



# Introduction to Message Passing Interface (MPI)

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# Outline

- Introduction – what is MPI and why MPI?
- Basic MPI functions
  - Environment and communicator management
  - Collective communication
  - Point to point communication
- An example of how to parallelize a serial code





# Message Passing

- Context: distributed memory parallel computers
  - Each processor has its own memory and cannot access the memory of other processors
  - Any data to be shared must be explicitly transmitted from one to another
- Most message passing programs use the *single program multiple data* (SPMD) model
  - Each processor executes the same set of instructions
  - Parallelization is achieved by letting each processor operate on a different piece of data





# MPI: Message Passing Interface

- MPI defines a **standard** API for message passing
  - What's in the standard:
    - A core set of functions
    - Both the syntax and semantics of these functions
  - What's not in the standard:
    - How to compile and link the code
    - How many processes on which the code will run
- MPI provides both C and Fortran bindings





# Why MPI?

- Portability
  - MPI implementations are available on almost all platforms
- Explicit parallelization
  - Users have control on when, where and how the data transmit occurs
- Scalability
  - Not limited by the number of processors on one computation node, as opposed to shared-memory parallel models





# MPI Functions

- Environment and communicator management functions
  - Initialization and termination
  - Communicator setup
- Collective communication functions
  - Message transfer involving all processes in a communicator
- Point-to-point communication functions
  - Message transfer from one process to another





# A sample MPI program

```
...  
include 'mpif.h'  
...  
call mpi_init(ierr)  
...  
call mpi_comm_size(comm,size,ierr)  
call mpi_comm_rank(comm,rank,ierr)  
...  
call mpi_finalize(ierr)  
...
```





# Header file

```
...  
include 'mpif.h'  
...  
call mpi_init(ierr)  
...  
call mpi_comm_size(comm, size, ierr)  
call mpi_comm_rank(comm, rank, ierr)  
...  
call mpi_finalize(ierr)
```

- Defines MPI-related parameters
- Must be included
- C/C++: mpi.h







# Initialization

```

...
include 'mpif.h'
...
call mpi_init(ierr)
...
call mpi_comm_size(comm,size,ierr)
call mpi_comm_rank(comm,rank,ierr)
...
call mpi_finalize(ierr)

```

- Must be called before any other MPI calls;
- MPI\_Init() for C and MPI::Init() for C++





# Termination

```
...  
include 'mpif.h'  
...  
call mpi_init(ierr)  
...  
call mpi_comm_size(comm, size, ierr)  
call mpi_comm_rank(comm, rank, ierr)  
...  
call mpi_finalize(ierr)
```

- Must be called after all other MPI calls;
- MPI\_Finalize() for C and MPI::Finalize() for C++





# Communicator size

```
...  
include 'mpif.h'  
...  
call mpi_init(ierr)  
...  
call mpi_comm_size(comm, size, ierr)  
call mpi_comm_rank(comm, rank, ierr)  
...  
call mpi_finalize(ierr)
```

- Return the number of processes (`size`) in a communicator (`comm`);
- `MPI_Comm_size` for C and `MPI::Comm::Get_size` for C++





# Process rank

```
...  
include 'mpif.h'  
...  
call mpi_init(ierr)  
...  
call mpi_comm_size(comm, size, ierr)  
call mpi_comm_rank(comm, rank, ierr)  
...  
call mpi_finalize(ierr)
```

- Return the rank of the current processes (`rank`) in a communicator (`comm`);
- Allow us to make the behavior of each process different by using the value of its rank;
- `MPI_Comm_rank` for C and `MPI::Comm::Get_rank` for C++





# Example

```
include 'mpif.h'  
call mpi_init(ierr)  
call mpi_comm_size(comm,size,ierr)  
call mpi_comm_rank(comm,rank,ierr)  
if (rank.eq.0) then  
    print(*,*) 'I am the root'  
    print(*,*) 'My rank is',rank  
else  
    print(*,*) 'I am not the root'  
    print(*,*) 'My rank is',rank  
endif  
call mpi_finalize(ierr)
```

## Output (assume 3 processes):

```
I am not the root  
My rank is 2  
I am the root  
My rank is 0  
I am not the root  
My rank is 1
```





# Communicators

- A communicator is an identifier associated with a group of processes
  - Can think of it as an ordered list of processes (a mapping from MPI processes to physical processes)
  - Each process has a unique id (rank) within a communicator
    - Ex: if there are 8 processes in a communicator, their ranks will be 0, 1, ..., 7.
  - It is the context of any MPI communication
    - Unless a context is specified, MPI cannot understand “get this message to **all** processes” or “ get this message from process **#1** to process **#2**”.





