Parallel Programming Using MPI

Short Course on HPC

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Why use MPI?

- General
  - MPI-1 ’92-’94, MPI-2 ~2008, MPI-3 2012. Has been around for ~25 years
  - Widely used parallel model
  - Libraries and algorithms readily available
  - Very scalable: 1 ~ 300,000 cores
  - Portable
  - Works well with Hybrid models (MPI+OpenMP, MPI+CUDA,… MPI+X)
- Your problem
  - Want to speed up your calculation
  - Your problem size is too large for a single node

What is MPI?

- MPI stands for Message Passing Interface
- It is a message-passing **specification**, a **standard,** for the vendors to implement
- In practice, MPI is a **library** consisting of C functions and Fortran subroutines (Fortran) used for **exchanging** data between processes
- An MPI library exists on **ALL** parallel computers so it is **highly portable**
- Also available for Python (mpi4py.scipy.org), R (Rmpi)

MPI

Context: Distributed memory parallel computers

- Each processor has its own memory and cannot access the memory of other processors
- A copy of the same executable runs on each MPI process (processor core)
- All variables are private to each process
- Any data to be shared must be explicitly transmitted from one to another

Basic MPI

- Basic functionality in a parallel program
  - Start processes
  - Send messages
  - receive messages
  - Synchronize

A simple program in C

```
#include <stdio>
#include <stdlib>

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

    printf("Hello \n")

return 0;
}
```

Any PC

$ ./a.out

Hello

A simple MPI program in C

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

int main( int argc, char *argv[] )
{
  int nproc, myrank;

    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&nproc);
    MPI_Comm_rank(MPI_COMM_WORLD,&myrank);

    printf("Hello from %d. \n",myrank)

  /* Finalize */
    MPI_Finalize();
 return 0;
}
```

Any Cluster

$ mpirun -n 8 ./a.out

SahasraT

$ aprun -n 8 ./a.out

Hello from 0.
Hello from 1.
Hello from 2.
Hello from 3.
Hello from 4.
Hello from 5.
Hello from 6.
Hello from 7.

Header file

- Defines MPI-related parameters and functions
- Must be included in all routines calling MPI functions
- Can also use include file:
  include mpif.h

```
#include "mpi.h"
int main( int argc, char *argv[]
{
  int nproc, myrank;
  /* Initialize MPI */
    MPI_Init(&argc,&argv);
  /* Get the number of processes */
    MPI_Comm_size(MPI_COMM_WORLD,&nproc);
  /* Get my process number (rank) */
    MPI_Comm_rank(MPI_COMM_WORLD,&myrank);

    Do work and make message passing calls…

  /* Finalize */
    MPI_Finalize();
 return 0;
}
```

Initialization

```
#include "mpi.h"
int main( int argc, char *argv[] )
{
  int nproc, myrank;
  /* Initialize MPI */
    MPI_Init(&argc,&argv);
  /* Get the number of processes */
    MPI_Comm_size(MPI_COMM_WORLD,&np
  /* Get my process number (rank) */
    MPI_Comm_rank(MPI_COMM_WORLD,&myrank);

    Do work and make message passing calls…

  /* Finalize */
    MPI_Finalize();
 return 0;
}
```

- Must be called at the beginning of the code before any other calls to MPI functions
- Sets up the communication channels between the processes and gives each one a rank.

How many processes do we have?

- Returns the number of processes available under MPI_COMM_WORLD communicator
- This is the number used on the mpiexec (or mpirun) command:

  mpiexec –n nproc a.out

```
    MPI_Init(&argc,&argv);
  /* Get the number of processes */
    MPI_Comm_size(MPI_COMM_WORLD,&nproc);
  /* Get my process number (rank) */
    MPI_Comm_rank(MPI_COMM_WORLD,&myrank);

    Do work and make message passing calls…

  /* Finalize */
    MPI_Finalize();
 return 0;
}
```

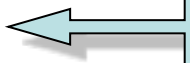
What is my rank?

```
#include "mpi.h"
int main( int
{
  int nproc, r
  /* Initiali
    MPI_Init(
  /* Get the
    MPI_Comm_size(MPI_COMM_WORLD,&np
  /* Get my process number (rank) */
    MPI_Comm_rank(MPI_COMM_WORLD,&myrank);

    Do work and make message passing calls…

  /* Finalize */
    MPI_Finalize();
 return 0;
}
```

- Get my rank among all of the nproc processes under MPI_COMM_WORLD
- This is a unique number that can be used to distinguish this process from the others

Termination

