Programming with Message Passing PART II: MPI

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Overview

- MPI overview
- MPI process creation
- MPI point-to-point communication
- MPI collective communications
- MPI groups and communicators
- MPI virtual topologies
- MPE and Jumpshot
- Further reading

MPI

- Message Passing Interface (MPI) is an *API and protocol standard* with *portable implementations*
  - MPICH, LAM-MPI, OpenMPI, …
- Hardware platforms:
  - Distributed Memory
  - Shared Memory
    - Particularly SMP / NUMA architectures
  - Hybrid
    - SMP clusters, workstation clusters, and heterogeneous networks
- Parallelism is explicit
  - Programmer is responsible for correctly identifying parallelism and implementing parallel algorithms using MPI constructs
- SPMD model with static process creation
  - MPI-2 allows dynamic process creation: **`MPI_Comm_spawn()`**

MPI Process Creation

- Static process creation
  - Start a *N* processes running the same program *prog1*

    `mpirun` ***`prog1`*** **`-np`** ***`N`***

    but this does not specify where the prog1 copies run
  - Use batch processing tools, such as SGE, to run MPI programs on a cluster

- MPI-2 supports dynamic process creation:

  `MPI_Comm_spawn()`

MPI SPMD Computational Model

```
main(int argc, char *argv[])
{
  MPI_Init(&argc, &argv);

  doWork();

  MPI_Finalize();
}
```

All processes execute this work

All processes belong to the **MPI_COMM_WORLD** *communicator, and each process has a rank from 0 to P-1 in the communicator*

```
doWork()
{
  int myrank;
  MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
  if (myrank == 0)
    printf("I'm the master process");
}
```

Use rank numbers to differentiate work

MPI Point-to-point Send Format

"Data parameters" — &buf, count, datatype

"Envelope parameters" — dest, tag, comm

```
MPI_Send(&buf, count, datatype, dest, tag, comm)
```

- &buf: *Address of send buffer with data*
- count: *Number of items to send*
- datatype: *Data type of each item* **MPI_Datatype**
- dest: *Rank of destination process* (**int**)
- tag: *Message tag* (**int**)
- comm: *Communicator* **MPI_Comm**

MPI Point-to-point Recv Format

"Data parameters" *"Envelope parameters"*

```
MPI_Recv(&buf, count, datatype, src, tag, comm, &status)
```

Address of buffer to collect data

Maximum number of items to receive

Data type of each item `MPI_Datatype`

Rank of source process (`int`)

Message tag (`int`)