# More on communicators

- MPI\_COMM\_WORLD: default communicator contains all processes
- More than one communicators can co-exist
  - Useful when communicating among a subset of processes
- A process can belong to different communicators
  - Ex: A physical process can be proc #4 in comm1 and proc #0 in comm2
  - An analogy is that a person can have different identities under different contexts





# Point-to-point communication

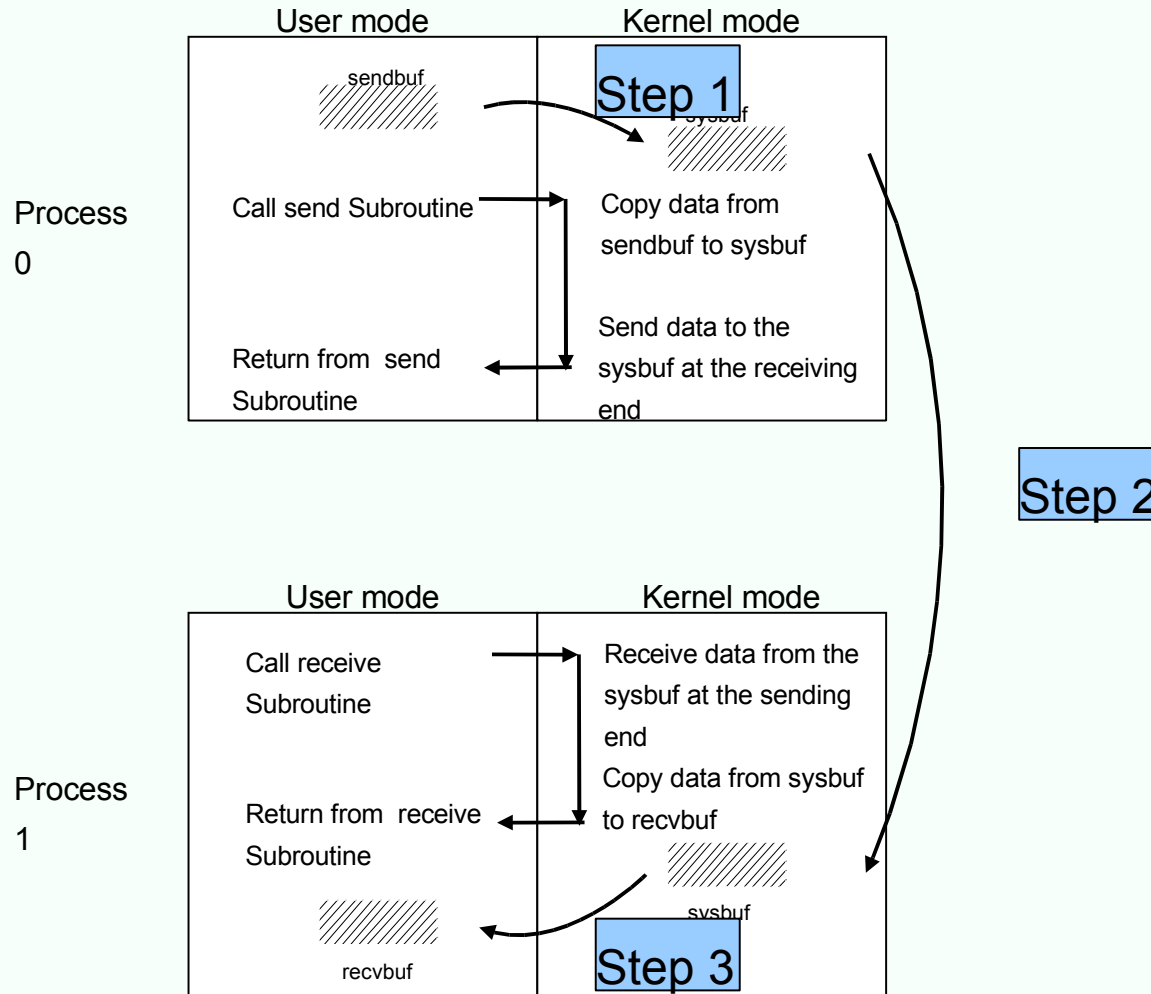
- Process to process communication (two processes are involved)
- There are two types of point-to-point communication
  - Blocking
  - Non-blocking