```
#include "mpi.h"
int main( int argc, char *argv[] )
{
  int nproc, myrank;
  /* Initialize MPI */
    MPI_Init(&argc,&argv);
  /* Get the number of processes */
    MPI_Comm_size(MPI_COMM_WORLD,&nproc);
  /* Get my process number (rank) */
    MPI_Comm_rank(MPI_COMM_WORLD,&myrank);

    Do work and make message passing calls…

  /* Finalize */
    MPI_Finalize();
 return 0;
}
```



- Must be called at the end of the properly close all communication channels
- No more MPI calls after finalize

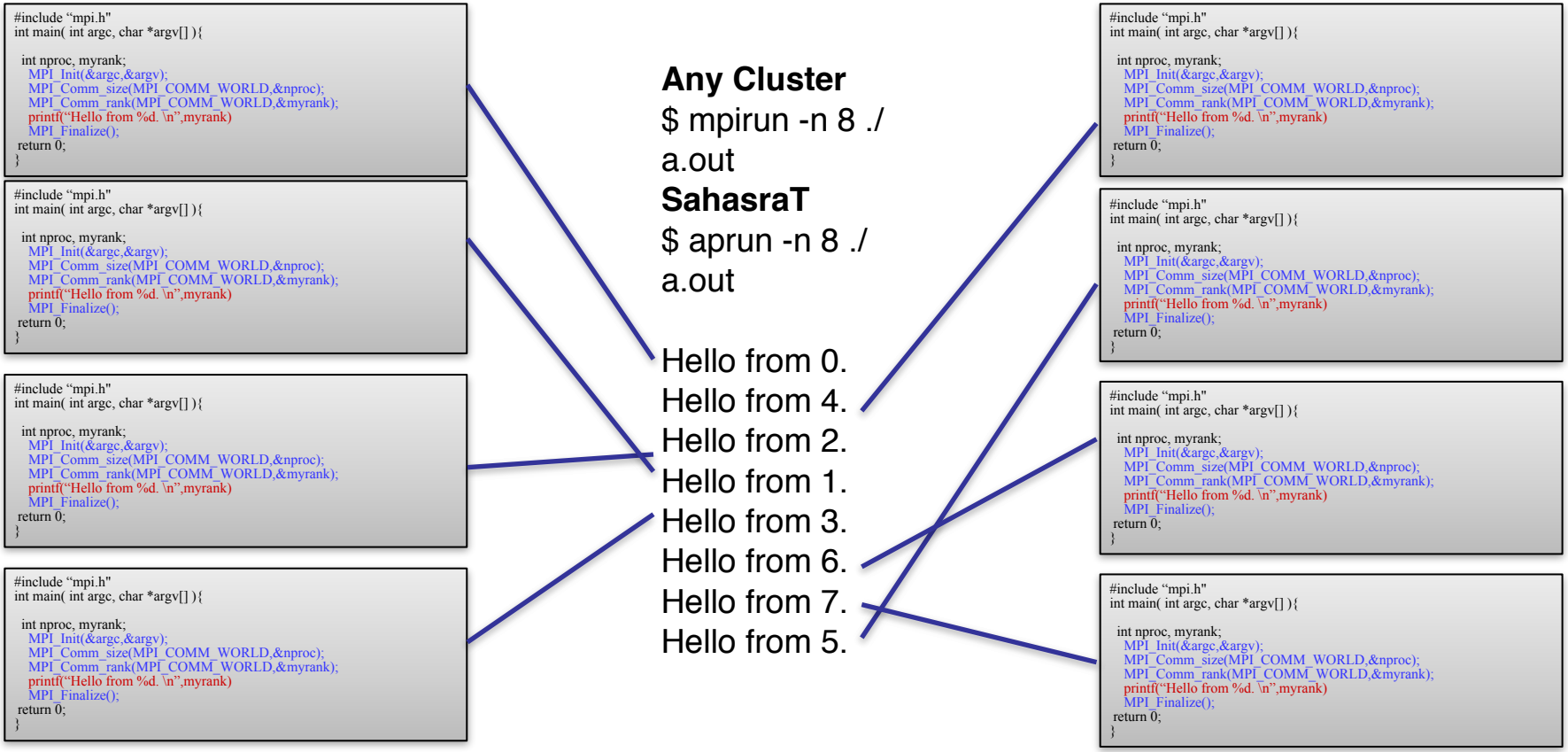
MPI Communicators

- **An MPI Function: MPI_Comm_size(MPI_COMM_WORLD, &nproc);**
- **MPI_COMM_WORLD** - communicator
- A communicator is a group of processes
  - Each process has a unique rank within a specific communicator
  - Rank starts from **0** and has a maximum value of (nproc-1). Fortran programmers beware!
  - Internal mapping of processes to processing units
  - Necessary to specify communicator when initiating a communication by calling an MPI function or routine.
- Default communicator MPI_COMM_WORLD, which contains all available processes.
- Several communicators can coexist
  - A process can belong to different communicators at the same time, but has a unique rank in each communicator

A sample MPI program in Fortran 90

