Introduction to Code Parallelization Using MPI (Part I)

Ping Luo

TAMU HPRC

HIGH PERFORMANCE RESEARCH COMPUTING
TEXAS A&M UNIVERSITY

September 24, 2017

HPRC Short Course – Fall 2017

Outline

- Why parallel programming
- Parallel programming models
  - OpenMP for Shared Memory System
  - MPI for Distributed Memory System
  - MPI+OpenMP for hybrid systems
- Layout of an MPI program
- Compiling and running an MPI program
- Basic MPI concepts
  - size, rank, communicator, message, MPI datatype, tag
- Point-to-point communication
- Collective communication

Why Parallel Programming

- The semiconductor industry has long ago switched from boosting a single core CPU performance to producing multi-core systems
  - Free performance gain for a serial program has come to an end
- Almost all of today's computers are multi-core systems, ranging from desktops to HPC clusters
- A serial code won't automatically benefit from the multiple cores
- Some applications may take years to get a solution if running in serial
- Parallel programming is the key!

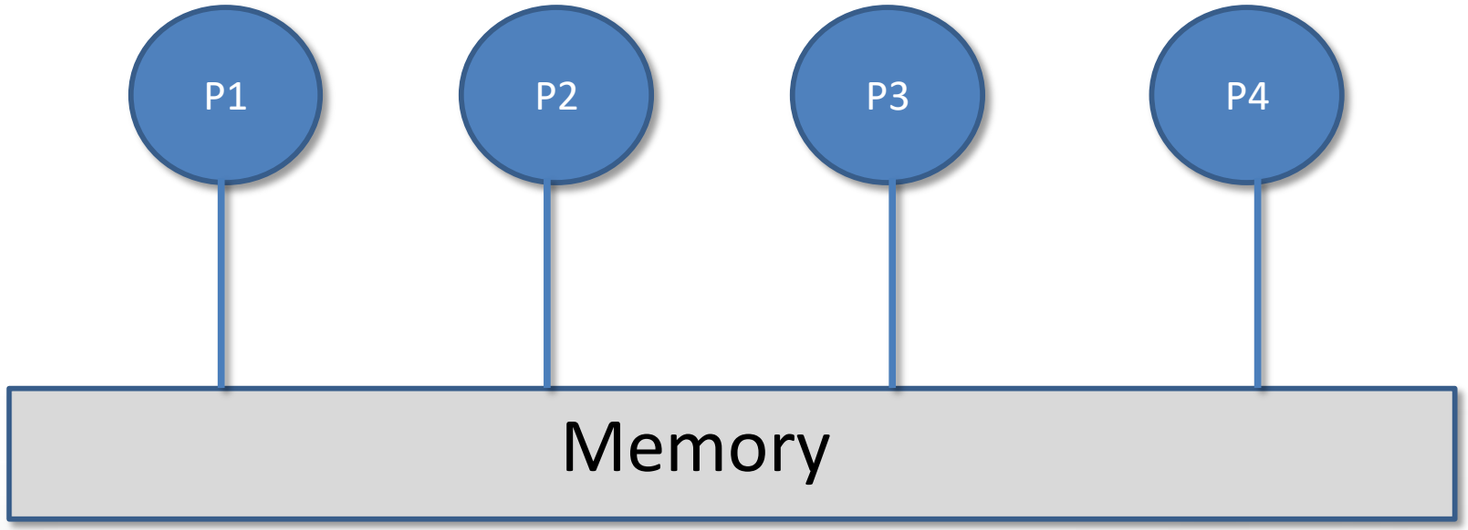
Parallel Computing Systems

We will use the term processor to refer to the smallest physical processing unit where a program is executed. It is synonymous to CPU core in this sense.

- Shared Memory Systems
- Distributed Memory Systems
- Hybrid Systems

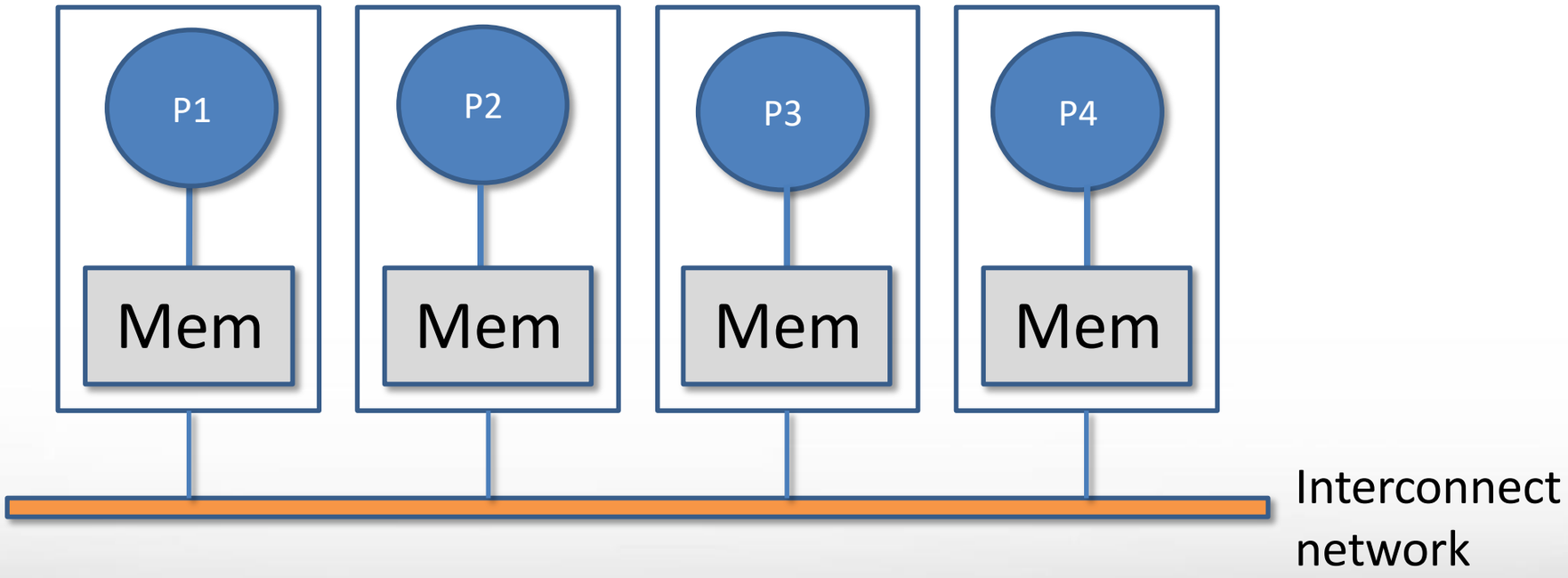
Parallel Computing Systems

- Shared Memory System – an abstraction to a parallel system where all processors share the same memory subsystem



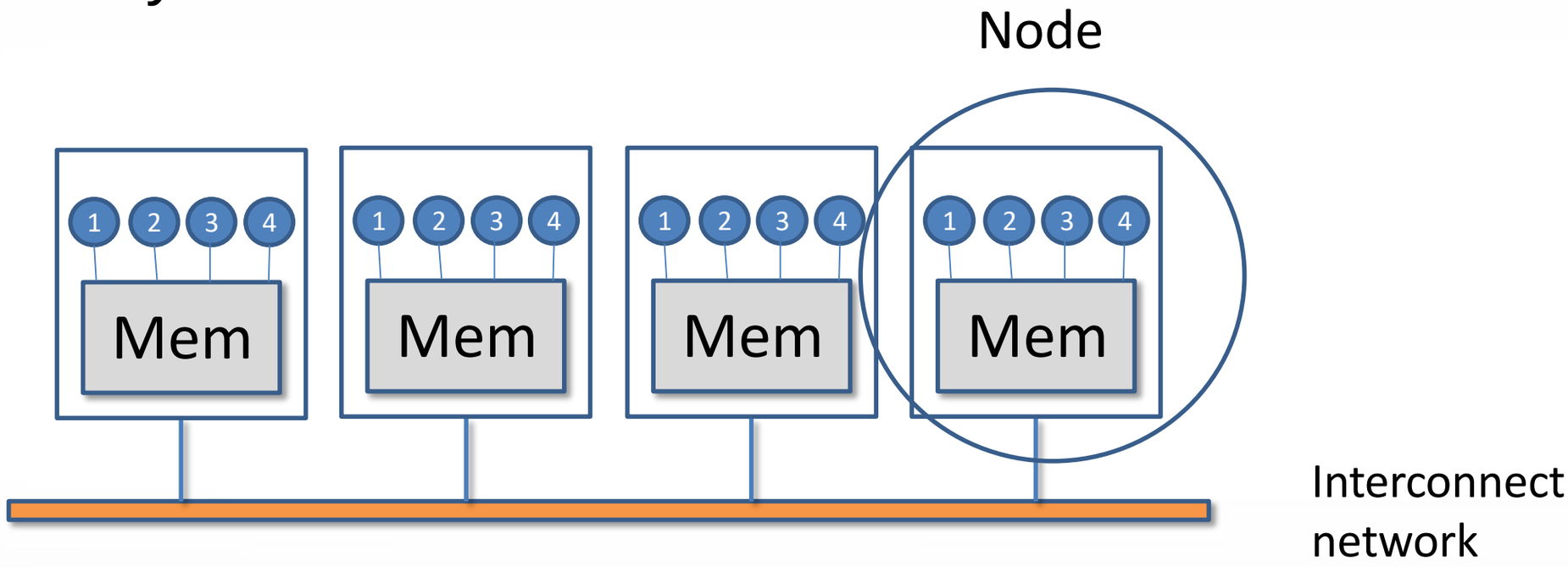
Parallel Computing Systems

- Distributed Memory System – an abstraction to a parallel system where each processor has its own local memory and the processors don't share a global memory subsystem.