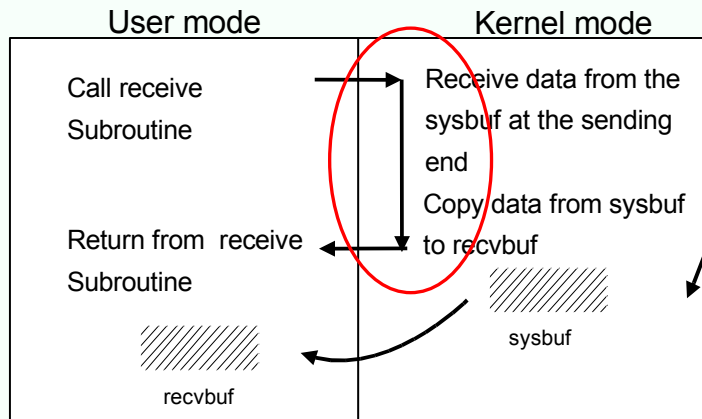
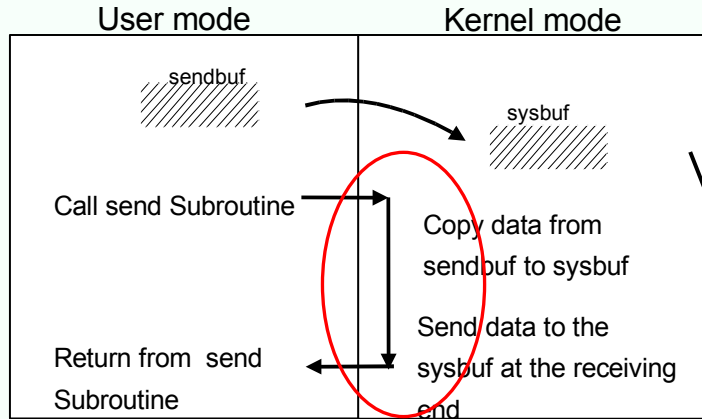