Communicator `MPI_Comm`

Status after operation `MPI_Status`

Example: Send-Recv Between two Processes

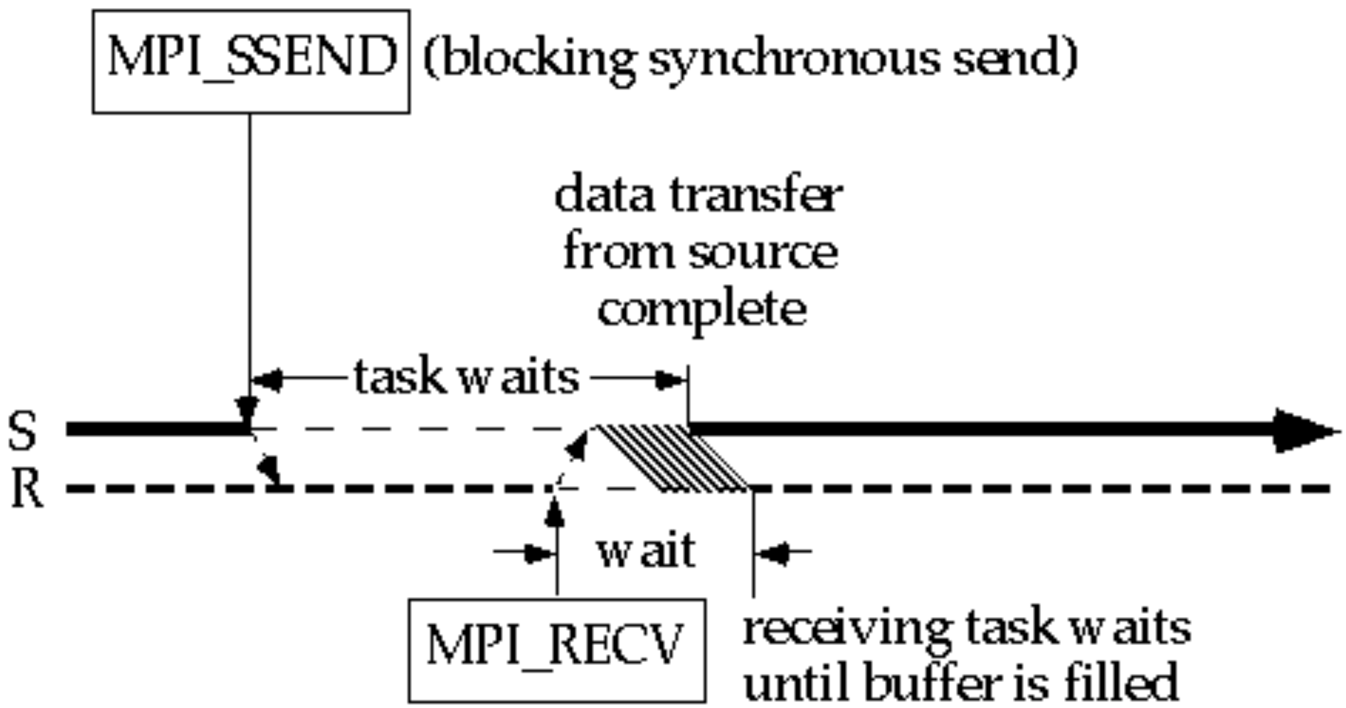
```
main(int argc, char *argv[])
{
  int myrank;
  int value = 123;
  MPI_Status status;

  MPI_Init(&argc, &argv);

  MPI_Comm_Rank(MPI_COMM_WORLD, &myrank);

  if (myrank == 0)
    MPI_Send(&value, 1, MPI_INT, 1, MPI_ANY_TAG, MPI_COMM_WORLD);
  else if (myrank == 1)
    MPI_Recv(&value, 1, MPI_INT, 0, MPI_ANY_TAG, MPI_COMM_WORLD, &status);

  MPI_Finalize();
}
```

MPI Point-to-point Communication Modes

Communication mode	Blocking routines	Nonblocking routines
Synchronous	**MPI_Ssend**	**MPI_Issend**
Ready	**MPI_Rsend**	**MPI_Irsend**
Buffered	**MPI_Bsend**	**MPI_Ibsend**
Standard	**MPI_Send**	**MPI_Isend**
	MPI_Recv	**MPI_Irecv**
	MPI_Sendrecv	
	MPI_Sendrecv_replace	

Roughly speaking: **MPI_*X*send** = **MPI_I*x*send** + **MPI_Wait**
MPI_Recv = **MPI_Irecv** + **MPI_Wait**

