q R S T
AoEoIoMoQ

Minloc and Maxloc

- Designed to compute a global minimum/maximum and and index associated with the extreme value
  - Common application: index is the processor rank (see sample program)
- If more than one extreme, get the first
- Designed to work on operands that consist of a value and index pair
- `MPI_Datatypes` include:

C:

```
MPI_FLOAT_INT, MPI_DOUBLE_INT, MPI_LONG_INT, MPI_2INT,
   MPI_SHORT_INT, MPI_LONG_DOUBLE_INT
```

Fortran:

```
MPI_2REAL, MPI_2DOUBLEPRECISION, MPI_2INTEGER
```

Sample Program #7 - C

```
#include <mpi.h>
/* Run with 16 processes */
void main (int argc, char *argv[]) {
   int rank;

   struct {
     double value;
     int rank;
   } in, out;

   int root;
   MPI_Init(&argc, &argv);
   MPI_Comm_rank(MPI_COMM_WORLD,&rank);

   in.value=rank+1;
   in.rank=rank;
   root=7;

   MPI_Reduce(&in,&out,1,MPI_DOUBLE_INT,MPI_MAXLOC,root,MPI_COMM_WORLD);
   if(rank==root) printf("PE:%d max=%lf at rank %d\n",rank,out.value,out.rank);
   MPI_Reduce(&in,&out,1,MPI_DOUBLE_INT,MPI_MINLOC,root,MPI_COMM_WORLD);
   if(rank==root) printf("PE:%d min=%lf at rank %d\n",rank,out.value,out.rank);
   MPI_Finalize();
}
```

```
        Program Output
P:7 max=16.000000 at rank 15
P:7 max=1.000000 at rank 0
```

Sample Program #7 - Fortran

```
      PROGRAM MaxMin
C
C Run with 8 processes
C
      INCLUDE 'mpif.h'
      INTEGER err, rank, size
      integer in(2),out(2)
      CALL MPI_INIT(err)
      CALL MPI_COMM_RANK(MPI_WORLD_COMM,rank,err)
      CALL MPI_COMM_SIZE(MPI_WORLD_COMM,size,err)
      in(1)=rank+1
      in(2)=rank
      call MPI_REDUCE(in,out,1,MPI_2INTEGER,MPI_MAXLOC,
     &                7,MPI_COMM_WORLD,err)

      if(rank.eq.7) print *,"P:",rank," max=",out(1)," at rank ",out(2)

      call MPI_REDUCE(in,out,1,MPI_2INTEGER,MPI_MINLOC,
     &                2,MPI_COMM_WORLD,err)

      if(rank.eq.2) print *,"P:",rank," min=",out(1)," at rank ",out(2)

      CALL MPI_FINALIZE(err)
      END
```

```
    Program Output
P:2 min=1 at rank 0
P:7 max=8 at rank 7
```

User-Defined Reduction Operators

- Reducing using an arbitrary operator χ

C -- function of type `MPI_User_function`:

```
void my_operator (void *invec, void *inoutvec, int *len,
                  MPI_Datatype *datatype)
```

Fortran -- function of type:

```
FUNCTION MY_OPERATOR (INVEC(*), INOUTVEC(*), LEN, DATATYPE)

<type> INVEC(LEN),INOUTVEC(LEN)
INTEGER LEN,DATATYPE
```

Reduction Operator Functions

- Operator function for χ must act as:

```
for (i=1 to len)
      inoutvec(i) = inoutvec(i) χ invec(i)
```

- Operator χ need not commute
- `inoutvec` argument acts as both a second input operand as well as the output of the function

Registering a User-Defined Reduction Operator

- Operator handles have type `MPI_Op` or `INTEGER`
- If `commute` is TRUE, reduction may be performed faster

C:

```
int MPI_Op_create (MPI_User_function *function, int commute,
                   MPI_Op *op)
```

Fortran:

```
MPI_OP_CREATE (FUNC, COMMUTE, OP, IERROR)

EXTERNAL FUNC
INTEGER OP,IERROR
LOGICAL COMMUTE
```

Sample Program #8 - C

```
#include <mpi.h>
 typedef struct {
    double real,imag;
 } complex;

 void cprod(complex *in, complex *inout, int *len, MPI_Datatype *dptr) {
    int i;
    complex c;
    for (i=0; i<*len; ++i) {
       c.real=(*in).real * (*inout).real - (*in).imag * (*inout).imag;
       c.imag=(*in).real * (*inout).imag + (*in).imag * (*inout).real;
       *inout=c;
       in++;
       inout++;
    }
 }

 void main (int argc, char *argv[]) {
    int rank;
    int root;
    complex source,result;
```