# Basic concept





# Blocking

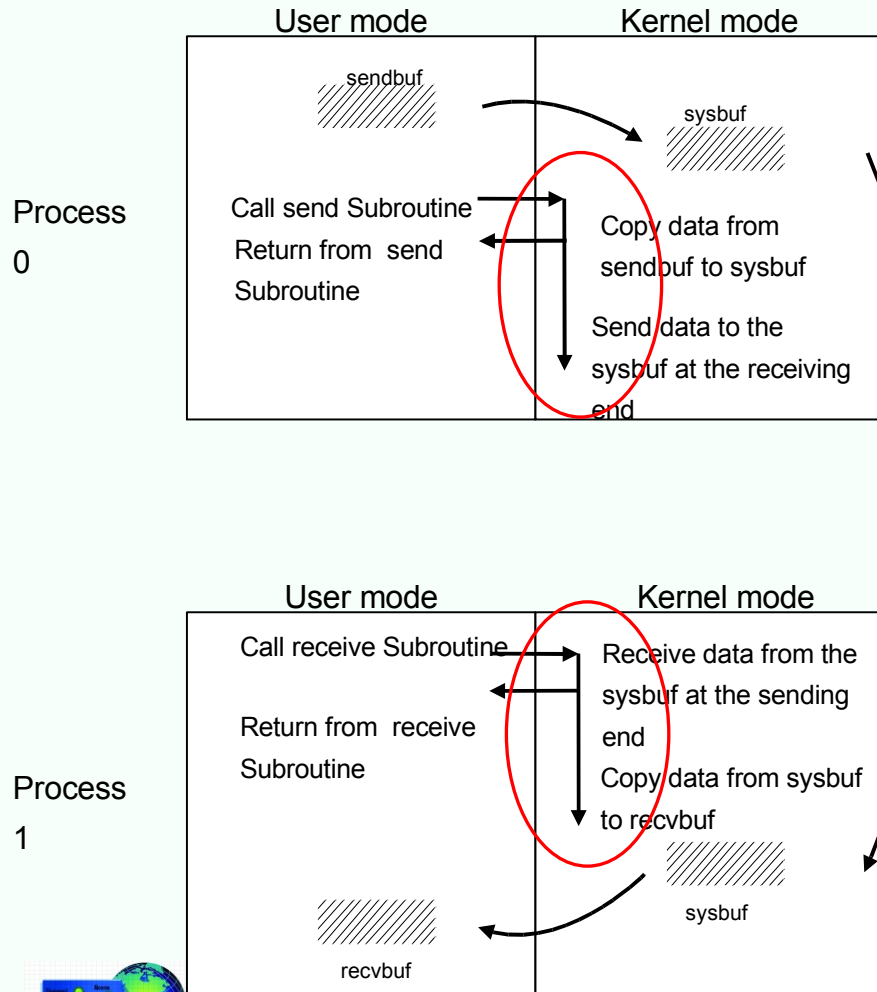


- The call will wait until the data transfer process is over.
  - The sending process will wait until all data are transferred from the send buffer to the system buffer.
  - The receiving process will wait until all data are transferred from the system buffer to the receive buffer
- All collective communications are blocking





# Non-blocking



- Returns immediately after the data transfer is initiated.
- More efficient than blocking procedures
- Could cause problems
  - When send and receive buffers are updated before the transfer is over, the result might not be the one expected
  - Example provided in the hand-on lab





# Examples

- Transfer data from process 0 to process 1
  - Blocking send and receive

```
IF (myrank==0) THEN
  CALL MPI_SEND(sendbuf, count, datatype, destination, tag, comm, ierror)
ELSEIF (myrank==1) THEN
  CALL MPI_RECV(recvbuf, count, datatype, source, tag, status, comm, ierror)
ENDIF
```

- Non-blocking send and receive

```
IF (myrank==0) THEN
  CALL MPI_ISEND(sendbuf, count, datatype, destination, tag, comm, ireq, ierror)
ELSEIF (myrank==1) THEN
  CALL MPI_Irecv(recvbuf, count, datatype, source, tag, comm, ireq, ierror)
ENDIF
CALL MPI_WAIT(ireq, istatus, ierror)
```





# Data exchange between 2 processes

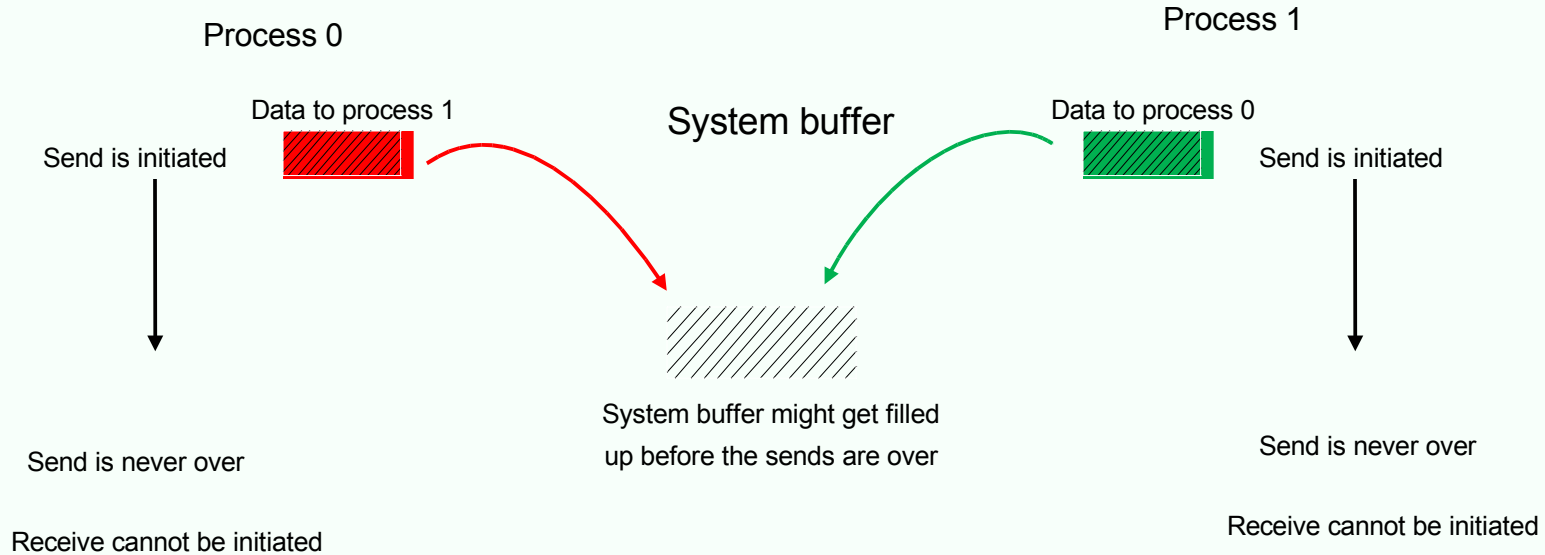
- We can do two separate send-receive pairs
  - Inefficient
- Simultaneous send-receive
  - Efficient
  - Possible deadlock
    - One processor is waiting for a message from the other, which is also waiting for a message from the first – nothing will happen and your job will be killed when the queue time runs out (MPI does not have timeout!!!)
    - Something to avoid

```
IF (myrank==0) THEN
  CALL MPI_SEND(sendbuf,...)
  CALL MPI_RECV(recvbuf,...)
ELSEIF (myrank==1) THEN
  CALL MPI_SEND(sendbuf,...)
  CALL MPI_RECV(recvbuf,...)
ENDIF
```