Parallel Computing Systems

- A Hybrid System

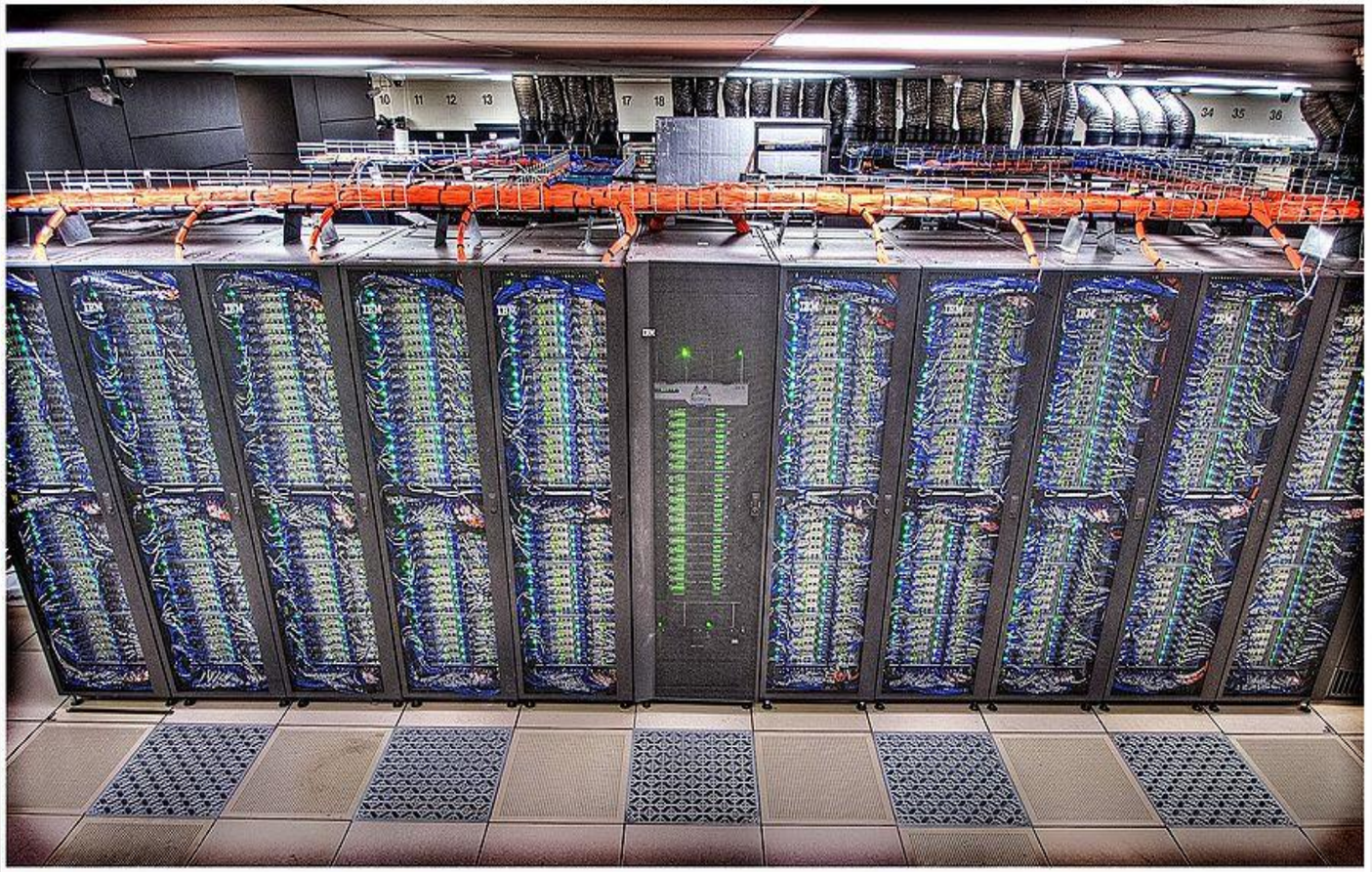


Parallel Programming Models

- Mapping from the parallel programming models to the computing systems

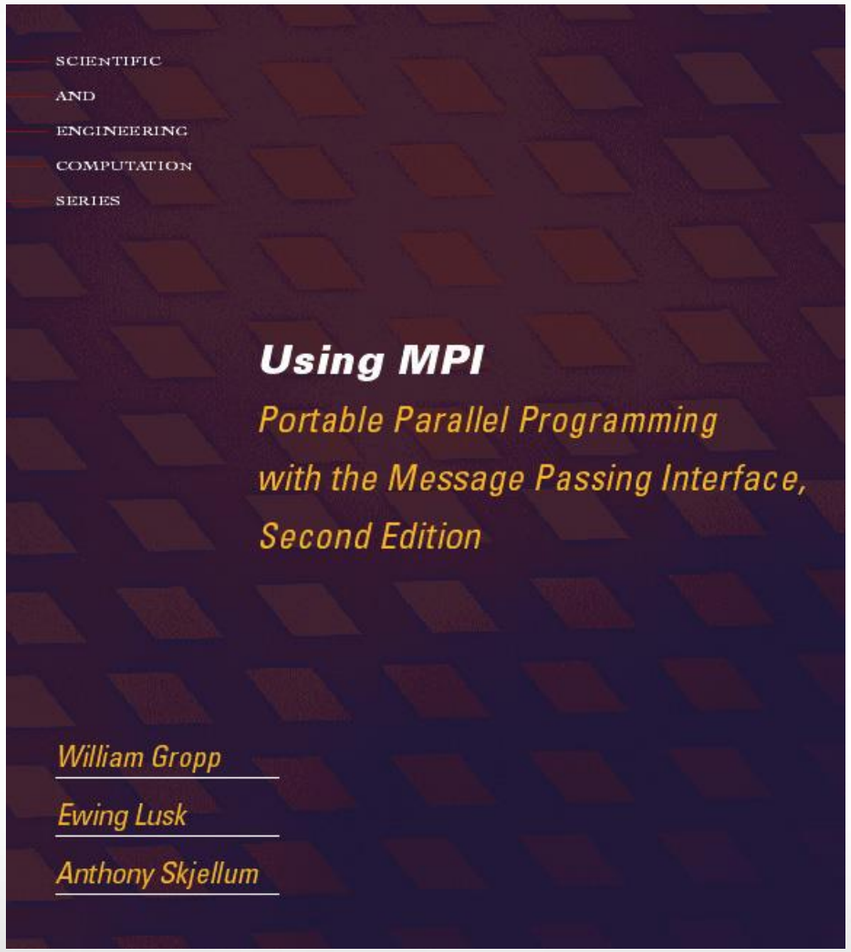
OpenMP	Shared Memory Systems
MPI	Distributed Memory Systems
MPI+OpenMP	Hybrid Systems

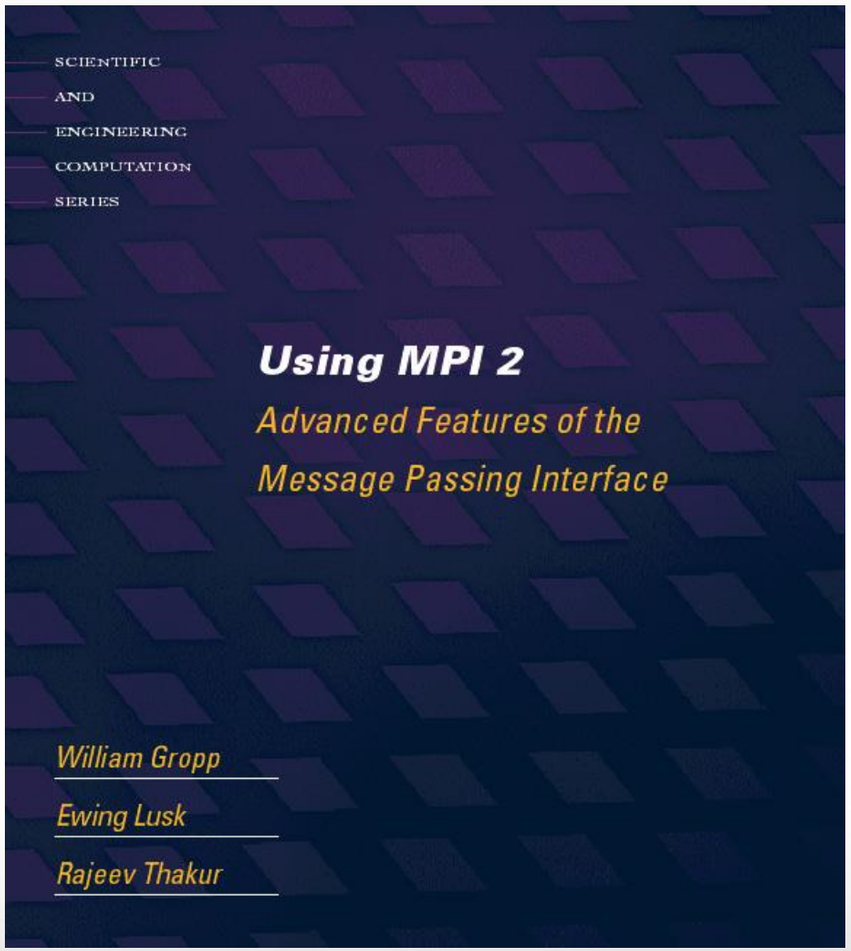
Ada and Terra



- Ada has 852 nodes and 17340 cores
- Terra has 304 compute nodes and 8512 cores
- Both support all three parallel programming models
  - OpenMP at node level
  - MPI at node and cluster level
  - Hybrid at node and cluster level

Books


SCIENTIFIC
AND
ENGINEERING
COMPUTATION
SERIES
Using MPI
Portable Parallel Programming
with the Message Passing Interface,
Second Edition
William Gropp
Ewing Lusk
Anthony Skjellum


SCIENTIFIC
AND
ENGINEERING
COMPUTATION
SERIES
Using MPI 2
Advanced Features of the
Message Passing Interface
William Gropp
Ewing Lusk
Rajeev Thakur

Example 1: Hello World

C

```
#include <stdlib.h>

int main(int argc, char **argv){

    printf("Hello, world\n");

}
```

Fortran

```
program hello
implicit none


print *, “Hello, world”

end program hello
```

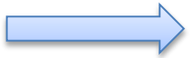
Example 1: Hello World

C

```
#include <stdlib.h>

int main(int argc, char **argv){

    printf("Hello, world\n");

}
```

Fortran

```
program hello
implicit none


print *, “Hello, world”

end program hello
```

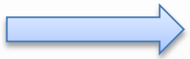


C

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

int main(int argc, char **argv){
    MPI_Init(&argc, &argv);
    printf("Hello, world\n");
    MPI_Finalize();
}
```

Fortran

```
program hello
use mpi
implicit none

call MPI_INIT(ierr)
print *, “Hello, world”
call MPI_Finalize(ierr)
end program hello
```



Layout of an MPI Program

C

```
#include <mpi.h>
int main(
   int argc, char **argv)
{
   …
   MPI_Init(&argc, &argv);

   MPI_Finalize();
   …
}
```

no mpi calls

mpi calls happen here

multiple concurrent processes execute at their own pace unless synchronization is applied.

Fortran