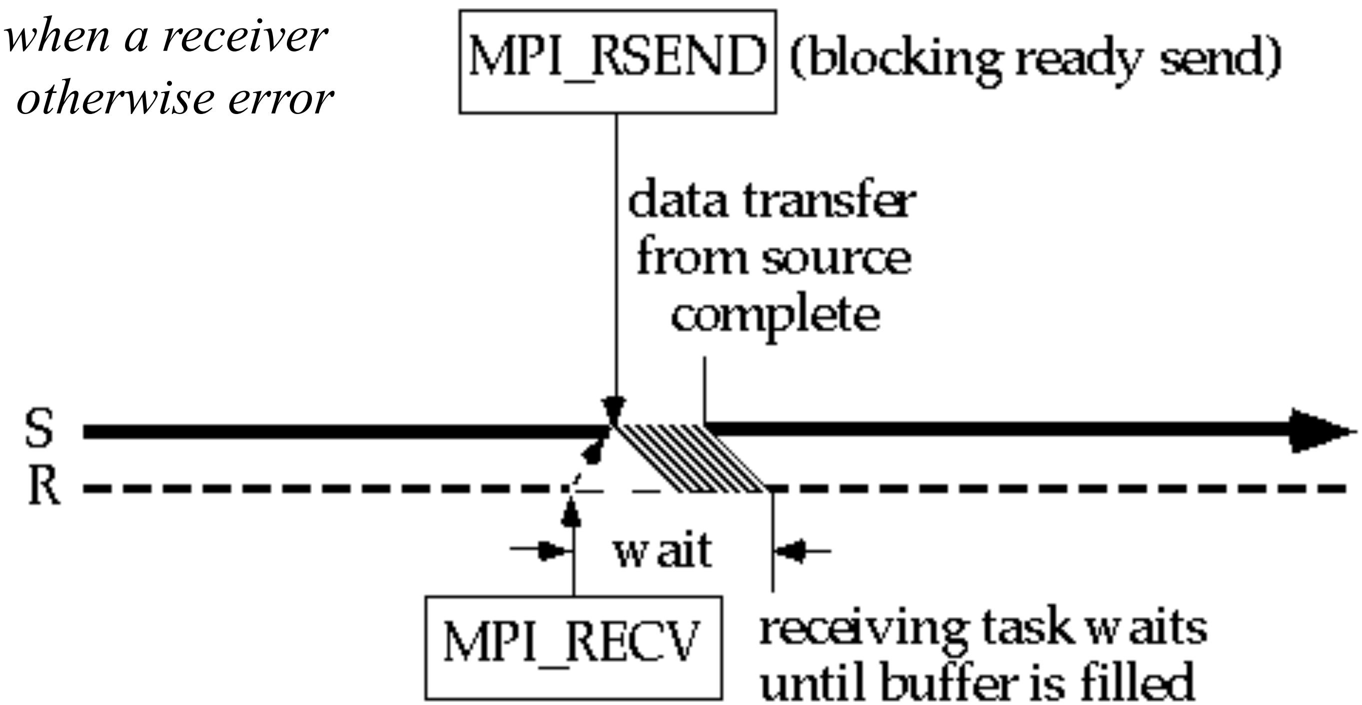
MPI Synchronous Send




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

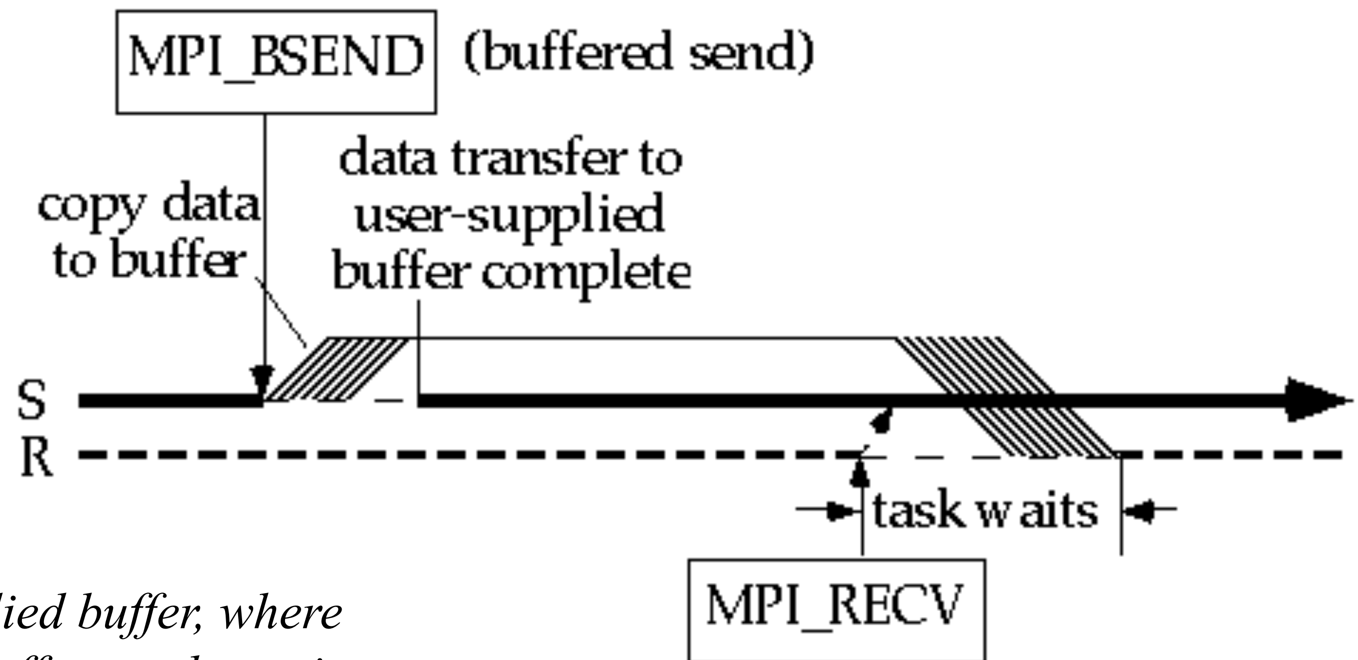
MPI Blocking Ready Send

Only sends when a receiver was posted, otherwise error