Sample Program #8 - C (cont.)

```
   MPI_Op myop;
   MPI_Datatype ctype;
   MPI_Init(&argc, &argv);
   MPI_Comm_rank(MPI_COMM_WORLD,&rank);

   MPI_Type_contiguous(2,MPI_DOUBLE,&ctype);
   MPI_Type_commit(&ctype);
   MPI_Op_create(cprod,TRUE,&myop);
   root=2;
   source.real=rank+1;
   source.imag=rank+2;
   MPI_Reduce(&source,&result,1,ctype,myop,root,MPI_COMM_WORLD);
   if(rank==root) printf ("PE:%d result is %lf + %lfi\n",rank, result.real, result.imag);
   MPI_Finalize();
}

-----------------------------------------

P:2 result is -185.000000 + -180.000000i
```

Sample Program #8 - Fortran

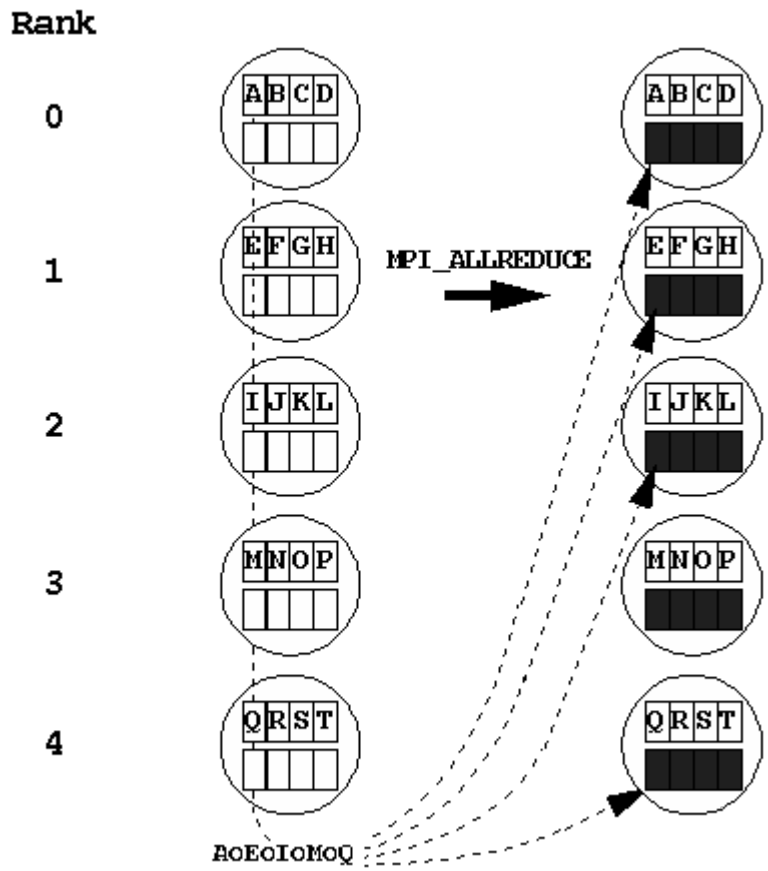
```
PROGRAM UserOP
  INCLUDE 'mpif.h'
  INTEGER err, rank, size
  integer source, reslt
  external digit
  logical commute
  integer myop
  CALL MPI_INIT(err)
  CALL MPI_COMM_RANK(MPI_WORLD_COMM,rank,err)
  CALL MPI_COMM_SIZE(MPI_WORLD_COMM,size,err)
  commute=.true.
  call MPI_OP_CREATE(digit,commute,myop,err)
  source=(rank+1)**2
  call MPI_BARRIER(MPI_COM_WORLD,err)
  call MPI_SCAN(source,reslt,1,MPI_INTEGER,myop,MPI_COMM_WORLD,err)
  print *,"P:",rank," my result is ",reslt
  CALL MPI_FINALIZE(err)
END
integer function digit(in,inout,len,type)
  integer in(len),inout(len)
  integer len,type
  do i=1,len
      inout(i)=mod((in(i)+inout(i)),10)
  end do
  digit = 5
end
```

```
     Program Output
P:6 my result is 0
P:5 my result is 1
P:7 my result is 4
P:1 my result is 5
P:3 my result is 0
P:2 my result is 4
P:4 my result is 5
P:0 my result is 1
```