```
Program mpi_code
  ! Load MPI definitions
    use mpi  (or include mpif.h)

  ! Initialize MPI
    call MPI_Init(ierr)
  ! Get the number of processes
    call MPI_Comm_size(MPI_COMM_WORLD,nproc,ierr)
  ! Get my process number (rank)
    call MPI_Comm_rank(MPI_COMM_WORLD,myrank,ierr)

    Do work and make message passing calls…

  ! Finalize
    call MPI_Finalize(ierr)

end program mpi_code
```

When hello-mpi runs

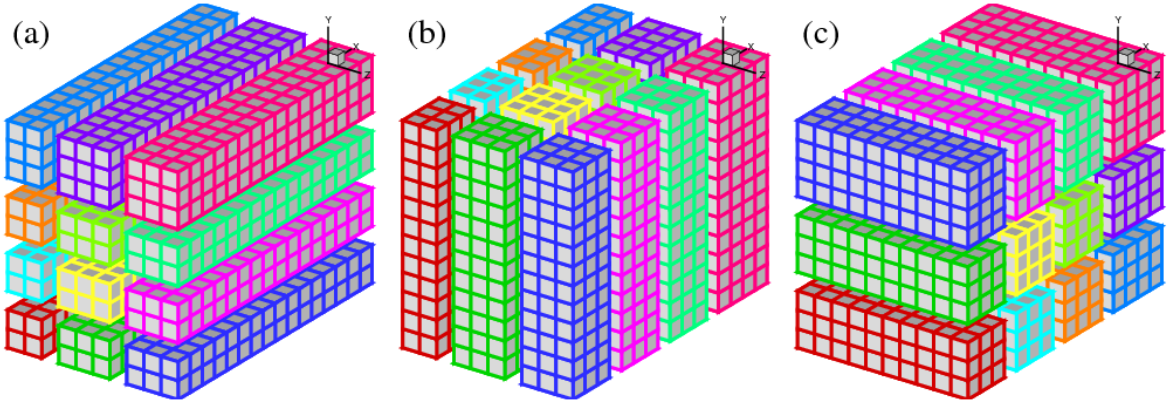


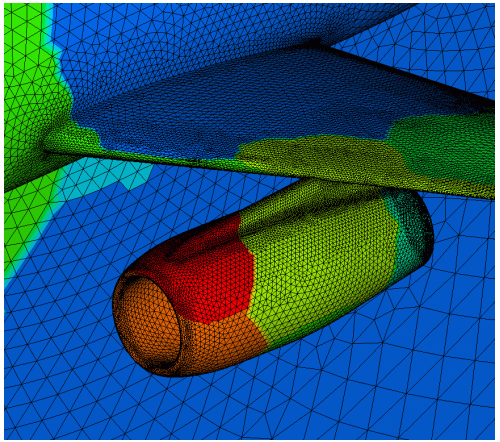
How much do I need to know?

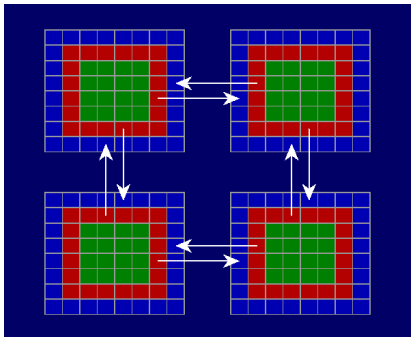
- MPI is large: MPI-1 has over 125 functions/subroutines. MPI-3 has over 400
- MPI is small: Can actually most work with about 6 functions!
- Collective functions are EXTREMELY useful since they simplify the coding and vendors optimize them for their interconnect hardware
- One can access flexibility when it is required.
- One need not master all parts of MPI to use it.

How to split the work between ranks?
Domain Decomposition

- Most widely used method for grid-based calculations

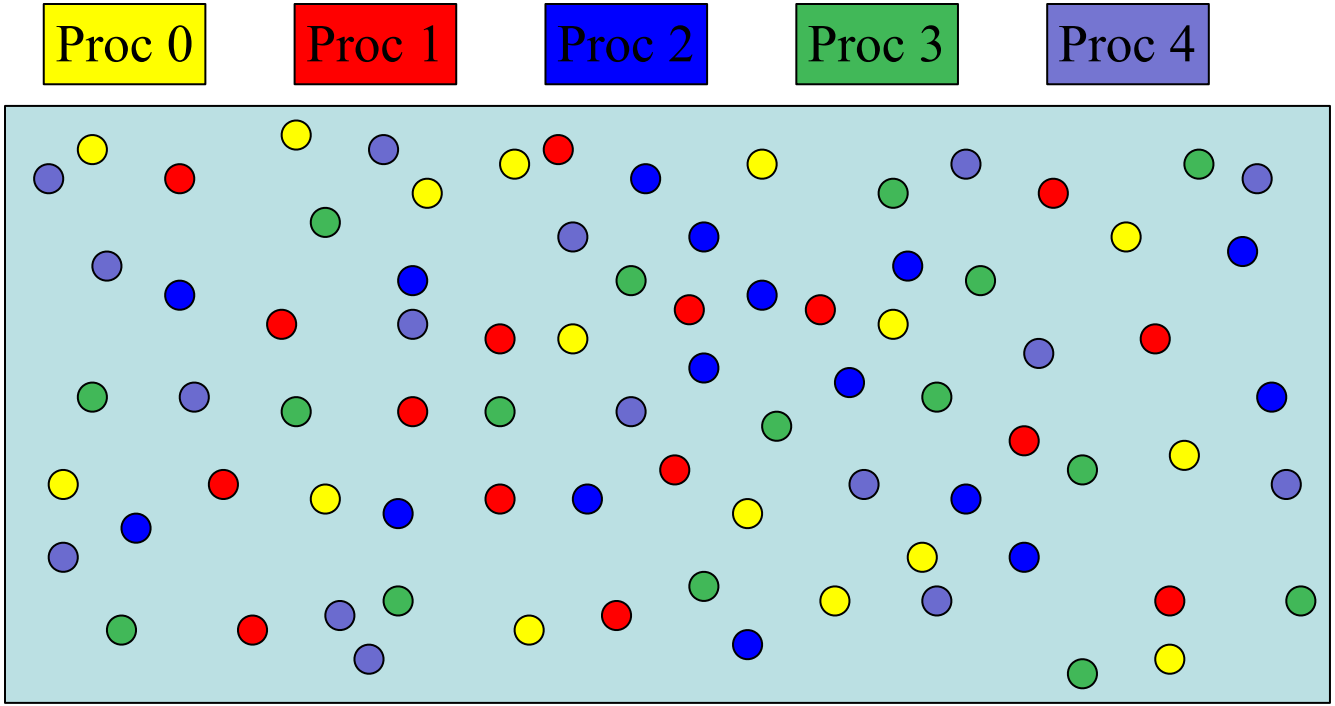






How to split the work between ranks?
"Coloring"

- Useful for particle simulations



MPI Function Categories

- MPI calls to exchange data
  - Point-to-Point communications
    - Only 2 processes exchange data
    - It is the basic operation of all MPI calls
  - Collective communications
    - A single call handles the communication between all the processes in a communicator
    - There are 2 types of collective communications
      - Data movement (e.g. MPI_Bcast)
      - Reduction (e.g. MPI_Reduce)
- Synchronization:
  - MPI_Barrier
  - MPI_Wait

Send Message: MPI_Send