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

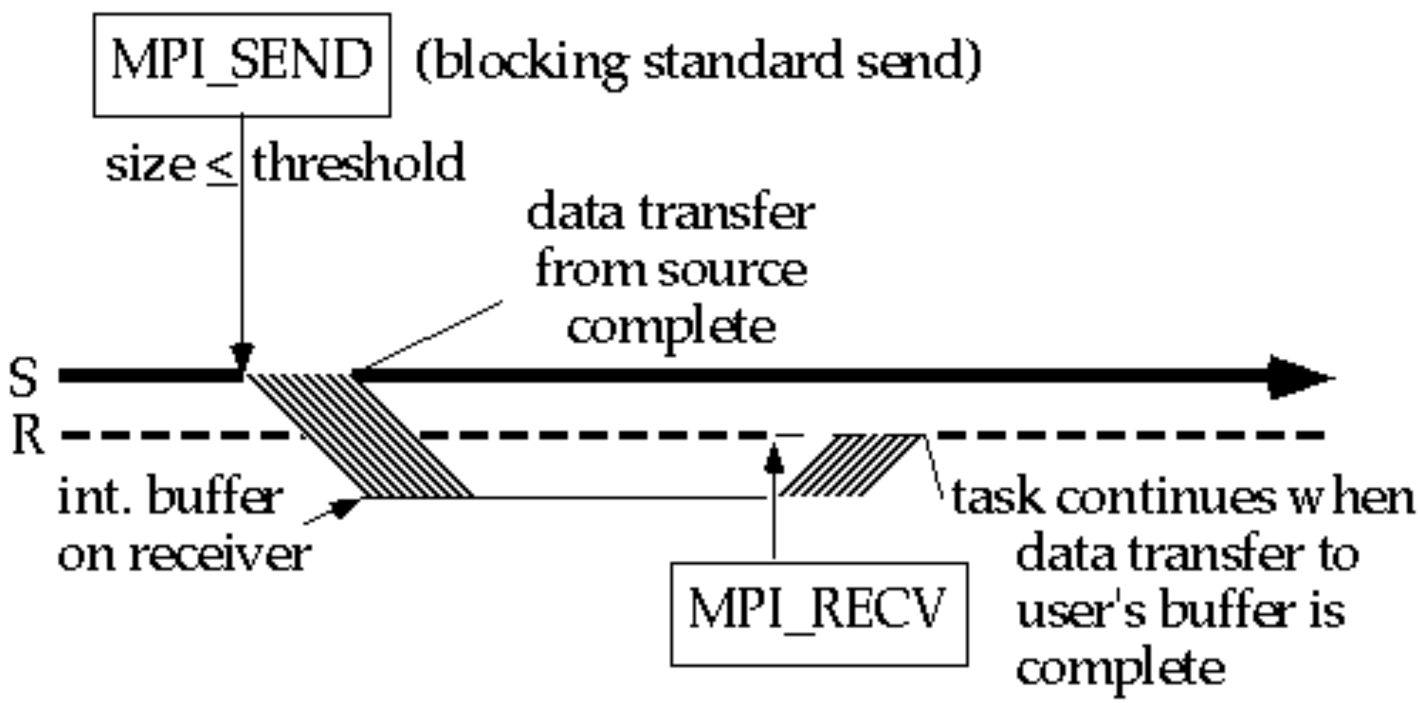
MPI Buffered Send



User-supplied buffer, where only one buffer can be active
Note: buffer size must be the maximum data size + **MPI_BSEND_OVERHEAD** *+ 7*