```
PROGRAM SAMPLE1
USE MPI !F90
!f77: include "mpif.h"
integer ierr
…
CALL MPI_INIT(ierr)

CALL MPI_FINALIZE(ierr)
…
END PROGRAM SAMPLE1
```

no mpi calls

mpi calls happen here

no mpi calls

Compiling and Linking MPI Programs

```
module load intel/2017A
mpiicc    prog.c   [options] -o prog.exe   (C)
mpicpc    prog.cpp [options] -o prog.exe   (C++)
mpiifort  prog.f   [options] -o prog.exe   (Fortran)
(Intel compilers)

mpicc     prog.c   [options] -o prog.exe   (C)
mpicxx    prog.cpp [options] -o prog.exe   (C++)
mpif90    prog.f   [options] -o prog.exe   (Fortran)
(GNU compilers)
```

Running MPI Programs

- Load the modules first

```
module load intel/2017A
```

- Run the mpi program interactively

```
mpirun –np n [options] prog.exe [prog_args]
```

- Useful options

```
-ppn/-perhost
-hosts
-hostfile
-h
```

Running MPI Programs

- Batch Examples

Ada

```
#BSUB -J MPIBatchExample
#BSUB -L /bin/bash
#BSUB -W 24:00
#BSUB -n 40
#BSUB -R "span[ptile=20]"
#BSUB -R "rusage[mem=2560]"
#BSUB -M 2560
#BSUB -o MPIBatchExample.%J

module load intel/2017A
mpirun prog.exe
```

bsub < mpibatch.job

Terra

```
#!/bin/bash
#SBATCH --export=NONE
#SBATCH --get-user-env=L
#SBATCH --job-name=MPIBatchExample
#SBATCH --time=24:00:00
#SBATCH --ntasks=56
#SBATCH --ntasks-per-node=28
#SBATCH --mem=56000M
#SBATCH --output=MPIBatchExample.%j
module load intel/2017A
mpirun prog.exe
```

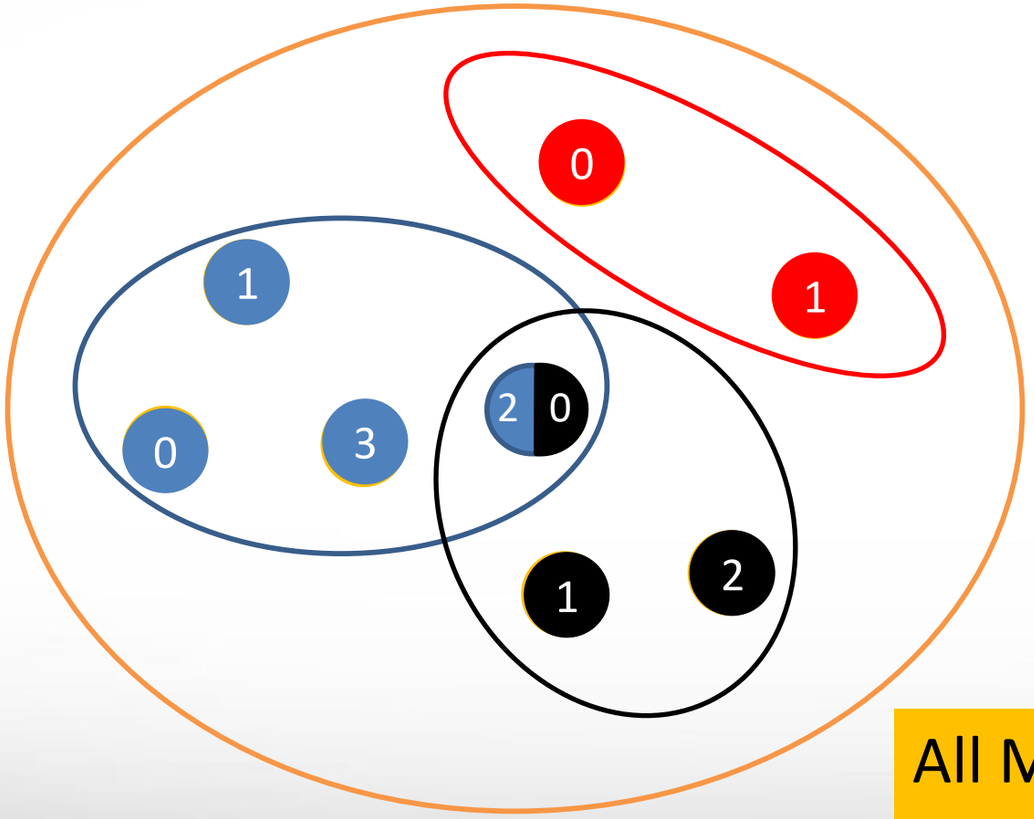
sbatch mpibatch.job

What is MPI

- Message Passing Interface: a specification for the library interface that implements message passing in parallel programing.
- Is standardized by the MPI forum for implementing portable, flexible, and reliable codes for distributed memory systems, regardless of the underneath architecture.
  - First edition: MPI-1(1994)
  - Evolving over time: MPI-2(1998), MPI-3(2012), MPI-3.1(2015)
  - MPI-4.0 is under discussion
- Has C/C++/Fortran bindings.
  - C++ binding deprecated since MPI-2.2
- Different implementations (libraries) available: Intel MPI, MPICH, OpenMPI, etc.
- It is the mostly widely used parallel programing paradigm for large scale scientific computing.

Basic MPI Concepts

communicator, size, rank

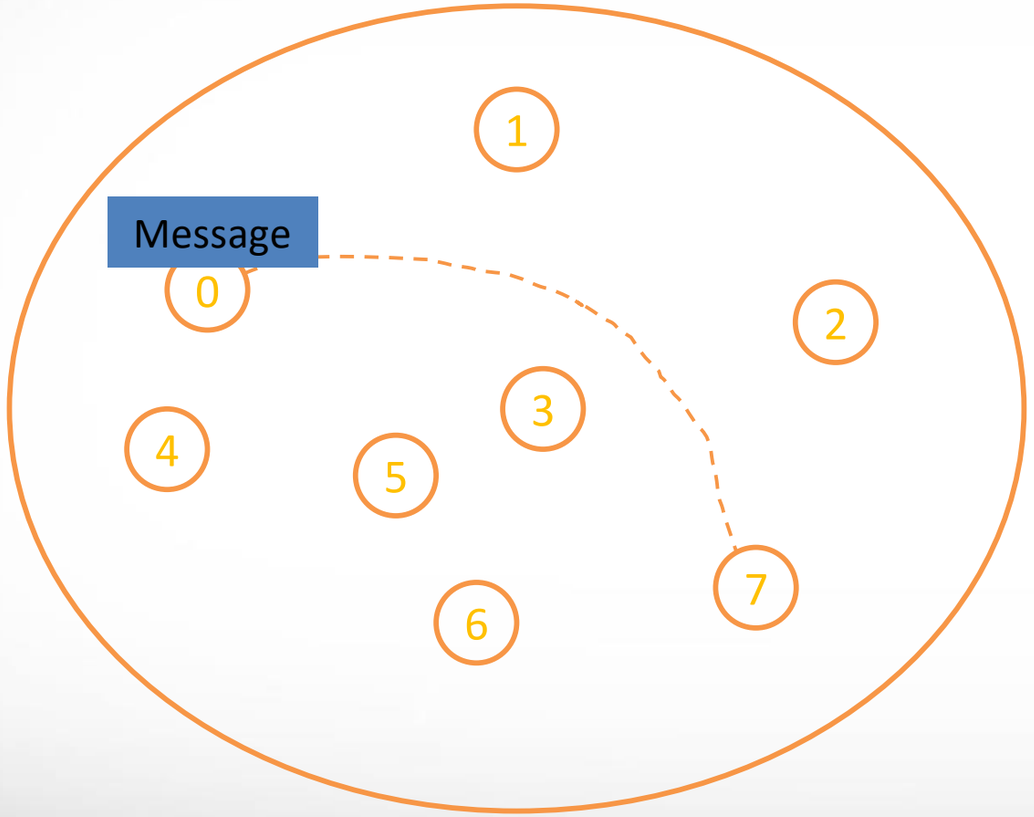


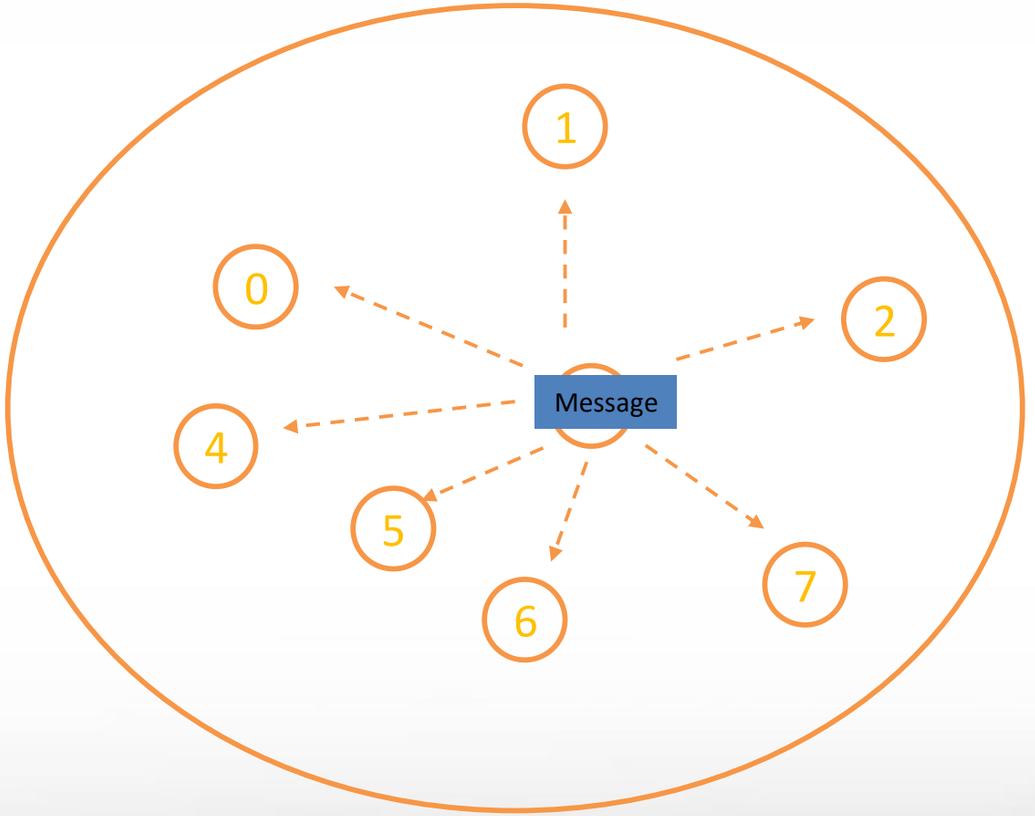
Communicator: MPI_COMM_WORLD
Size: 8
Rank: 0, 1, …, 7
Communicator: comm1
Size: 2
Rank: 0, 1
Communicator: comm2
Size: 4
Rank: 0, 1, 2, 3
Communicator: comm3
Size: 3
Rank: 0, 1, 2

All MPI communications must specify a communicator.

Basic MPI Concepts

message, point-to-point communication, collective communication





Example 2

C

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

int main(int argc, char **argv){
   int np, rank, number;
   MPI_Status status;

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

   if (rank == 0){
      number = 1234;
      MPI_Send(&number, 1, MPI_INT, 1, 0, MPI_COMM_WORLD);
      printf("Process %d sends out %d to process 1\n", rank, number);
   }else if(rank == 1){
      MPI_Recv(&number, 1, MPI_INT, 0, 0,
                              MPI_COMM_WORLD, &status);
      printf("Process %d receives %d from process 0\n", rank, number);
   }
   MPI_Finalize();
}
```