```
MPI_Send(&numToSend,1,MPI_INT,0,10,MPI_COMM_WORLD);
```

&numToSend	Pointer to whatever information to send. In this case, an integer
1	the number of items to send. If sending a vector of 10 int's, we would point to the first one in the above argument and set this to the size of the array.
MPI_INT	the type of object we are sending. In this case, an integer
0	Destination of the message. In this case, Rank 0
10	Message Tag. Useful to identify/sort messages
MPI_COMM_WORLD	We don’t have any subsets yet. We just choose the “default”

Point to point: 2 processes at a time

```
MPI_Recv(recvbuf,count,datatype,source,tag,comm,status)

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

Datatypes are:

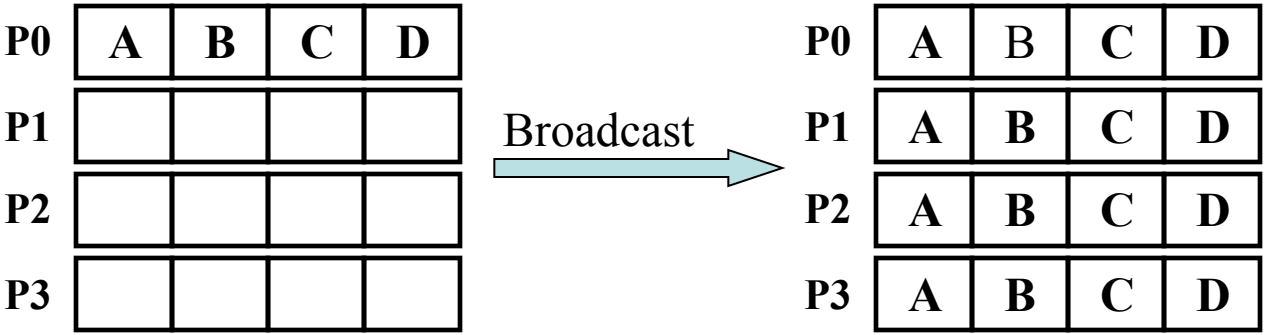
FORTRAN: MPI_INTEGER, MPI_REAL, MPI_DOUBLE_PRECISION, MPI_COMPLEX,MPI_CHARACTER, MPI_LOGICAL, etc…