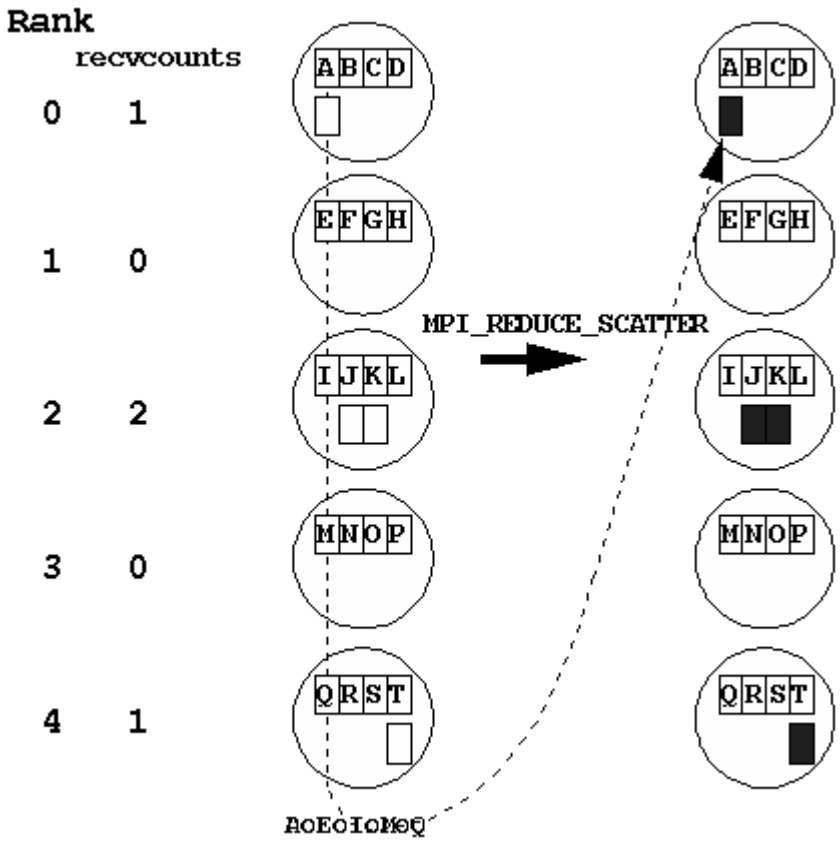
Variants of MPI_REDUCE

- `MPI_ALLREDUCE` -- no root process (all get results)
- `MPI_REDUCE_SCATTER` -- multiple results are scattered
- `MPI_SCAN` -- “parallel prefix”

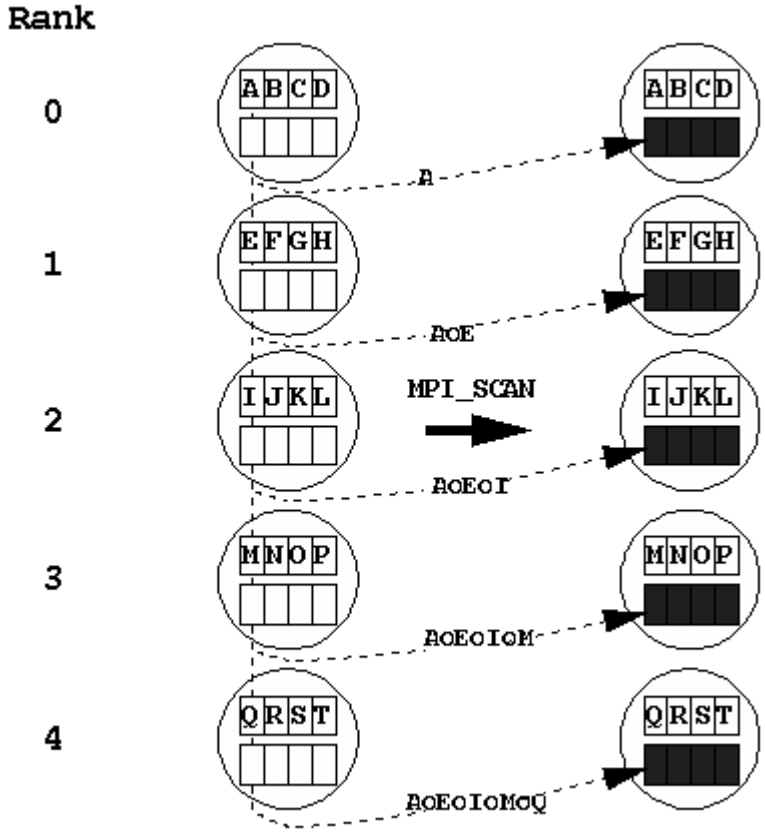
MPI_ALLREDUCE



MPI_REDUCE_SCATTER



MPI_SCAN


Rank
0
1
2
3
4
A B C D
E F G H
I J K L
M N O P
Q R S T
MPI_SCAN
A
AoE
AoEoI
AoEoIoM
AoEoIoMoQ