Fortran

```
program simple
use mpi
implicit none
integer ierr, np, rank, number, status ;

call MPI_INIT(ierr)

call MPI_COMM_SIZE(MPI_COMM_WORLD, np, ierr)
call MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierr)

if (rank == 0) then
   number = 1234
   call MPI_SEND(number, 1, MPI_INTEGER 1, 0, MPI_COMM_WORLD, ierr)
   print *, "process ", rank, " sends ", number

else if (rank == 1) then
   call MPI_RECV(number, 1, MPI_INTEGER, 0, 0, MPI_COMM_WORLD, status, ierr)
   print *, "process ",rank," receives ", number
endif

call MPI_Finalize(ierr)
end program simple
```

Communicator

- In MPI, a communicator is a software structure through which we specify a group of processes.
- Each process in a communicator is assigned a unique rank (an integer) ranging from 0 to (group_size -1). group_size is the size of the communicator.
- The constant **MPI_COMM_WORLD** (obtained from MPI include file) is an initial communicator that includes all the MPI processes activated in the running of a program. MPI_COMM_WORLD is typically the most used communicator.
- Communicators are especially useful in characterizing the tasks that different groups of processes carry out.

Size and Rank

- How many processes in a communicator?

C	`int MPI_Comm_size(MPI_Comm comm, int *size)`
Fortran	`SUBROUTINE MPI_COMM_SIZE(comm, size, ierr)` `integer comm, size, ierr`

- What's the rank (identity) of each process in a communicator?

C	`int MPI_Comm_rank(MPI_Comm comm, int *rank)`
Fortran	`SUBROUTINE MPI_COMM_RANK(comm, rank, ierr)` `integer comm, rank, ierr`

Message

Envelope

Source
Destination
Tag
Communicator

Tag is an integer used in a message to differentiate the message from other messages. Its valid value is between 0 to MPI_TAG_UB.

Data

Buffer Initial Address
Count
Datatype

Type of the data to be sent or received. Datatype can be predefined or user defined.

Commonly used predefined datatypes, also called MPI basic datatypes:
C: MPI_CHAR (char), MPI_SHORT(short int), MPR_INT (int), MPI_LONG(long int), MPI_LONG(float), MPI_DOUBLE(double) MPI_LONG_DOUBLE(long double)
Fortran: MPI_CHARACTER (character), MPI_INTEGER (integer), MPI_REAL (real*4) MPI_REAL8 (REAL*8), MPI_COMPLEX (complex), MPI_LOGICAL (logical)

```
MPI_Send(&number, 1, MPI_INT, 1, 0, MPI_COMM_WORLD);
```

Data

Envelope

Send and Receive a Message

- The structure of a message and how the data will be sent and received determine the interface of send and receive operations are similar

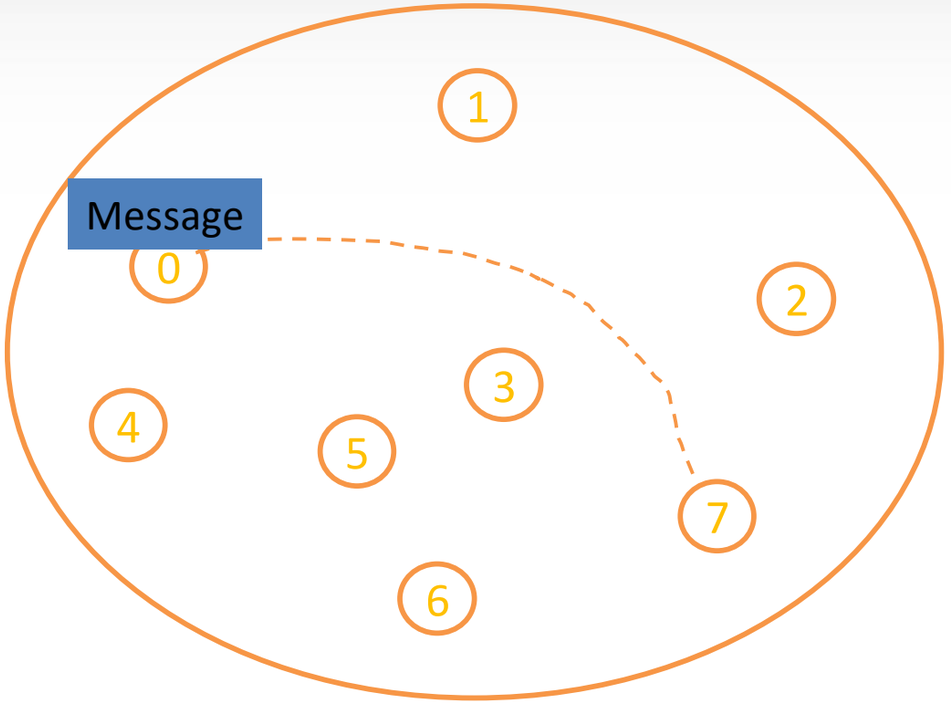
C

```
MPI_Send(&number, 1, MPI_INT, 1, 0, MPI_COMM_WORLD);
MPI_Recv(&number, 1, MPI_INT, 0, 0, MPI_COMM_WORLD, status);
```

Fortran

```
call MPI_SEND(number, 1, MPI_INTEGER, 1, 0, MPI_COMM_WORLD, ierr)
call MPI_RECV(number, 1, MPI_INTEGER, 0, 0, MPI_COMM_WORLD, status, ierr)
```

Point-to-Point Communication



- Blocking — `MPI_Send, MPI_Recv`
- Non-blocking — `MPI_Isend, MPI_Irecv`
- Send-Receive — `MPI_Sendrecv`

Blocking Send

C	int MPI_Send(void *buf, int count, MPI_Datatype datatype, int dest, int tag, MPI_Comm comm)
Fortran	MPI_SEND(buf, count, datatype, dest, tag, comm, ierr) <type> buf(*) integer count, datatype, dest, tag, comm, ierr

buf	initial address of send buffer
count	number of elements in send buffer
datatype	datatype of each send buffer element
dest	rank of destination
tag	message tag
comm	communicator

Comments on Blocking Send

MPI_SEND(buf, count, datatype, dest, tag, comm)

- The calling process causes count many contiguous elements of type datatype to be sent, starting from buf.
- The message sent by MPI_SEND can be received by either MPI_RECV or MPI_IRECV.
- MPI_SEND doesn't return (i.e., blocked) until it is safe to write to the send buffer.
  - Safe means the message has been copied either into a system buffer, or into the receiver's buffer, depending on which mode the send call is currently working under.

Blocking Receive

C	int MPI_Recv(void *buf, int count, MPI_Datatype datatype, int source, int tag, MPI_Comm comm, MPI_Status *status)
Fortran	MPI_RECV(buf, count, datatype, source, tag, comm, status, ierr) <type> buf(*) integer count, datatype, source, tag, comm, ierr, status[MPI_STATUS_SIZE]

buf	initial address of receive buffer
count	number of elements in receive buer
datatype	datatype of each receive buer element
source	rank of source or MPI_ANY_SOURCE
tag	message tag or MPI_ANY_TAG
comm	communicator
status	status object

MPI_ANY_SOURCE and MPI_ANY_TAG are MPI defined wildcards.

Comments on Blocking Receive

```
MPI_RECV(buf,count,datatype,source,tag,comm,status)
```

- The calling process attempts to receive a message with specified envelope (source, tag, communicator).
  - **MPI_ANY_SOURCE** and **MPI_ANY_TAG** are valid values.
- When the matching message arrives, elements of the specified datatype are placed in the buffer in contiguous locations, starting at the address of buf.
- The buffer starting at buf is assumed pre-allocated and has capacity for at least count many datatype elements.
  - An error returns if buf is smaller than data received.

Comments on Blocking Receive

```
MPI_RECV(buf,count,datatype,source,tag,comm,status)
```

- MPI_RECV can receive a message send by MPI_SEND or MPI_ISEND.
- Agreement in datatype between the send and receive is required.
- MPI_RECV is blocked until the message has been copied into buf.
- The actual size of the message received can be extracted with MPI_GET_COUNT.