# Deadlock



```

IF (myrank==0) THEN
  CALL MPI_SEND(sendbuf, ...)
  CALL MPI_RECV(recvbuf, ...)
ELSEIF (myrank==1) THEN
  CALL MPI_SEND(sendbuf, ...)
  CALL MPI_RECV(recvbuf, ...)
ENDIF
  
```





# Solution for deadlock

```
IF (myrank==0) THEN
  CALL MPI_ISEND(sendbuf, ...)
  CALL MPI_RECV(recvbuf, ...)
  CALL MPI_WAIT(ireq, ...)
ELSEIF (myrank==1) THEN
  CALL MPI_ISEND(sendbuf, ...)
  CALL MPI_RECV(recvbuf, ...)
  CALL MPI_WAIT(ireq, ...)
ENDIF
```

- Non-blocking send

- Process 0: Start sending; then start receiving while the data is being sent;
- Process 1: Start sending; then start receiving while the data is being sent;





# Collective communication

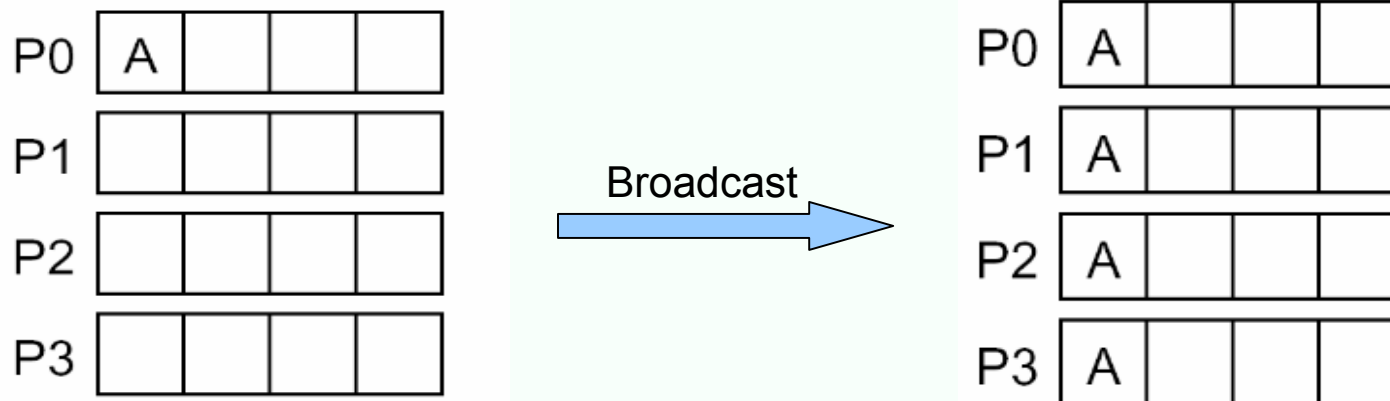
- Collective communications are communications that involve all processes in a communicator
- There are three types of collective communications
  - Data movement
    - Example: `mpi_bcast`
  - Reduction (computation)
    - Example: `mpi_reduce`
  - Synchronization
    - Example: `mpi_barrier`