C : MPI_INT, MPI_LONG, MPI_SHORT, MPI_FLOAT, MPI_DOUBLE, etc…

Predefined Communicator: MPI_COMM_WORLD

Collective communication: Broadcast

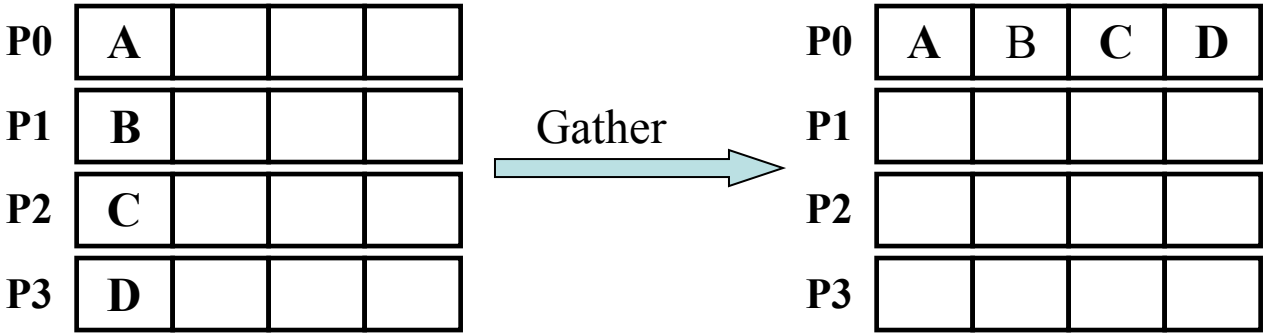
```
MPI_Bcast(buffer,count,datatype,root,comm,ierr)
```



- One process (called “root”) sends data to all the other processes in the same communicator
- Must be called by ALL processes with the same arguments

Collective communication: Gather

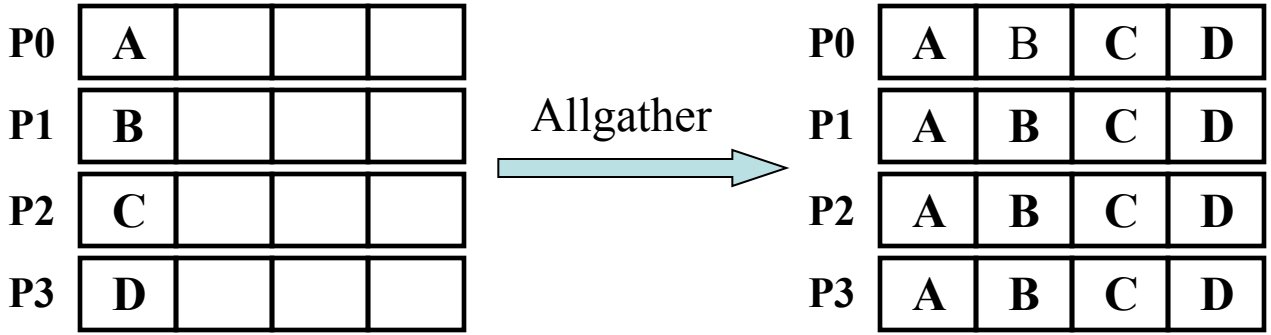
```
MPI_Gather(sendbuf,sendcount,sendtype,recvbuf,recvcount,
           recvtype,root,comm,ierr)
```



- One root process collects data from all the other processes in the same communicator
- Must be called by all the processes in the communicator with the same arguments
- "sendcount" is the number of basic datatypes sent, not received (example above would be sendcount = 1)
- Make sure that you have enough space in your receiving buffer!