Class Exercise: Last Ring

- Rewrite the “Structured Ring” program to use MPI global reduction to perform its global sums
- Extra credit: Rewrite it so that each process computes a partial sum
- Extra extra credit: Rewrite this so that each process prints out its partial result in rank order

Virtual Topologies

- Virtual Topologies
- Topology Types
- Creating a Cartesian Virtual Topology
- Cartesian Example
- Cartesian Mapping Functions
  - MPI_CART_RANK*
  - MPI_CART_COORDS*
  - MPI_CART_SHIFT*
- Cartesian Partitioning
- Exercise

*includes sample C and Fortran programs

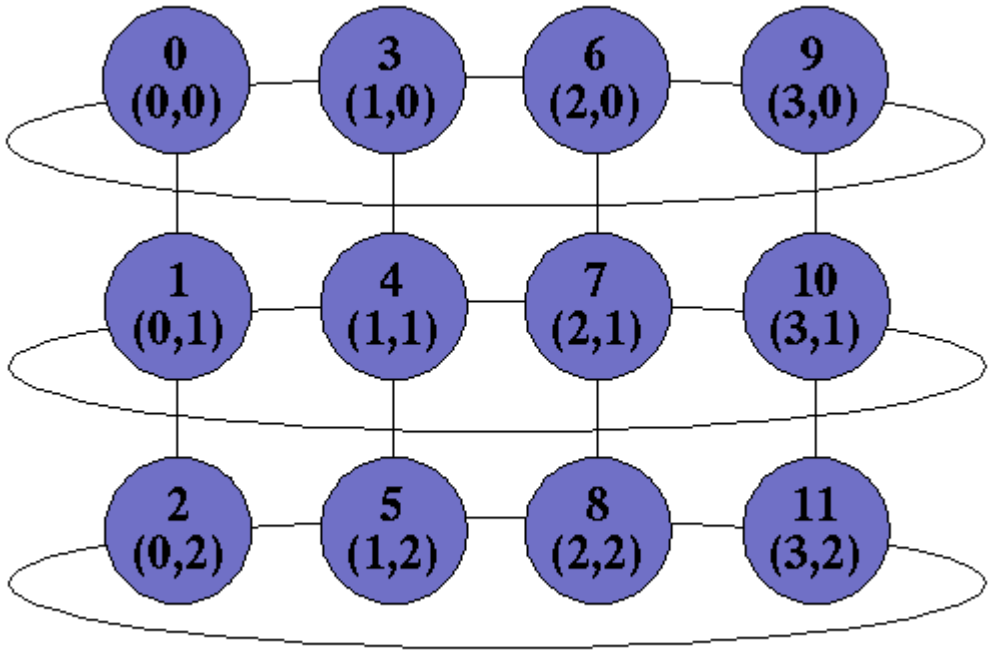
Virtual Topologies

- Convenient process naming
- Naming scheme to fit the communication pattern
- Simplifies writing of code
- Can allow MPI to optimize communications
- Rationale: access to useful topology routines

How to use a Virtual Topology

- Creating a topology produces a new communicator
- MPI provides “mapping functions”
- Mapping functions compute processor ranks, based on the topology naming scheme

Example - 2D Torus



Topology types

- Cartesian topologies
  - Each process is connected to its neighbors in a virtual grid
  - Boundaries can be cyclic
  - Processes can be identified by cartesian coordinates
- Graph topologies
  - General graphs
  - Will not be covered here

Creating a Cartesian Virtual Topology

C:

```
int MPI_Cart_create (MPI_Comm comm_old, int ndims,
                     int *dims, int *periods, int reorder,
                     MPI_Comm *comm_cart)
```