## Broadcast



- Send data from one process (called root) to all other processes in the same communicator.
- Called by all processes in the communicator using the same arguments





# Example

```

PROGRAM bcast
INCLUDE 'mpif.h'
INTEGER imsg(4)
CALL MPI_INIT(ierr)
CALL MPI_COMM_SIZE(MPI_COMM_WORLD, nprocs, ierr)
CALL MPI_COMM_RANK(MPI_COMM_WORLD, myrank, ierr)
IF (myrank==0) THEN
    DO i=1,4
        imsg(i) = i
    ENDDO
ELSE
    DO i=1,4
        imsg(i) = 0
    ENDDO
ENDIF
PRINT *, 'Before:', imsg
CALL MP_FLUSH(1)
CALL MPI_BCAST(imsg, 4, MPI_INTEGER,
&                0, MPI_COMM_WORLD, ierr)
PRINT *, 'After :', imsg
CALL MPI_FINALIZE(ierr)
END
    
```

## Output

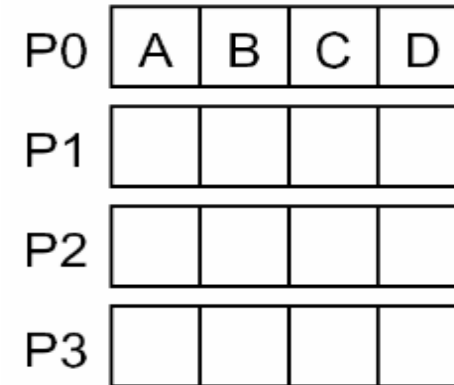
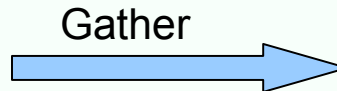
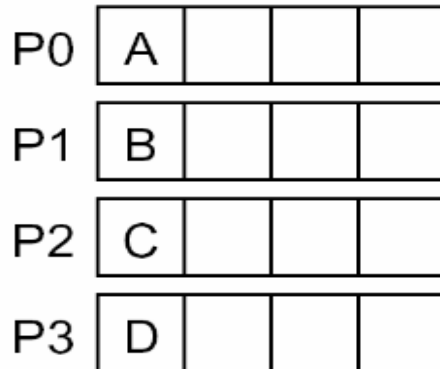
```

0: Before: 1 2 3 4
1: Before: 0 0 0 0
2: Before: 0 0 0 0
0: After  : 1 2 3 4
1: After  : 1 2 3 4
2: After  : 1 2 3 4
    
```





## Gather



- Collects data from all processes in the communicator to the root process (the data have to be of the same size).
- Called by all processes in the communicator using the same arguments





# Example

```
PROGRAM gather
INCLUDE 'mpif.h'
INTEGER irecv(3)
CALL MPI_INIT(ierr)
CALL MPI_COMM_SIZE(MPI_COMM_WORLD, nprocs, ierr)
CALL MPI_COMM_RANK(MPI_COMM_WORLD, myrank, ierr)
isend = myrank + 1
CALL MPI_GATHER(isend, 1, MPI_INTEGER,
&               irecv, 1, MPI_INTEGER,
&               0, MPI_COMM_WORLD, ierr)
IF (myrank==0) THEN
  PRINT *, 'irecv =', irecv
ENDIF
CALL MPI_FINALIZE(ierr)
END
```

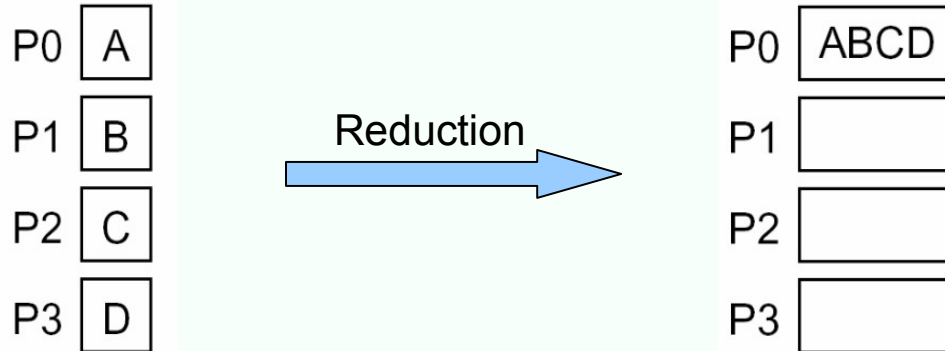
## Output

```
0: irecv = 1 2 3
```





## Reduction



- Similar to gather: collects data from all processes
- Then perform some operation on the collected data.
- Called by all processes in the communicator using the same arguments