Collective communication: Gather to All

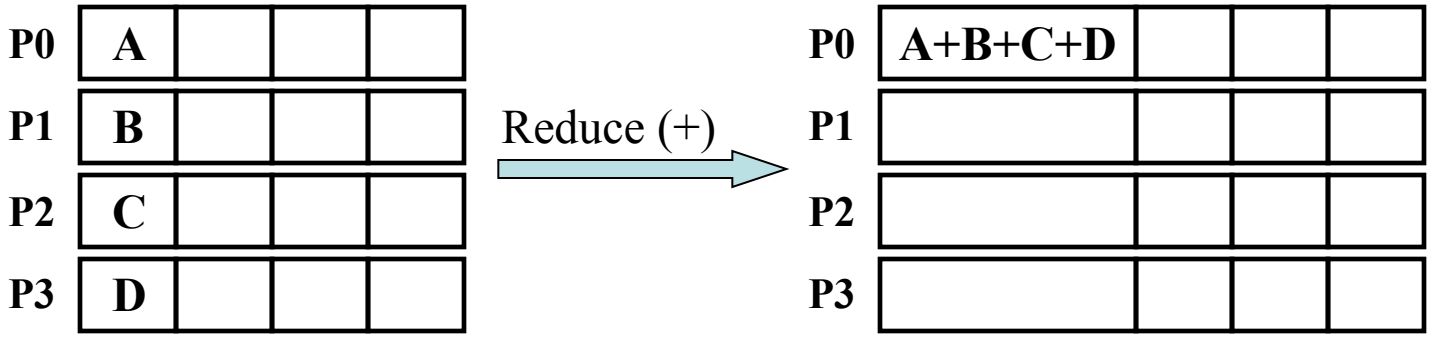
```
MPI_Allgather(sendbuf,sendcount,sendtype,recvbuf,recvcount,
              recvtype,comm,info)
```



- All processes within a communicator collect data from each other and end up with the same information
- Must be called by all the processes in the communicator with the same arguments
- Again, sendcount is the number of elements sent

Collective communication: Reduction

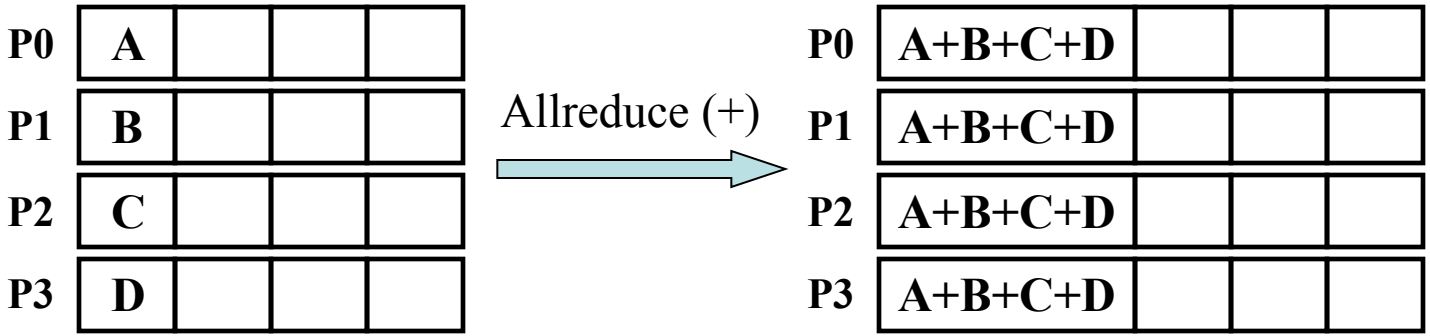
```
MPI_Reduce(sendbuf,recvbuf,count,datatype,op,root,comm,ierr)
```



- One root process collects data from all the other processes in the same communicator and performs an operation on the received data
- Called by all the processes with the same arguments
- Operations are: MPI_SUM, MPI_MIN, MPI_MAX, MPI_PROD, logical AND, OR, XOR, and a few more
- User can define own operation with MPI_Op_create()

Collective communication: Reduction to All

```
MPI_Allreduce(sendbuf,recvbuf,count,datatype,op,comm,ierr)
```



- All processes within a communicator collect data from all the other processes and performs an operation on the received data
- Called by all the processes with the same arguments
- Operations are the same as for MPI_Reduce

More MPI collective calls

One "root" process send a different piece of the data to each one of the other Processes (inverse of gather)

```
MPI_Scatter(sendbuf,sendcnt,sendtype,recvbuf,recvcnt,
            recvtype,root,comm,ierr)
```

Each process performs a scatter operation, sending a distinct message to all the processes in the group in order by index.

```
MPI_Alltoall(sendbuf,sendcount,sendtype,recvbuf,recvcnt,
             recvtype,comm,ierr)
```

Synchronization: When necessary, all the processes within a communicator can be forced to wait for each other although this operation can be expensive