Return Status

- The argument status in MPI_Recv provides a way of retrieving message source, message tag, and message error from the message.
- status is useful when MPI wildcards (MPI_ANY_SOURCE, MPI_ANY_TAG) are used in MPI_Recv.
- status can be ignored with MPI_STATUS_IGNORE

C

```
MPI_Status status
…
MPI_Recv(…,&status)
Source_id = status.MPI_SOURCE
tag       = status.MPI_TAG
```

Fortran

```
integer status(MPI_STATUS_SIZE)
…
CALL MPI_RECV(…,status,ierr)
source_id = status(MPI_SOURCE)
tag       = status(MPI_TAG)
```

Example 3

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

int main(int argc, char **argv){
   int number, size, rank;
   int i;

   MPI_Init(&argc, &argv);
   MPI_Comm_size(MPI_COMM_WORLD, &size);
   if (size < 2){
      MPI_Abort(MPI_COMM_WORLD, 99);
   }
   MPI_Comm_rank(MPI_COMM_WORLD, &rank);
   if (rank == 0){
      printf("Type any number from the input: ");
      scanf("%d", &number);
      for (i=1; i<size; i++)
         MPI_Send(&number, 1, MPI_INT, i, 0, MPI_COMM_WORLD);
   }else{
      MPI_Recv(&number, 1, MPI_INT, 0, 0, MPI_COMM_WORLD,
                                          MPI_STATUS_IGNORE);
      printf("My id is %d. I received %d\n", rank, number);
   }
   MPI_Finalize();
}
```

```fortran
program ex3
use mpi
implicit none
integer rank, np, ierr, number, i

call MPI_INIT(ierr)
call MPI_COMM_SIZE(MPI_COMM_WORLD, np, ierr)
call MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierr)

if (np < 2) then
   call MPI_ABORT(MPI_COMM_WORLD, 99, ierr)
endif
if (rank == 0) then
   print *, "Type an integer from the input"
   read *, number
   do i=1, np-1
      call MPI_SEND(number, 1, MPI_INTEGER, i, 0, MPI_COMM_WORLD, ierr)
   enddo
else
   call MPI_RECV(number, 1, MPI_INTEGER,  0, 0,MPI_COMM_WORLD,   &
                                          MPI_STATUS_IGNORE, ierr)
   print "(2(A,I6))","Process ",rank, " received ", number
Endif
call MPI_FINALIZE(ierr)
end program ex3
```

Non-blocking Send

MPI_ISEND(buf, count, datatype, dest, tag, comm, request)

IN	buf	initial address of send buffer
IN	count	number of elements in send buffer (non-negative integer)
IN	datatype	datatype of each send buffer element
IN	dest	rank of destination
IN	tag	message tag
IN	comm	communicator
OUT	request	communication request (a handle that can be used later to refer the outstanding receive)

Non-blocking Receive

MPI_IRECV(buf, count, datatype, source, tag, comm, request)

IN	buf	initial address of send buffer
IN	count	number of elements in receive buffer (non-negative integer)
IN	datatype	datatype of each receive buffer element
IN	source	rank of source or MPI_ANY_SOURCE
IN	tag	message tag or MPI_ANY_TAG
IN	comm	communicator
OUT	request	communication request (a handle that can be used later to refer the outstanding receive)

Non-blocking Send/Receive

- A non-blocking send/receive call initiates the send/receive operation, and returns immediately with a request handle, before the message is copied out/into the send/receive buffer.
- A separate send/receive complete call is needed to complete the communication before the buffer can be accessed again.
- A non-blocking send can be matched by a blocking receive; a non-blocking receive can be matched by a blocking send.
- Used correctly, non-blocking send/receive can improve program performance.
- They also make the point-to-point transfers “safer” by not depending on the size of the system buffers.
  - No deadlock caused by unavailable buffer
  - No buffer overflow

Auxiliary Routines for Non-blocking Send/Receive

- Auxiliary routines are used to complete a non-blocking communication or communications.
- Commonly used auxiliary routines:

MPI_Wait(request, status)	The calling process waits for the completion of a non-blocking send/receive identified by *request*.
MPI_Waitall(count, requests, statuses)	The calling process waits for all pending operations in a list of *requests*.
MPI_Test(request, flag, status)	The calling process tests a non-blocking send/receive specified by *request* has completed delivery/receipt of a message.

MPI_WAIT

MPI_WAIT(request, status)

request	request (handle)
status	status object (Status)

C

```
MPI_Request request;
MPI_Status  status;
…
MPI_Irecv(recv_buf,count,…,
                comm,&request);
…do some computations …

MPI_Wait(&request, &status);
```

Fortran

```
integer request
integer status(MPI_STATUS_SIZE)
…
call MPI_IRECV(recv_buf,count,…&
                     comm,request,ierr)
… do some computations …

call MPI_WAIT(request,status,ierr)
```

status can be ignored with MPI_STATUS_IGNORE

MPI_WAITALL

MPI_WAITALL(count, requests, statuses)

count	lists length (non-negative integer)
requests	array of requests (array of handles)
statuses	array of status objects (array of Status)

C

```
integer reqs(4)
integer statuses(MPI_STATUS_SIZE,4)
…
call MPI_ISEND(…,reqs(1),ierr)
call MPI_IRECV(…,reqs(2),ierr)
call MPI_ISEND(…,reqs(3),ierr)
call MPI_IRECV(…,reqs(4),ierr)
…
… do some computations …
…
call
MPI_WAITALL(4,reqs,statuses,ierr)
```

Fortran

```
MPI_Request reqs[4];
MPI_Status  status[4];
…
MPI_Isend(…,&reqs[0]);
MPI_Irecv(…,&reqs[1]);
MPI_Isend(…,&reqs[2]);
MPI_Irecv(…,&reqs[3]);
…
… do some com computations …
…
MPI_Waitall(4,reqs,statuses);
```

statuses can be ignored with MPI_STATUSES_IGNORE

Example 4

C

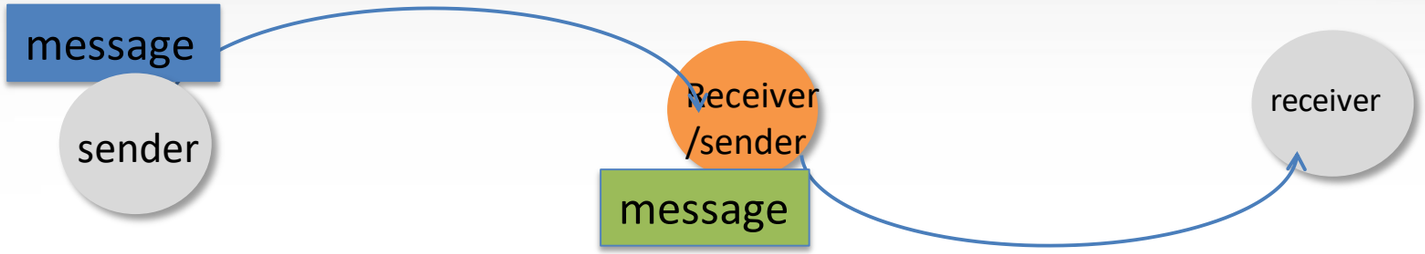
```
MPI_Request *requests;
   ….
if (rank == 0){
   printf("Type any number from the input: ");
   scanf("%d", &number);
   requests = (MPI_Request *)(malloc(npof(MPI_Request)*(np-1)));