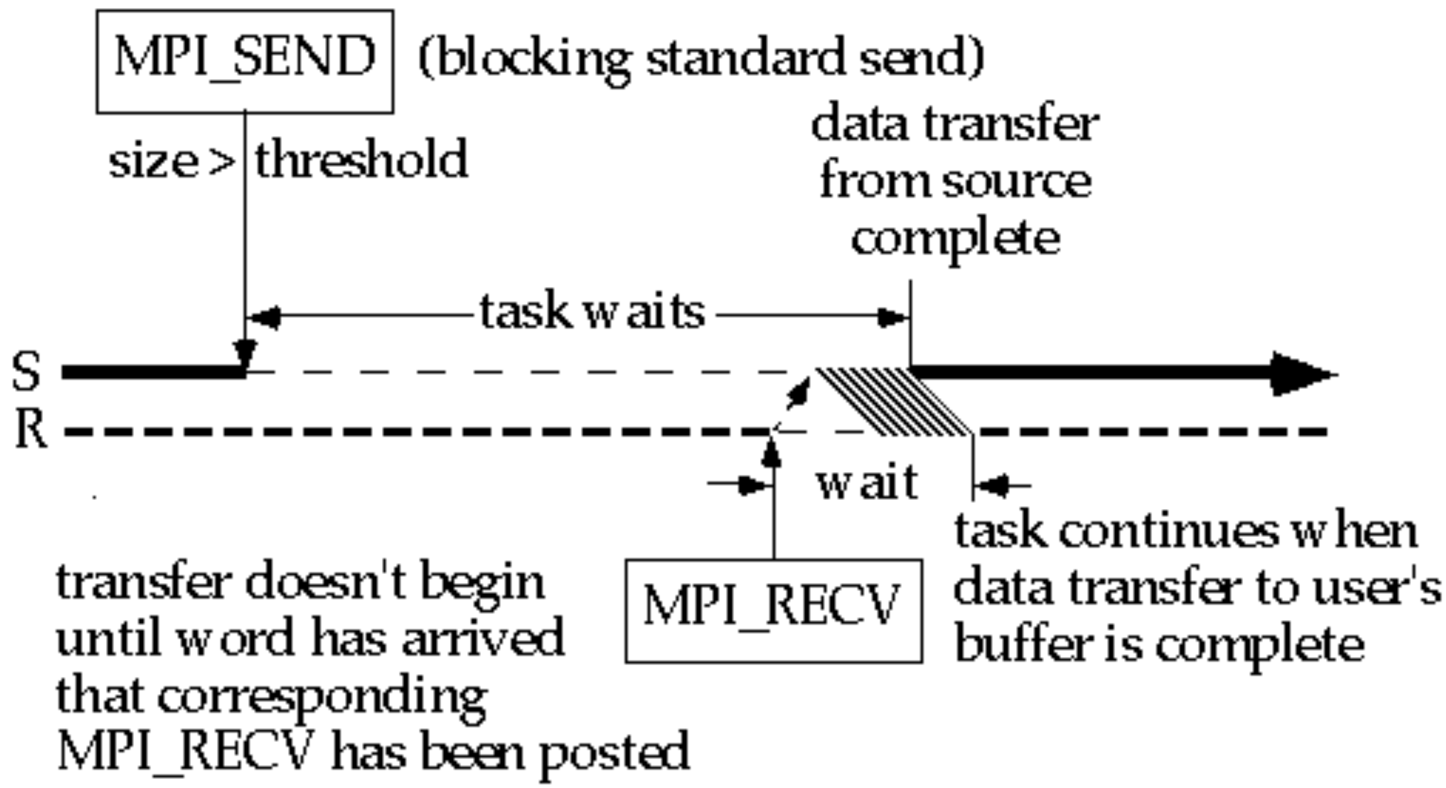
```
MPI_Buffer_attach(void *buf, int size)

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

MPI Blocking Standard Send Small Message Size



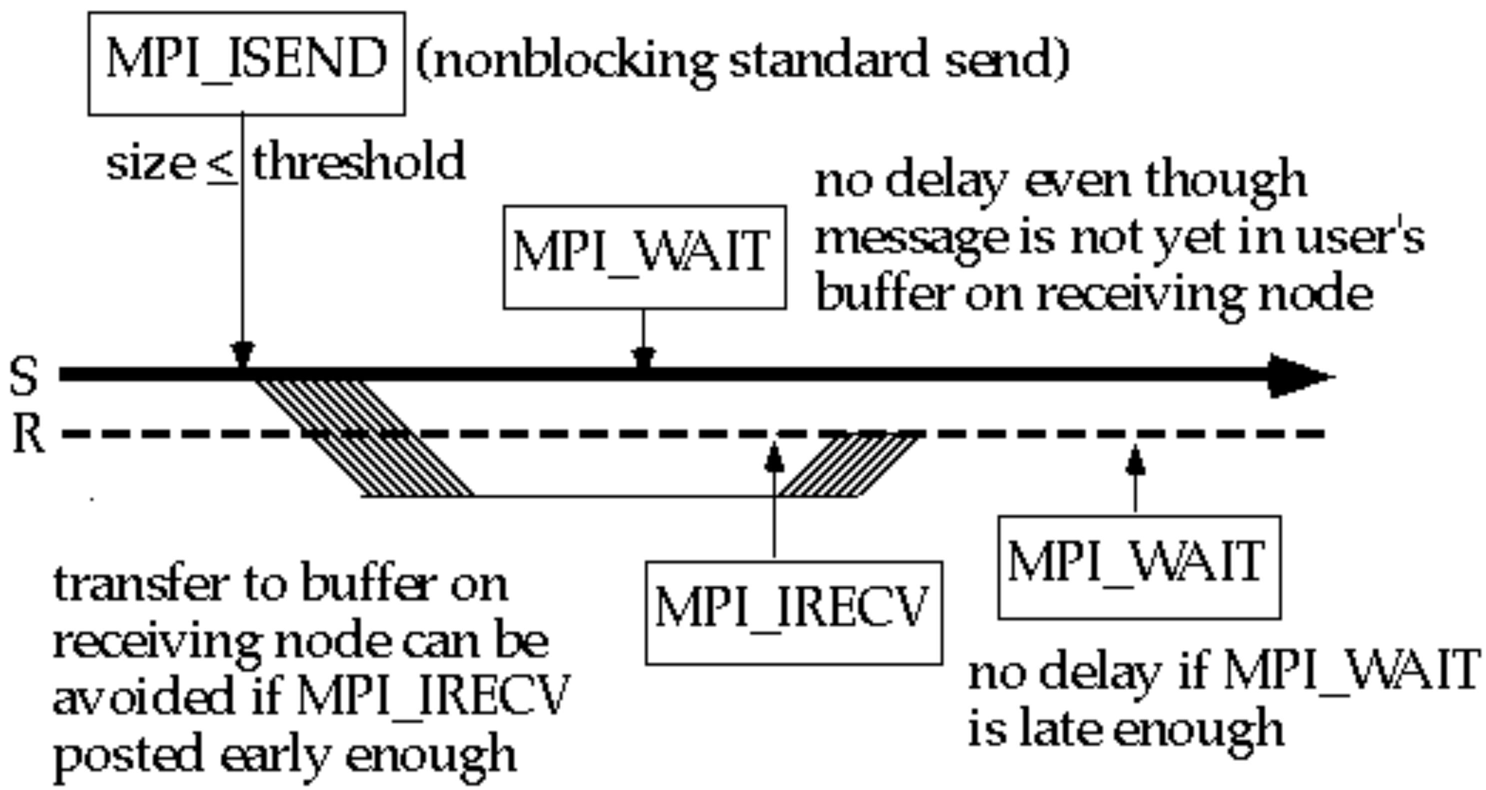
The threshold value (also called the "eager limit") differs between systems

MPI Blocking Standard Send Large Message Size