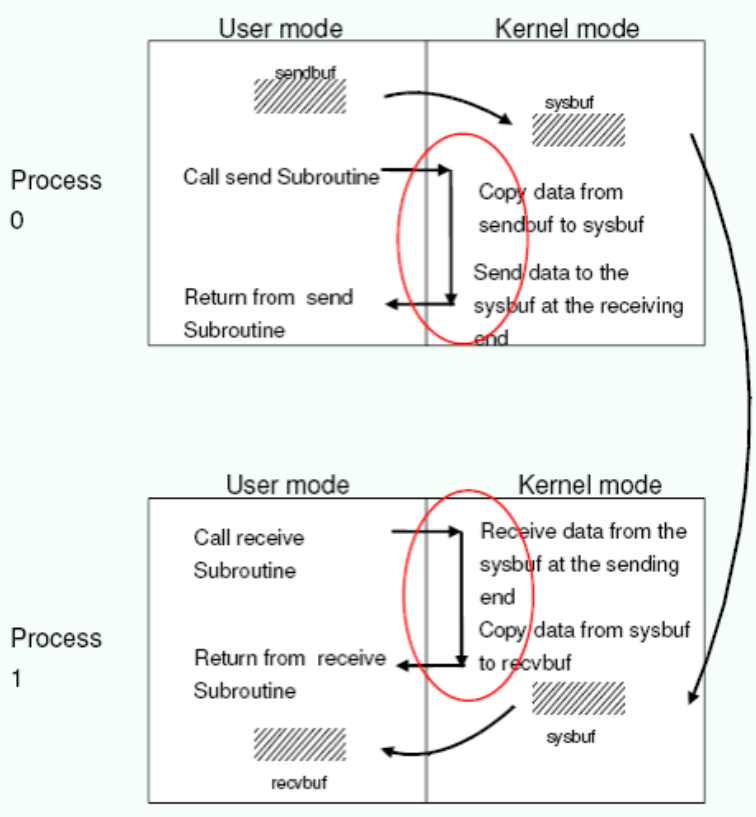
```
MPI_Barrier(comm,ierr)
```

How to time your MPI code

- Several possibilities but MPI provides an easy to use function called "MPI_Wtime()". It returns the number of seconds since an arbitrary point of time in the past.

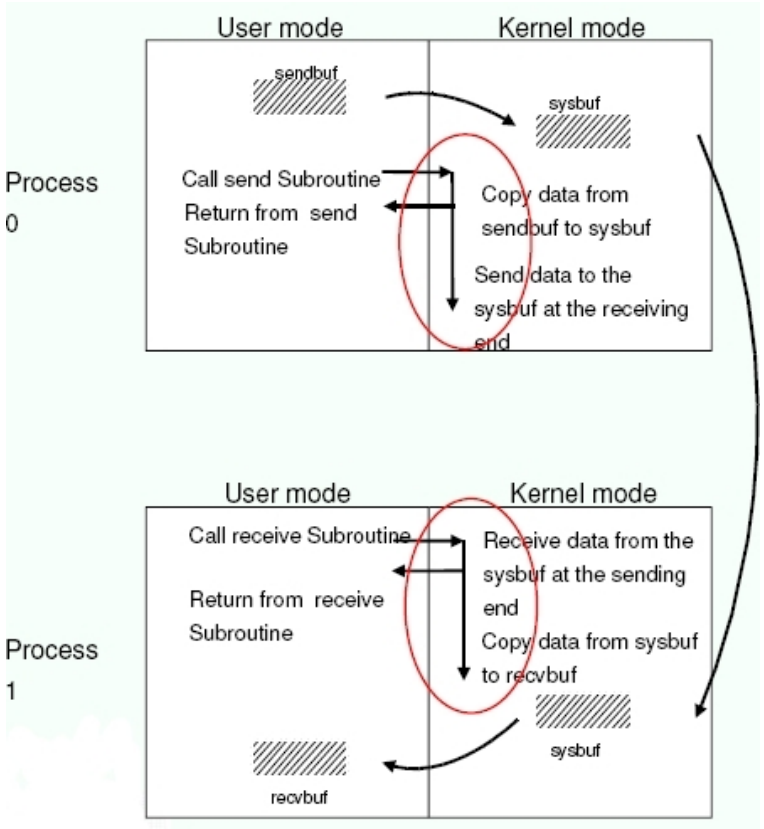
```
FORTRAN: double precision MPI_WTIME()
      C: double MPI_Wtime()

starttime=MPI_WTIME()
   ... program body ...
endtime=MPI_WTIME()
elapsetime=endtime-starttime
```

Blocking communications



- The call waits until the data transfer is done
  - The sending process waits until all data are transferred to the system buffer (differences for *eager vs rendezvous* protocols...)
  - The receiving process waits until all data are transferred from the system buffer to the receive buffer
- All collective communications are blocking