   for (i=1; i<np; i++)
      MPI_Isend(&number, 1, MPI_INT, i, 0, MPI_COMM_WORLD,
                                                &requests[i-1]);
   MPI_Waitall(np-1, requests, MPI_STATUSES_IGNORE);
   free(requests);
}else{
   MPI_Recv(&number, 1, MPI_INT, 0, 0, MPI_COMM_WORLD,
                                          MPI_STATUS_IGNORE);
   printf("My id is %d. I received %d\n", rank, number);
}
```

Fortran

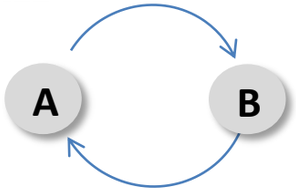
```
integer, allocatable::requests(:)
  ….
if (rank == 0) then
   print *, "Type an integer from the input"
   read *, number
   allocate(requests(np-1))
   do i=1, np-1
      call MPI_ISEND(number, 1, MPI_INTEGER, i, 0,   &
                              MPI_COMM_WORLD, ierr)
   enddo
   call MPI_WAITALL(np-1, requests, MPI_STATUSES_IGNORE, ierr)
   deallocate(requests)
else
   call MPI_RECV(number, 1, MPI_INTEGER, 0, 0,    &
                          MPI_COMM_WORLD, MPI_STATUS_IGNORE, ierr)
   print "(2(A,I6))","Process ",rank, " received ", number
endif
```

Send-Receive

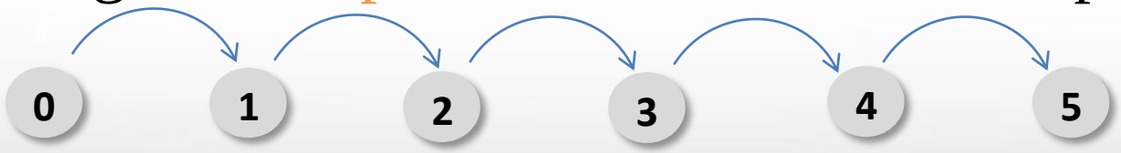
MPI_SENDRECV(sendbuf, sendcount, sendtype, dest, sendtag, recvbuf, recvcount, recvtype, source, recvtag, comm, status)



- Combines send and receive operations in one call
- The source and destination can be the same.



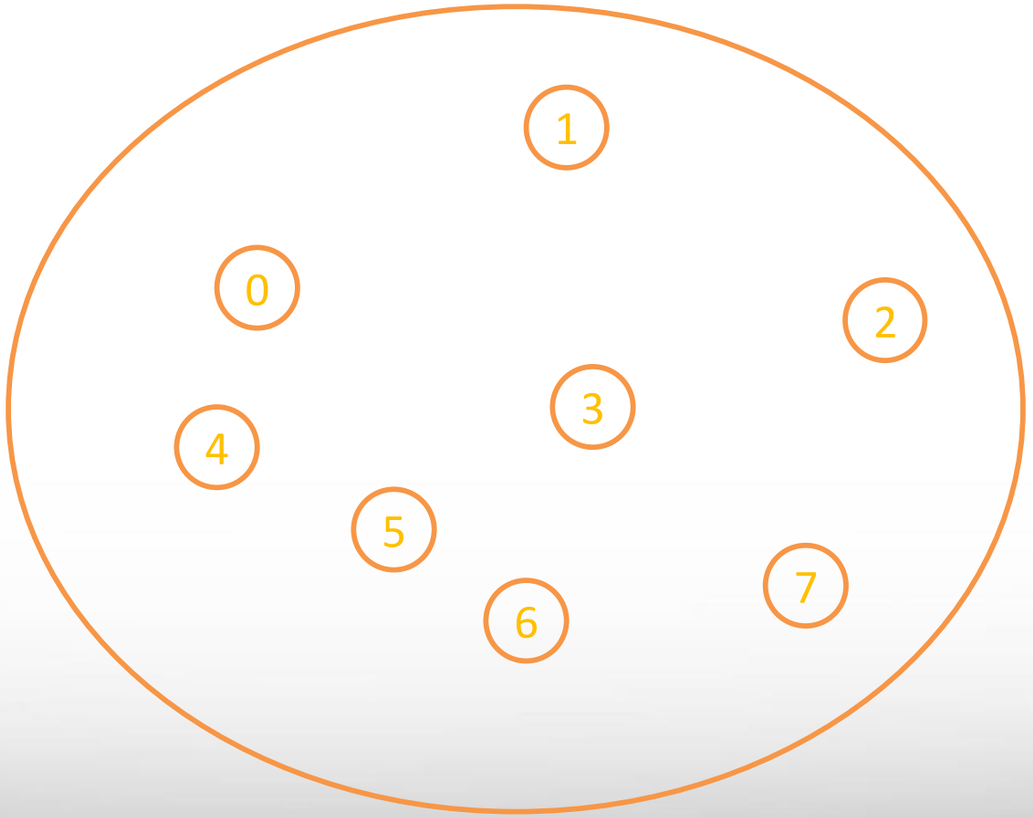
- The message sent out by send-receive can be received by blocking/non-blocking receive or another send-receive
- It can receive a message sent by blocking/non-blocking send or another send-receive.
- Useful for executing a shift operation across a chain of processes.



- Dependencies will be taken care of by the communication subsystem to eliminate the possibility of deadlock.

Collective Communication

- A collective communication refers to a communication that involves all processes in a communicator.



Routines for Collective Communication

MPI_BARRIER	All processes within a communicator will be blocked until all processes within the communicator have entered the call.
MPI_BCAST	Broadcasts a message from one process to members in a communicator.
MPI_REDUCE	Performs a reduction operation to the vector of elements in the sendbuf of the group members and places the result in recvbuf on root.
MPI_GATHER MPI_GATHERV	Collects data from the sendbuf of all processes in comm and place them consecutively to the recvbuf on root based on their process rank.
MPI_SCATTER MPI_SCATTERV	Distribute data in sendbuf on root to recvbuf on all processes in comm.
MPI_ALLREDUCE	Same as MPI_REDUCE, except the result is placed in recvbuf on all members in a communicator.
MPI_ALLGATHER MPI_ALLGATHERV	Same as GATHER/GATHERV, except now data are placed in recvbuf on all processes in comm.
MPI_ALLTOALL	The j-th block of the sendbuf at process i is send to process j and placed in the i-th block of the recvbuf of process j.

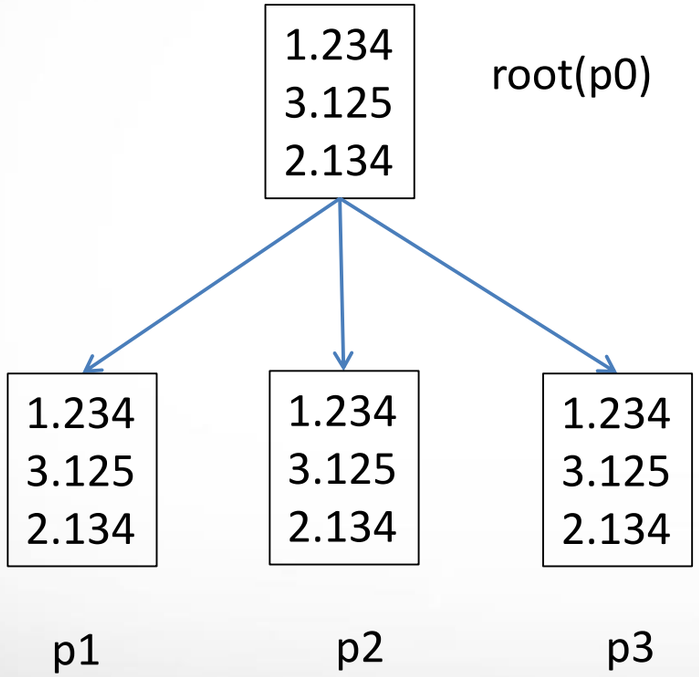
MPI_BARRIER

MPI_BARRIER(comm)

- Blocks all processes in comm until all processes have called it.
- Is used to synchronize the progress of all processes in comm.

MPI_BCAST

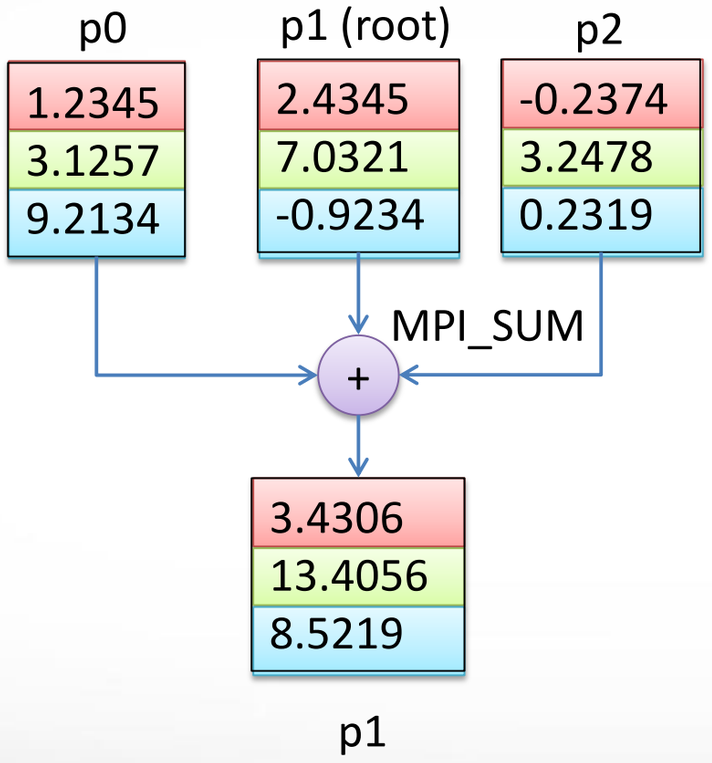
MPI_BCAST(buffer, count, datatype, root, comm)