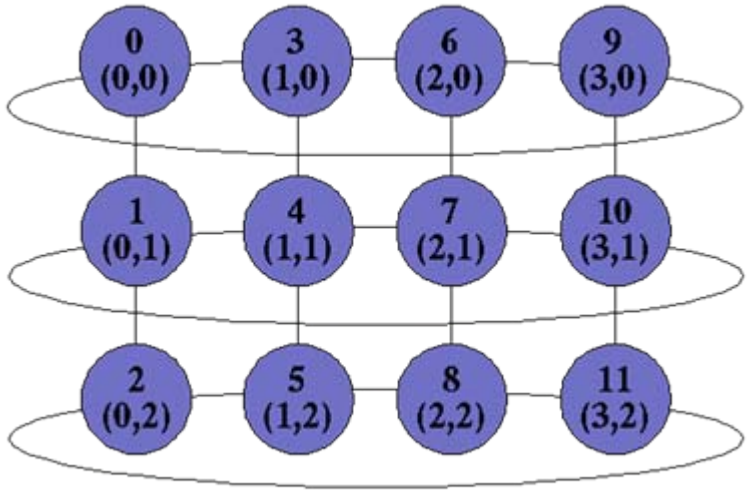
Fortran:

```
CALL MPI_CART_CREATE(COMM_OLD,NDIMS,DIMS,PERIODS,REORDER,
                     COMM_CART,IERROR)

INTEGER      COMM_OLD,NDIMS,DIMS(*),COMM_CART,IERROR
LOGICAL      PERIODS(*),REORDER
```

Arguments

comm_old	existing communicator
ndims	number of dimensions
periods	logical array indicating whether a dimension is cyclic (TRUE=>cyclic boundary conditions)
reorder	logical (FALSE=>rank preserved) (TRUE=>possible rank reordering)
comm_cart	new cartesian communicator

Cartesian Example




```
MPI_Comm vu;
int dim[2], period[2], reorder;

dim[0]=4; dim[1]=3;
period[0]=TRUE; period[1]=FALSE;
reorder=TRUE;

MPI_Cart_create(MPI_COMM_WORLD,2,dim,period,reorder,&vu);
```

Cartesian Mapping Functions

Mapping process grid coordinates to ranks

C:

```
int MPI_Cart_rank (MPI_Comm comm, init *coords, int *rank)
```

Fortran:

```
CALL MPI_CART_RANK(COMM,COORDS,RANK,IERROR)

INTEGER      COMM,COORDS(*),RANK,IERROR
```

Cartesian Mapping Functions

Mapping ranks to process grid coordinates

C:

```
int MPI_Cart_coords (MPI_Comm comm, int rank, int maxdims,
                     int *coords)
```

Fortran:

```
CALL MPI_CART_COORDS(COMM,RANK,MAXDIMS,COORDS,IERROR)

INTEGER      COMM,RANK,MAXDIMS,COORDS(*),IERROR
```

Sample Program #9 - C

```
#include<mpi.h>
/* Run with 12 processes */
 void main(int argc, char *argv[]) {
    int rank;
    MPI_Comm vu;
    int dim[2],period[2],reorder;
    int coord[2],id;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD,&rank);
    dim[0]=4; dim[1]=3;
    period[0]=TRUE; period[1]=FALSE;
    reorder=TRUE;
    MPI_Cart_create(MPI_COMM_WORLD,2,dim,period,reorder,&vu);
    if(rank==5){
      MPI_Cart_coords(vu,rank,2,coord);
      printf("P:%d My coordinates are %d %d\n",rank,coord[0],coord[1]);
    }
    if(rank==0) {
      coord[0]=3; coord[1]=1;
      MPI_Cart_rank(vu,coord,&id);
      printf("The processor at position (%d, %d) has rank %d\n",coord[0],coord[1],id);
    }
    MPI_Finalize();
 }
```

Program output

```
The processor at position (3,1) has rank 10
P:5 My coordinates are 1 2
```

Sample Program #9 - Fortran

```
      PROGRAM Cartesian
C
C Run with 12 processes
C
      INCLUDE 'mpif.h'
      INTEGER err, rank, size
      integer vu,dim(2),coord(2),id
      logical period(2),reorder
      CALL MPI_INIT(err)
      CALL MPI_COMM_RANK(MPI_COMM_WORLD,rank,err)
      CALL MPI_COMM_SIZE(MPI_COMM_WORLD,size,err)
      dim(1)=4
      dim(2)=3
      period(1)=.true.
      period(2)=.false.
      reorder=.true.
      call MPI_CART_CREATE(MPI_COMM_WORLD,2,dim,period,reorder,vu,err)
      if(rank.eq.5) then
        call MPI_CART_COORDS(vu,rank,2,coord,err)
        print*,'P:',rank,' my coordinates are',coord
      end if
      if(rank.eq.0) then
        coord(1)=3
        coord(2)=1
        call MPI_CART_RANK(vu,coord,id,err)
        print*,'P:',rank,' processor at position',coord,' is',id
        end if
      CALL MPI_FINALIZE(err)
      END
```

```
                Program Output
P:5 my coordinates are 1, 2
P:0 processor at position 3, 1 is 10
```