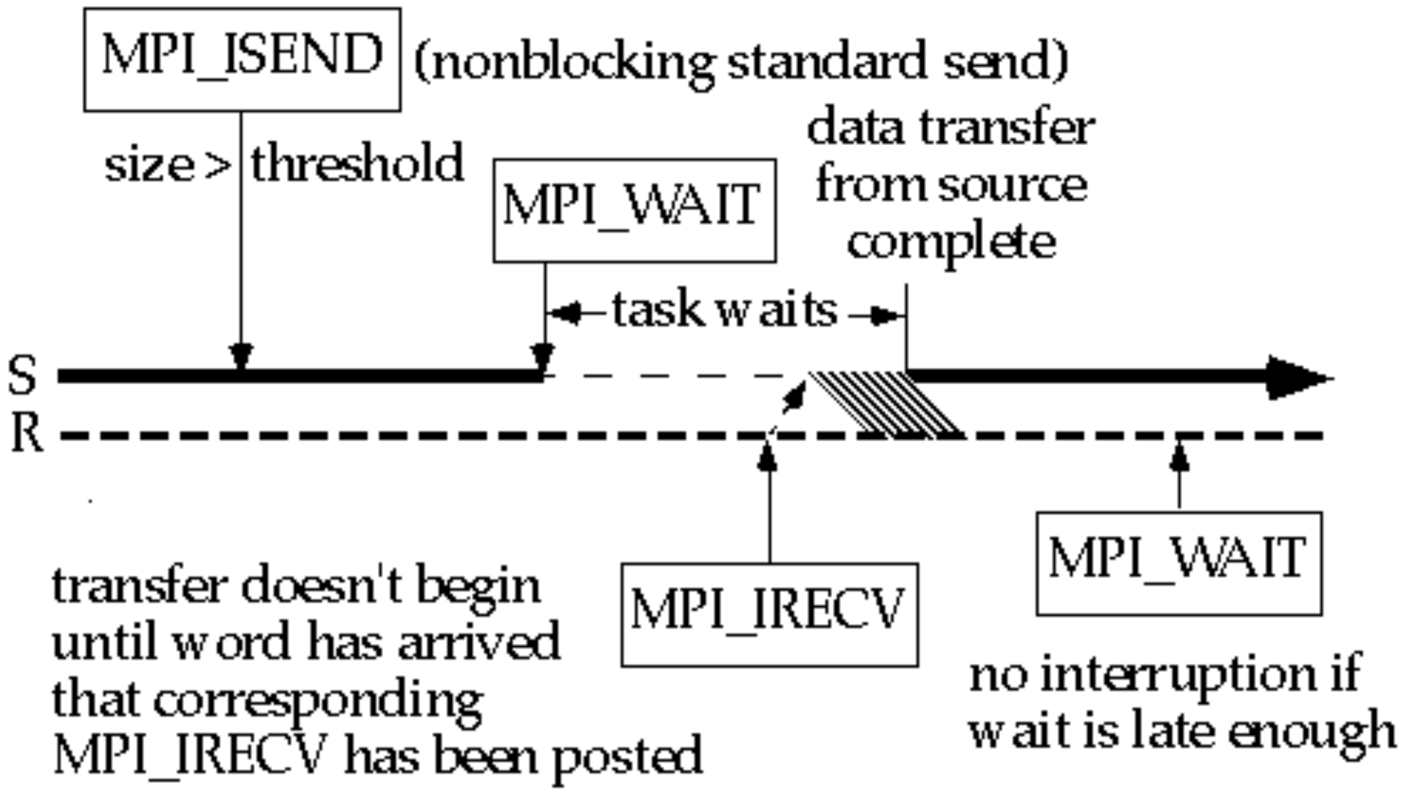
The threshold value (also called the "eager limit") differs between systems

MPI Nonblocking Standard Send Small Message Size




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

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

MPI_Wait(MPI_Request *request, MPI_Status *status)
```