- Root process: sends a message to all processes (including root) in the communicator comm.
- Non-root processes: receives a message from the specified root.
- Each receiving process blocks until the message has arrived its buffer.
- All processes in comm must call this routine.

MPI_REDUCE

MPI_REDUCE(sendbuf, recvbuf, count, datatype, op, root, comm)



C: MPI_Op op

Fortran: integer op

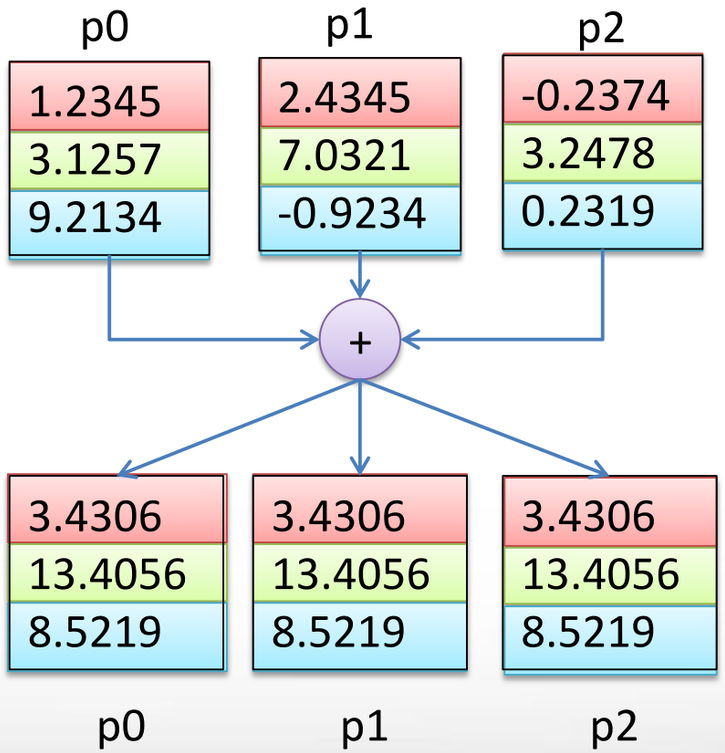
- Performs a reduction operation on all elements with same index in *sendbuf* on all processes and stores results in *recvbuf* of the root process.
- *recvbuf* is significant only at root.
- *sendbuf* and *recvbuf* cannot be the same.
- The size of *sendbuf* and *recvbuf* is equal to count.

Predefined Reduction Operations

PREDEFINED OPERATIONS	MPI DATATYPES
MPI_SUM, MPI_PROD	MPI_REAL8, MPI_INTEGER, MPI_COMPLEX, MPI_DOUBLE, MPI_INT, MPI_SHORT, MPI_LONG
MPI_MIN, MPI_MAX	MPI_INTEGER, MPI_REAL8, MPI_INT, MPI_SHORT, MPI_LONG, MPI_DOUBLE
MPI_LAND, MPI_LOR, MPI_LXOR	MPI_LOGICAL, MPI_INT, MPI_SHORT, MPI_LONG
MPI_BAND, MPI_BOR, MPI_BXOR	MPI_INTEGER, MPI_INT, MPI_SHORT, MPI_LONG

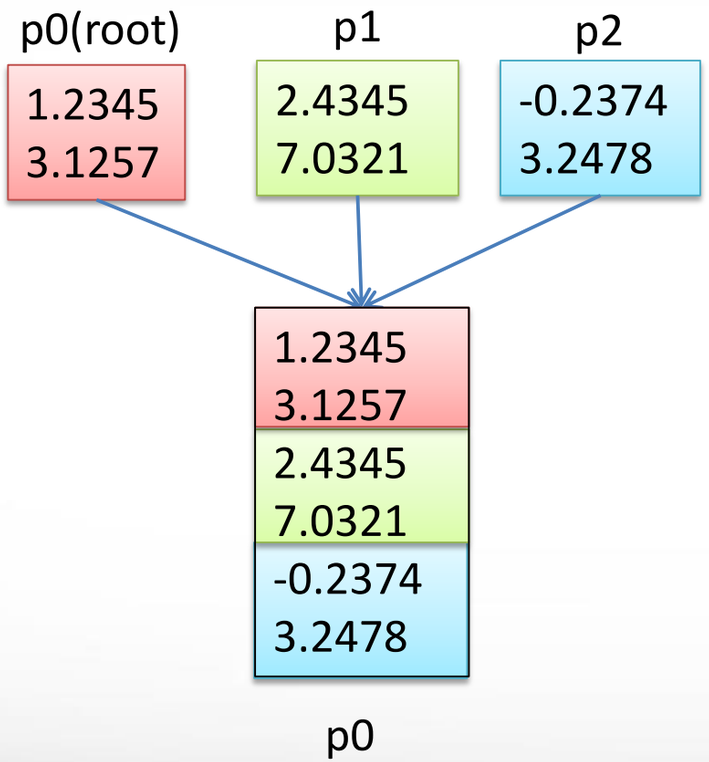
MPI_ALLREDUCE

MPI_ALLREDUCE(sendbuf, recvbuf, count, datatype, op, comm)



MPI_GATHER

MPI_GATHER(sendbuf, sendcnt, sendtype, recvbuf, recvcnt, recvtype, root, comm)



- Gathers together data from all process in comm and stores in root process.
- Data received by root are stored in rank order.
- recvcnt is number of elements received per process
- Recvbuf, recvcnt, recvtype are significant only at root.

MPI_GATHERV

MPI_GATHERV(sendbuf,sendcnt,sendtype,recvbuf,recvcnts,displs, recvtype,root,comm)

IN recvcnts an integer array of size of *comm*. recvnts[i] = number of elements received from process i.

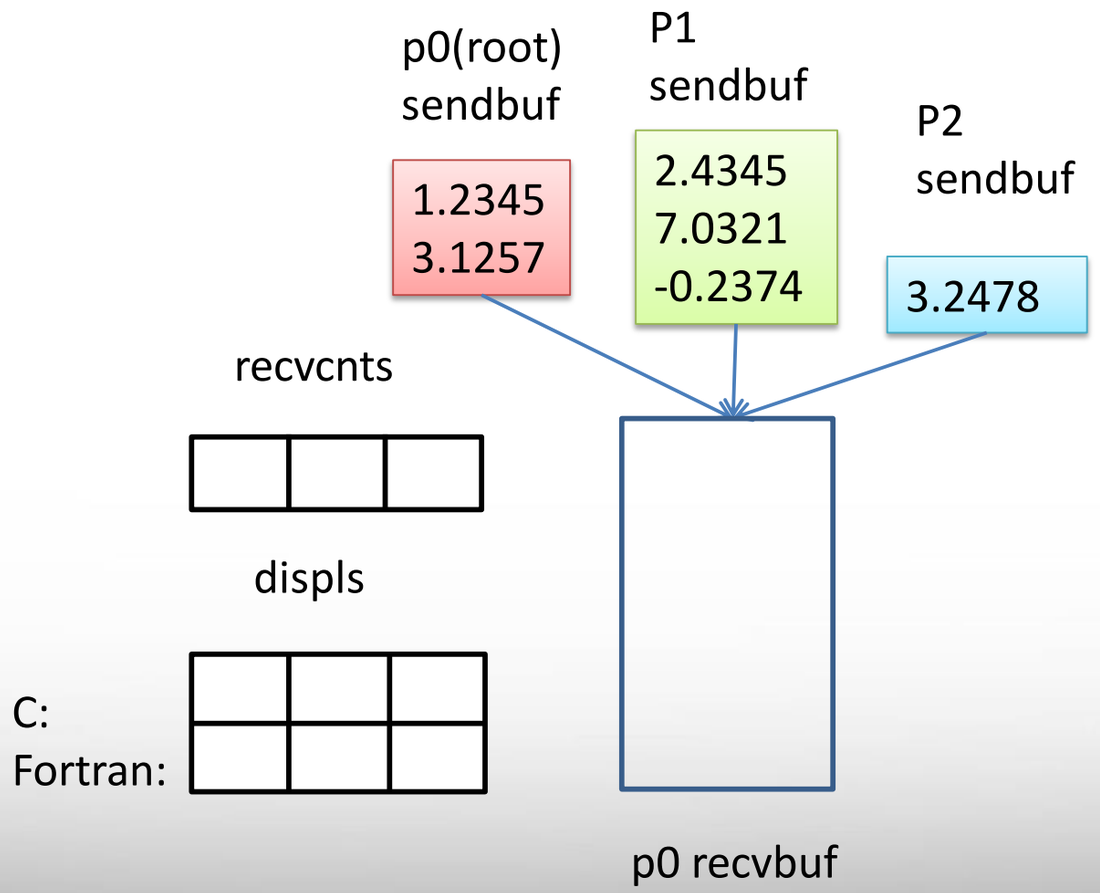
IN displs an integer array of size of *comm*. displs[i] = displacement from *recevbuf* for process i.

Fortran
integer recvcnts(*), displs(*)

C
int recvcnts[], displs[]

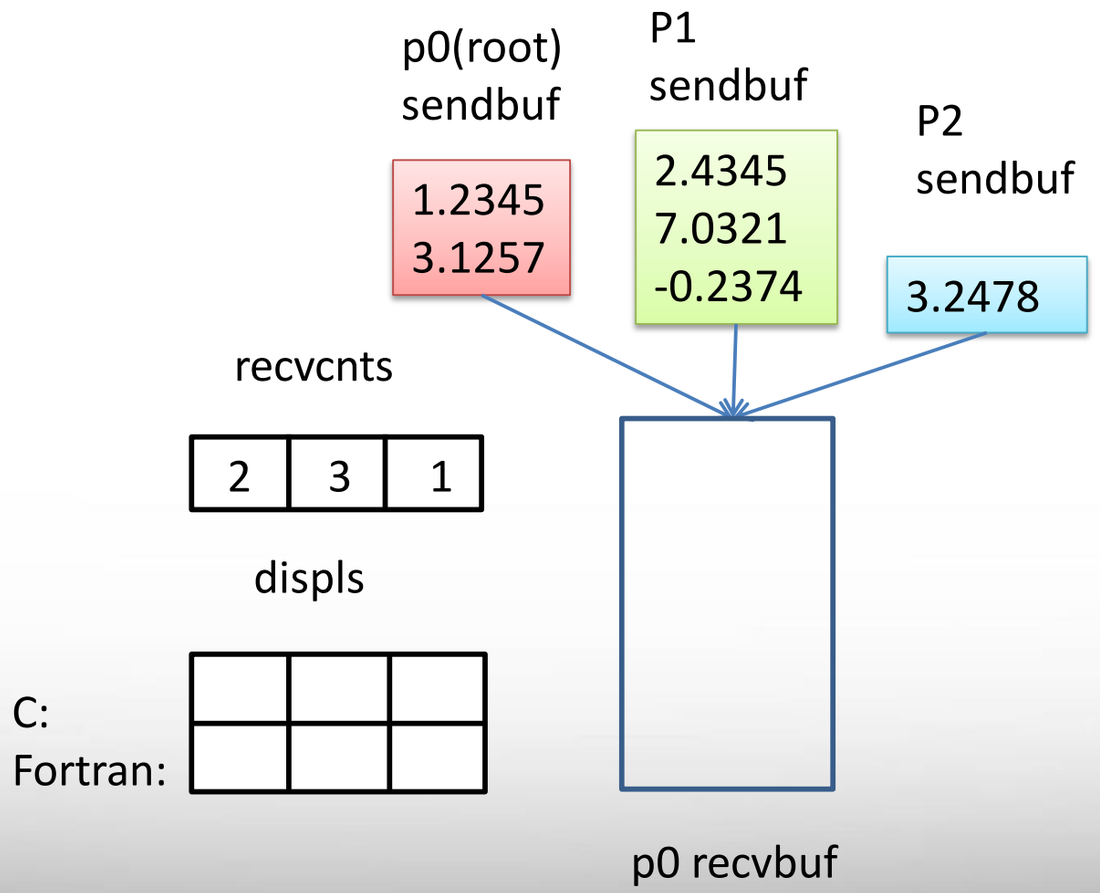
MPI_GATHERV (cont.)

MPI_GATHERV(sendbuf,sendcnt,sendtype,recvbuf,recvcnts,displs, recvtype,root,comm)



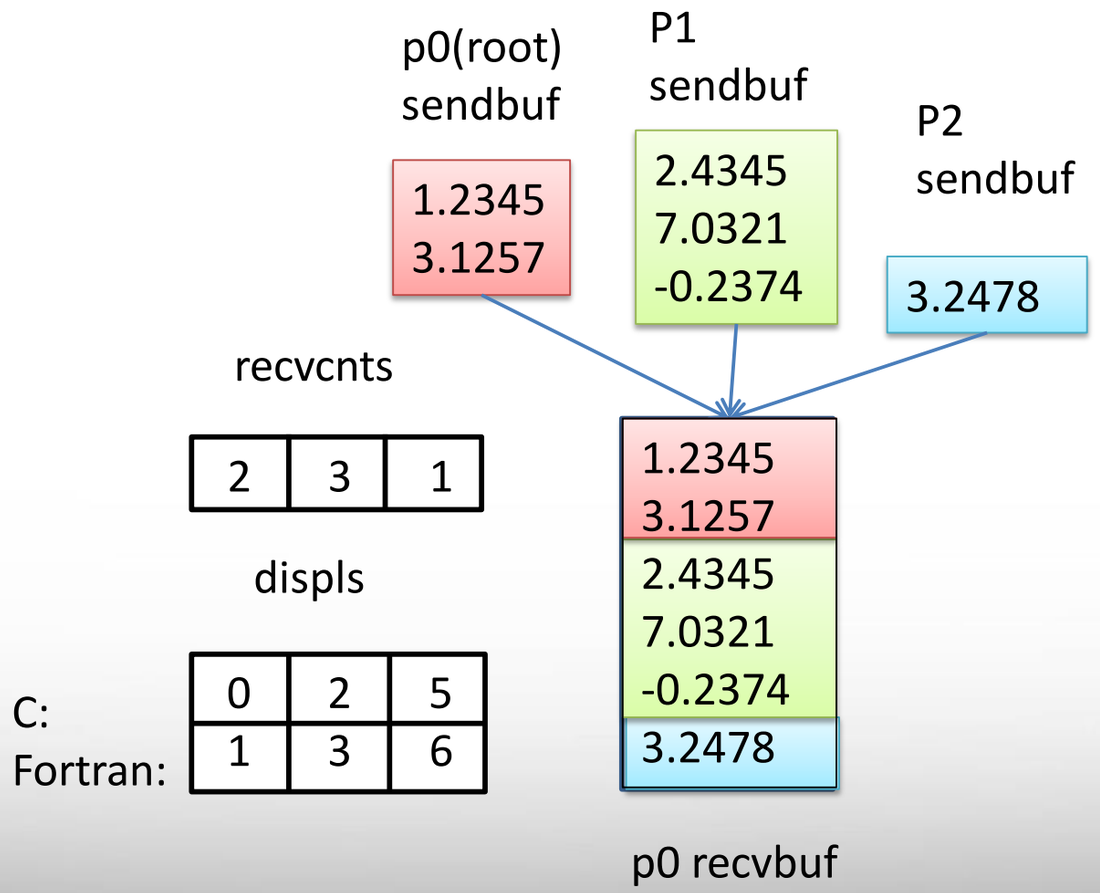
MPI_GATHERV (cont.)

MPI_GATHERV(sendbuf,sendcnt,sendtype,recvbuf,recvcnts,displs, recvtype,root,comm)



MPI_GATHERV (cont.)

MPI_GATHERV(sendbuf,sendcnt,sendtype,recvbuf,recvcnts,displs, recvtype,root,comm)



MPI_ALLGATHER/MPI_ALLGATHERV

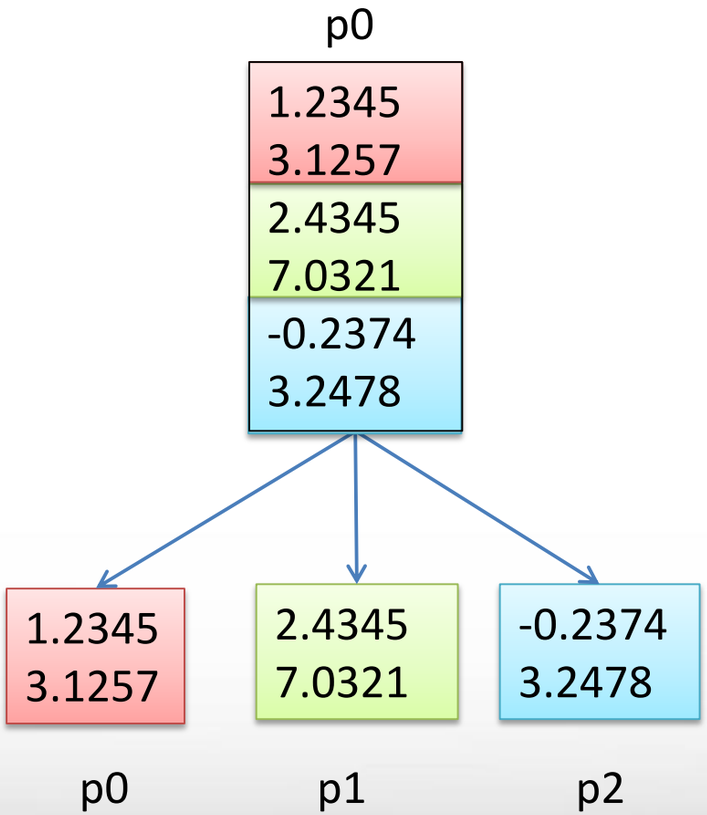
MPI_ALLGATHER(sendbuf,sendcnt,sendtype,recvbuf,recvcnt,recvtype,comm)

MPI_ALLGATHERV(sendbuf,sendcnt,sendtype,recvbuf,recvcnts,displs,recvtype,comm)

- Same as MPI_GATHER/MPI_GATHERV, except no root.
- Root is not needed since every process in the communicator stores the data gathered in its recvbuff.

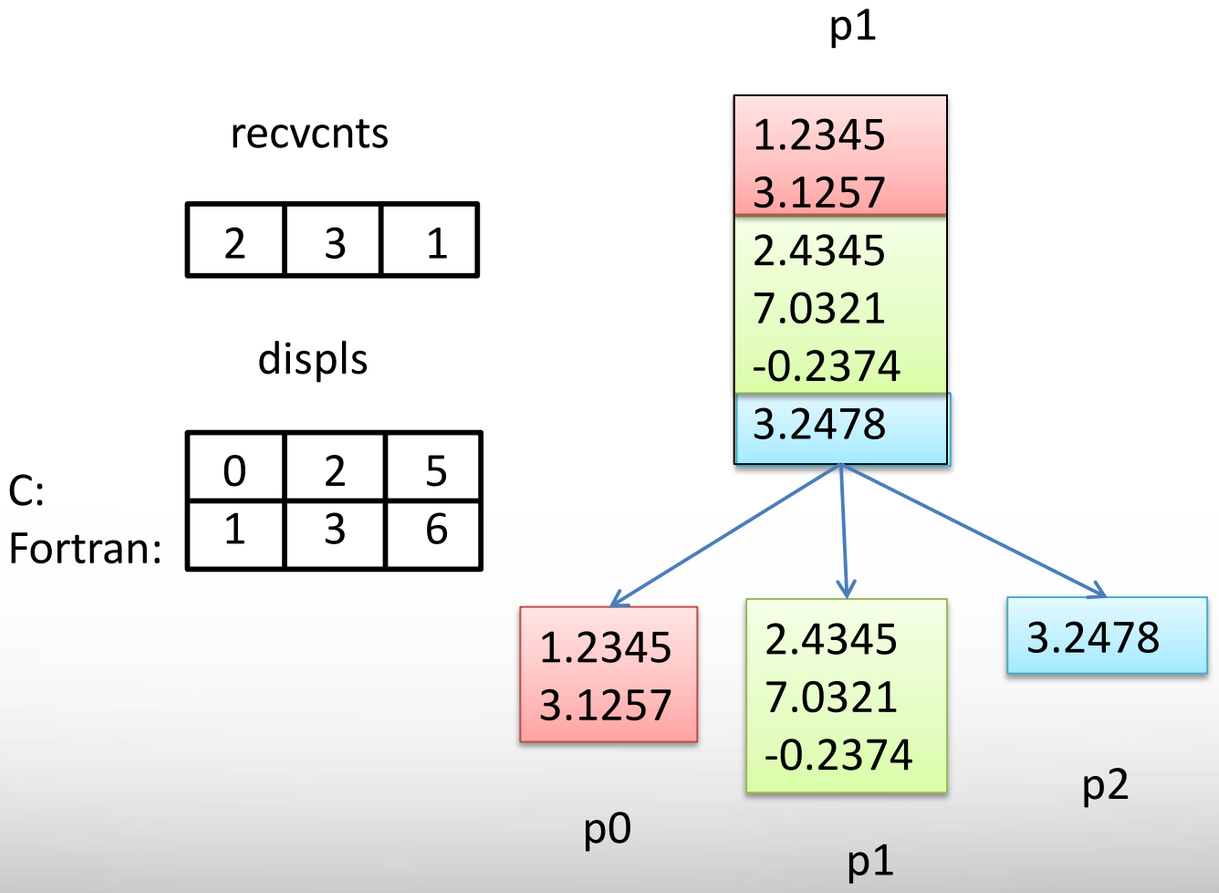
MPI_SCATTER

MPI_SCATTER(sendbuf, sendcnt, sendtype, recvbuf, recvcnt, recvtype, root, comm)



MPI_SCATTERV

MPI_SCATTERV(sendbuf, sendcnts, displs, sendtype, recvbuf, recvcnt, recvtype,root,comm)



Timing Routine

MPI_WTIME()

- returns a floating-point number in seconds, representing elapsed wall clock time since some time in the past.

C