# Reduction operations

- Summation and production
- Maximum and minimum
- Max and min location
- Logical (AND & OR & XOR)
- Bitwise (AND & OR & XOR)
- User defined
  - Subroutine `mpi_op_create`





# Examples

```
PROGRAM reduce
INCLUDE 'mpif.h'
CALL MPI_INIT(ierr)
CALL MPI_COMM_SIZE(MPI_COMM_WORLD, nprocs, ierr)
CALL MPI_COMM_RANK(MPI_COMM_WORLD, myrank, ierr)
isum = 0
ista = myrank * 3 + 1
iend = ista + 2
DO i=ista,iend
  isum = isum + i
ENDDO
CALL MPI_REDUCE(isum, itmp, 1, MPI_INTEGER, MPI_SUM, 0,
&               MPI_COMM_WORLD, ierr)
isum = itmp
IF (myrank==0) THEN
  PRINT *, 'isum =', isum
ENDIF
CALL MPI_FINALIZE(ierr)
END
```

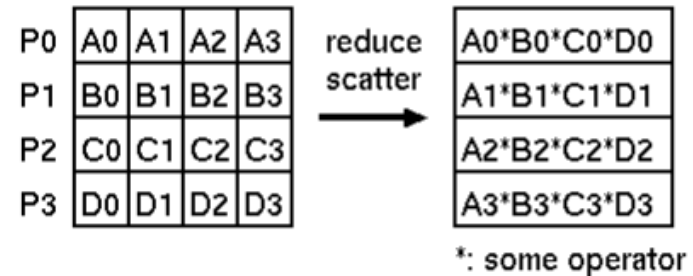
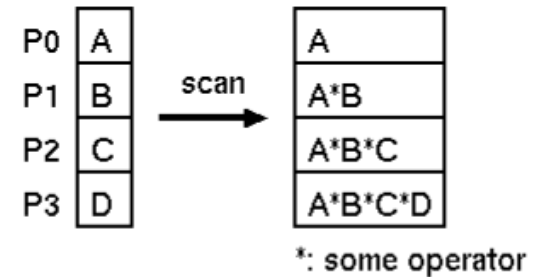
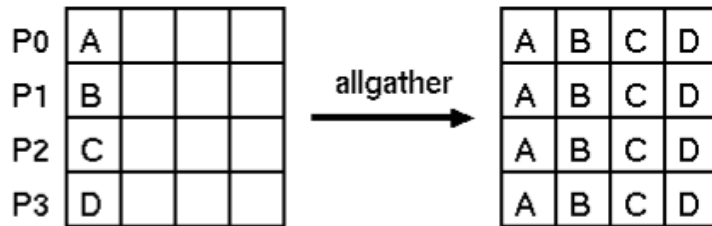
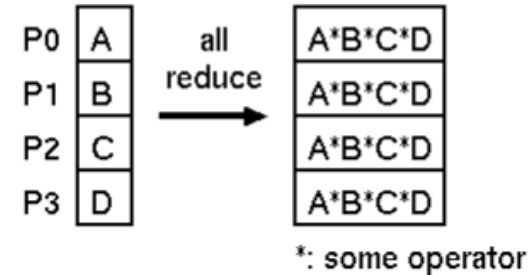
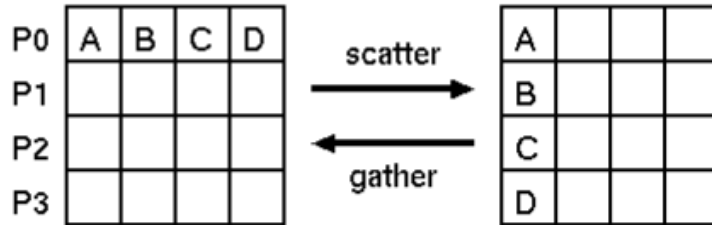
Output (with 3 processors)

```
0: isum = 45
```