MPI Nonblocking Standard Send Large Message Size



MPI Communication Modes

Communication mode	Advantages	Disadvantages
Synchronous	*Safest, and therefore most portable* *SEND/RECV order not critical* *Amount of buffer space irrelevant*	*Can incur substantial synchronization overhead*
Ready	*Lowest total overhead* *SEND/RECV handshake not required*	*RECV must precede SEND*
Buffered	*Decouples SEND from RECV* *No sync overhead on SEND* *Order of SEND/RECV irrelevant* *Programmer can control size of buffer space*	*Additional system overhead incurred by copy to buffer*
Standard	*Good for many cases*	*May not be suitable for your program*

Example 1: Nonblocking Send and Blocking Recv

```
main(int argc, char *argv[])
{
  int myrank;
  int value = 123;
  MPI_Status status;
  MPI_Request req;

  MPI_Init(&argc, &argv);

  MPI_Comm_Rank(MPI_COMM_WORLD, &myrank);

  if (myrank == 0)
  { MPI_Isend(&value, 1, MPI_INT, 1, MPI_ANY_TAG, MPI_COMM_WORLD, req);
    doWork(); /* do not modify value */
    MPI_Wait(&req, &status);
  }
  else if (myrank == 1)
    MPI_Recv(&value, 1, MPI_INT, 0, MPI_ANY_TAG, MPI_COMM_WORLD, &status);

  MPI_Finalize();
}
```