```
double t1, t2;
double elapsed;
t1 = MPI_Wtime();
…
// code segment to be timed
…
t2 = MPI_Wtime();
elapsed = t2 - t1;
```

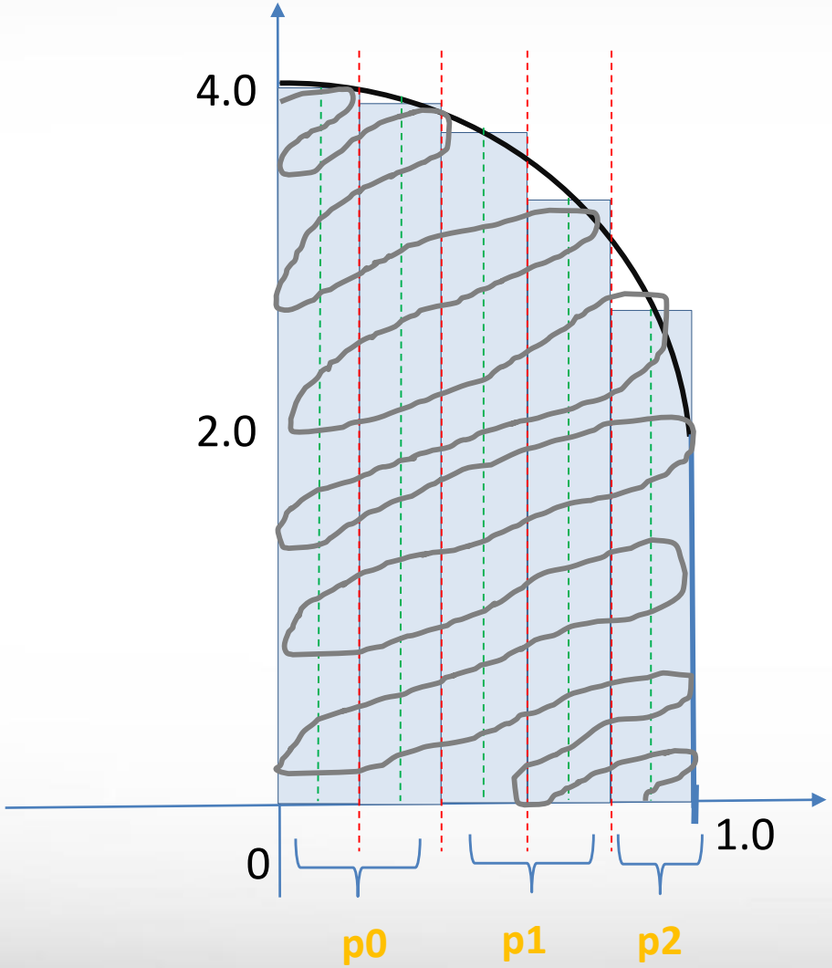
Fortran

```
real*8 t1, t2
real*8 elapsed
t1 = MPI_WTIME()
…
! Code segment to be timed
…
t2 = MPI_WTIME()
elapsed = t2 - t1
```

Important Note On Using MPI

- All parallelism is explicit: the programmer is responsible for correctly identifying parallelism and implementing parallel algorithms using MPI constructs

Example 5: Calculate PI



$$\pi = \int_0^1 \frac{4.0}{1+x^2}\,dx$$

Outline for MPI Part II

- Exploring parallelism
  - Task-parallelism
  - Data-parallelism
- Matrix-vector multiplication
- Solving the 2D Poisson equation
- Domain decomposition
- MPI/OMP hybrid programming
- MPI/OMP: A Case Study