## Some other collective communication







# Synchronization

- Called by all processes in a communicator
- Blocks each process in the communicator until all processes have called it.
- It can slow down the program remarkably, so do not use it unless really necessary





# Steps to parallelize a serial program

- Make sure the serial code works!
- Identify which part of your code will be parallelized
  - Which part consumes most of the CPU time
  - Which part can be parallelized
- Decide the details
  - How loops are parallelized
  - What data has to be transmitted between processes (the less the better)





# Example

! The serial version

Program summation\_ser

...

total=0.

do i=1,n

do j=1,n

<compute some\_result>

total=total+some\_result

enddo

enddo

...

In Case of n=10, nprocs=4

i	1	2	3	4	5	6	7	8	9	10
Process	0	0	0	1	1	1	2	2	3	3

! The parallel version

Program summation\_par

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

...

```
call mpi_init(ierr)
```

```
call mpi_comm_size(mpi_comm_world,nprocs,ierr)
```

```
call mpi_comm_rank(mpi_comm_world,myrank,ierr)
```

```
iwork=(n-1)/nprocs+1
```

```
ista=min(myrank*iwork+1,n+1)
```

```
iend=min(ista+iwork-1,10)
```

```
total_proc=0.
```

```
do i=ista,iend
```

```
do j=1,n
```

```
<compute some_result>
```

```
total_proc=total_proc+some_result
```

```
enddo
```

```
enddo
```

```
call mpi_reduce(total_proc,total,  
1,mpi_real8,mpi_sum,0,mpi_comm_world,ierr)
```

...

```
call mpi_finalize(ierr)
```

...





# Alternative

! The serial version

Program summation\_ser

...

total=0.

do i=1,n

do j=1,n

<compute some\_result>

total=total+some\_result

enddo

enddo

...

In Case of n=10, nprocs=4

i	1	2	3	4	5	6	7	8	9	10
Process	0	1	2	3	0	1	2	3	0	1

! The parallel version

Program summation\_par\_v2

include 'mpif.h'

...

call mpi\_init(ierr)

call mpi\_comm\_size(mpi\_comm\_world,nprocs,ierr)

call mpi\_comm\_rank(mpi\_comm\_world,myrank,ierr)

total\_proc=0.

do i=1+myrank,n,nprocs

do j=1,n

<compute some\_result>

total\_proc=total\_proc+some\_result

enddo

enddo

call mpi\_reduce(total\_proc,total,  
1,mpi\_real8,mpi\_sum,0,mpi\_comm\_world,ierr)

...

call mpi\_finalize(ierr)

...





# References

- Internet

- <http://www.mpi-forum.org>
- <http://www.mcs.anl.gov/mpi>
- <http://docs.loni.org>
- <http://www.hpc.lsu.edu/help>

- Books

- *Using MPI*, by W. Gropp, E. Lusk and A. Skjellum
- *Using MPI-2*, by W. Gropp, E. Lusk and A. Skjellum
- *Parallel programming with MPI*, by P. Pacheco
- *Practical MPI Programming*, IBM Redbook





# Hand-on Labs

- How to get the lab material
  - Log in any cluster of your choice
  - Issue the following commands:
    - `cp -r ~lyan1/mpilab .`
    - `cd mpilab`
- What's in it
  - A *README* file
    - How to compile and run a MPI code
  - Two directories corresponding to different languages
    - *C*
    - *Fortran*





# Overview of the sample programs

- *hello.f90, hello.c*
  - Each process prints a “Hello, world!” message.
- *bcast.f90, bcast.c*
  - An example of the broadcast collective communication.
- *allgatherv.f90, allgatherv.c*
  - An example of the allgatherv collective communication.
- *reduceprod.f90, reduceprod.c*
  - An example of the reduce collective communication.





# Overview of the sample programs

- *pointcomm.f90, pointcomm.c*
  - Examples of blocking and non-blocking point-point communications, and the potential problem of non-blocking communication
- *pointbcast.f90, pointbcast.c*
  - Use point-point communication to perform a data transfer equivalent to the bcast collective communication
- *paraloop.f90, paraloop.c*
  - Two basic techniques to parallelize a DO loop: block and cyclic