Cartesian Mapping Functions

Computing ranks of neighboring processes

C:

```
int MPI_Cart_shift (MPI_Comm comm, int direction, int disp,
                    int *rank_source, int *rank_dest)
```

Fortran:

```
CALL MPI_CART_SHIFT(COMM,DIRECTION,DISP,RANK_SOURCE,
                    RANK_DEST,IERROR)

INTEGER      COMM,DIRECTION,DISP,RANK_SOURCE,RANK_DEST,IERROR
```

MPI_Cart_shift

- Does not actually shift data: returns the correct ranks for a shift which can be used in subsequent communication calls
- Arguments:
  - `direction` dimension in which the shift should be made
  - `disp` length of the shift in processor coordinates (+ or -)
  - `rank_source` where calling process should receive a message **from** during the shift
  - `rank_dest` where calling process should send a message **to** during the shift
- If shift off of the topology, `MPI_Proc_null` is returned

Sample Program #10 - C

```
#include<mpi.h>
 #define TRUE 1
 #define FALSE 0
 void main(int argc, char *argv[]) {
    int rank;
    MPI_Comm vu;
    int dim[2],period[2],reorder;
    int up,down,right,left;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD,&rank);
    dim[0]=4; dim[1]=3;
    period[0]=TRUE; period[1]=FALSE;
    reorder=TRUE;
    MPI_Cart_create(MPI_COMM_WORLD,2,dim,period,reorder,&vu);
    if(rank==9){
      MPI_Cart_shift(vu,0,1,&left,&right);
      MPI_Cart_shift(vu,1,1,&up,&down);
      printf("P:%d My neighbors are r: %d d:%d 1:%d u:%d\n",rank,right,down,left,up);
    }
    MPI_Finalize();
 }
```

```
Program Output
P:9 my neighbors are r:0 d:10 1:6 u:-1
```

Sample Program #10- Fortran

```
      PROGRAM neighbors
C
C Run with 12 processes
C
      INCLUDE 'mpif.h'
      INTEGER err, rank, size
      integer vu
      integer dim(2)
      logical period(2),reorder
      integer up,down,right,left
      CALL MPI_INIT(err)
      CALL MPI_COMM_RANK(MPI_COMM_WORLD,rank,err)
      CALL MPI_COMM_SIZE(MPI_COMM_WORLD,size,err)
      dim(1)=4
      dim(2)=3
      period(1)=.true.
      period(2)=.false.
      reorder=.true.
      call MPI_CART_CREATE(MPI_COMM_WORLD,2,dim,period,reorder,vu,err)
      if(rank.eq.9) then
        call MPI_CART_SHIFT(vu,0,1,left,right,err)
        call MPI_CART_SHIFT(vu,1,1,up,down,err)
        print*,'P:',rank,' neighbors (rdlu)are',right,down,left,up
      end if
      CALL MPI_FINALIZE(err)
      END
```

```
Program Output
P:9 neighbors (rdlu) are 0, 10, 6, -1
```

Cartesian Partitioning

- Often we want to do an operation on only part of an existing cartesian topology
- Cut a grid up into ‘slices’
- A new communicator is produced for each slice
- Each slice can then perform its own collective communications
- `MPI_Cart_sub` and `MPI_CART_SUB` generate new communicators for the slice

MPI_Cart_sub

C:

```
int MPI_Cart_sub (MPI_Comm comm, int *remain_dims,
                  MPI_Comm *newcomm)
```

Fortran:

```
CALL MPI_CART_SUB(COMM,REMAIN_DIMS,NEWCOMM,IERROR)

INTEGER      COMM,NEWCOMM,IERROR
LOGICAL      REMAIN_DIMS(*)
```

- If comm is a 2x3x4 grid and remain_dims={TRUE,FALSE,TRUE}, then three new communicators are created each being a 2x4 grid
- Calling processor receives back only the new communicator it is in

Class Exercise: Ring Topology

- Rewrite the “Calculating Ring” exercise using a Cartesian Topology
- Extra credit: Extend the problem to two dimensions. Each row of the grid should compute its own separate sum