Non-blocking



- Returns immediately after the data transferred is initiated
- Allows to overlap computation with communication
- Need to be careful though
  - When send and receive buffers are updated before the transfer is over, the result will be wrong

Debugging tips

Use "unbuffered" writes to do "printf-debugging" and always write out the process id:

```
C:       fprintf(stderr,"%d: …",myid,…);
Fortran: write(0,*)myid,': …'
```

If the code detects an error and needs to terminate, use MPI_ABORT. The errorcode is returned to the calling environment so it can be any number.

```
C:       MPI_Abort(MPI_Comm comm, int errorcode);
Fortran: call MPI_ABORT(comm, errorcode, ierr)
```

Use a parallel debugger such as Totalview or DDT

References

- Keywords for google “mpi”, or “mpi standard”, or “mpi tutorial”…
- https://www.mpich.org/static/docs/latest/
- http://www.mpi-forum.org (location of the MPI standard)
- http://www.llnl.gov/computing/tutorials/mpi/
- http://www.nersc.gov/nusers/help/tutorials/mpi/intro/

- MPI on Linux clusters:
  - MPICH (http://www-unix.mcs.anl.gov/mpi/mpich/)
  - Open MPI (http://www.open-mpi.org/)

Example: calculating π using numerical integration

```
#include <stdio.h>
#include <math.h>
int main( int argc, char *argv[] )
{
    int n, myid, numprocs, i;
    double PI25DT = 3.14159265358979323846264 3;
    double mypi, pi, h, sum, x;
    FILE *ifp;

    ifp = fopen("ex4.in","r");
    fscanf(ifp,"%d",&n);
    fclose(ifp);
    printf("number of intervals = %d\n",n);

    h   = 1.0 / (double) n;
    sum = 0.0;
    for (i = 1; i <= n; i++) {
        x = h * ((double)i - 0.5);
        sum += (4.0 / (1.0 + x*x));
    }
    mypi = h * sum;

    pi = mypi;
    printf("pi is approximately %.16f, Error is %.16f\n",
           pi, fabs(pi - PI25DT));
    return 0;
}
```

C version

Root reads input and broadcast to all

```
#include "mpi.h"
#include <stdio.h>
#include <math.h>
int main( int argc, char *argv[] )
{
    int n, myid, numprocs, i, j, tag, my_n;
    double PI25DT = 3.14159265358979323846264643;
    double mypi,pi,h,sum,x,pi_frac,tt0,tt1,ttf;
    FILE *ifp;
    MPI_Status  Stat;
    MPI_Request request;

    n = 1;
    tag = 1;
    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);

    tt0 = MPI_Wtime();
    if (myid == 0) {
       ifp = fopen("ex4.in","r");
       fscanf(ifp,"%d",&n);
       fclose(ifp);
       //printf("number of intervals = %d\n",n);
    }
 /* Global communication. Process 0 "broadcasts" n to all other processes */
    MPI_Bcast(&n, 1, MPI_INT, 0, MPI_COMM_WORLD);
```

Each process calculates its section of the integral and adds up results with MPI_Reduce

```
…
    h   = 1.0 / (double) n;
    sum = 0.0;
    for (i = myid*n/numprocs+1; i <= (myid+1)*n/numprocs; i++) {
        x = h * ((double)i - 0.5);
        sum += (4.0 / (1.0 + x*x));
    }
    mypi = h * sum;

    pi = 0.;  /* It is not necessary to set pi = 0 */

 /* Global reduction. All processes send their value of mypi to process 0
    and process 0 adds them up (MPI_SUM) */
    MPI_Reduce(&mypi, &pi, 1, MPI_DOUBLE, MPI_SUM, 0, MPI_COMM_WORLD);

    ttf = MPI_Wtime();
    printf("myid=%d  pi is approximately %.16f, Error is %.16f  time = %10f\n",
              myid, pi, fabs(pi - PI25DT), (ttf-tt0));

    MPI_Finalize();
    return 0;
}
```

Thank you...

Non-blocking send and receive

Point to point:

```
MPI_Isend(buf,count,datatype,dest,tag,comm,request,ierr)

MPI_Irecv(buf,count,datatype,source,tag,comm,request,ierr)
```

The functions MPI_Wait and MPI_Test are used to complete a nonblocking communication

```
MPI_Wait(request,status,ierr)

MPI_Test(request,flag,status,ierr)
```

MPI_Wait returns when the operation identified by "request" is complete. This is a non-local operation.

MPI_Test returns "flag = true" if the operation identified by "request" is complete. Otherwise it returns "flag = false". This is a local operation.

MPI-3 standard introduces "non-blocking collective calls"