Example 2: Nonblocking Send/Recv

```
main(int argc, char *argv[])
{
  int myrank;
  int value = 123;
  MPI_Status status;
  MPI_Request req;

  MPI_Init(&argc, &argv);
  MPI_Comm_Rank(MPI_COMM_WORLD, &myrank);
  if (myrank == 0)
  { MPI_Isend(&value, 1, MPI_INT, 1, MPI_ANY_TAG, MPI_COMM_WORLD, &req);
    doWork(); /* do not modify value */
    MPI_Wait(&req, &status);
  }
  else if (myrank == 1)
  { MPI_Irecv(&value, 1, MPI_INT, 0, MPI_ANY_TAG, MPI_COMM_WORLD, &req);
    doWork(); /* do not read or modify value */
    MPI_Wait(&req, &status);
    /* using value is OK now */
  }
  MPI_Finalize();
}
```

MPI Wait

```
MPI_Wait(MPI_Request *request, MPI_Status *status)
```
Waits until pending send/recv request is completed, sets **`status`**

```
MPI_Waitall(int count, MPI_Request *array_of_requests,
            MPI_Status *array_of_statuses)
```
Wait for all pending send/recv requests to be completed, sets array of status values

```
MPI_Waitany(int count, MPI_Request *array_of_requests, int *index,
            MPI_Status *status)
```
Wait until any of the pending send/recv requests is completed, sets **`index`** *and* **`status`**

```
MPI_Waitsome(int incount, MPI_Request *array_of_requests,
             int *outcount, int* array_of_indices,
             MPI_Status *array_of_statuses)
```
Wait until some of the pending send/recv requests is completed, sets arrays of index and status

MPI Test

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

*Check if pending send/recv request is completed (***flag=1***), or pending (***flag=0***), sets* **status**

```
MPI_Testall(int count, MPI_Request *array_of_requests, int *flag,
            MPI_Status *array_of_statuses)
```

*Check if all pending send/recv requests are completed (***flag=1***), sets array of status values*

```
MPI_Testany(int count, MPI_Request *array_of_requests, int *index,
            int *flag, MPI_Status *status)
```

*Check if any of the pending send/recv requests is completed (***flag=1***), sets* **index** *and* **status**

```
MPI_Testsome(int incount, MPI_Request *array_of_requests,
             int *outcount, int* array_of_indices,
             MPI_Status *array_of_statuses)
```

Checks if some of the pending send/recv requests is completed, sets arrays of index and status

MPI Combined Sendrecv

```
MPI_Sendrecv(void *sendbuf, int sendcount, MPI_Datatype sendtype,
             int dest, int sendtag,
             void *recvbuf, int recvcount,
             MPI_Datatype recvtype, int source, int recvtag
             MPI_Comm comm, MPI_Status *status)
```

Combined send and receive operation (blocking), with disjoint send and receive buffers

```
MPI_Sendrecv_replace(void *buf, int count, MPI_Datatype datatype,
                     int dest, int sendtag, int source, int recvtag,
                     MPI_Comm comm, MPI_Status *status)
```

Combined send and receive operation (blocking), with shared send and receive buffers

Example 3: Combined Sendrecv

```
main(int argc, char *argv[])
{
  int myrank, hisrank;
  float value;
  MPI_Status status;

  MPI_Init(&argc, &argv);

  MPI_Comm_Rank(MPI_COMM_WORLD, &myrank);
  hisrank = 1-myrank;
  if (myrank == 0)
    value = 3.14;
  else
    value = 1.41;

  MPI_Sendrecv_replace(&value, 1, MPI_FLOAT, hisrank, MPI_ANY_TAG,
                       hisrank, MPI_ANY_TAG, MPI_COMM_WORLD, &status);

  printf("Process %d got value %g\n", myrank, value);

  MPI_Finalize();
}
```

MPI Basic Datatypes

`MPI_CHAR`	*signed char*
`MPI_SHORT`	*signed short int*
`MPI_INT`	*signed int*
`MPI_LONG`	*signed long 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 Collective Communications

- Coordinated communication within a group of processes identified by an MPI communicator
- Collective communication routines block until locally complete
- Amount of data sent must exactly match amount of data specified by receiver
- No message tags are needed

MPI Collective Communications Performance Considerations

- Communications are hidden from user
  - Communication patterns depend on implementation and platform on which MPI runs
  - In some cases, the root process originates or receives all data
  - Performance depends on implementation of MPI
- Communications may, or may not, be synchronized (implementation dependent)
  - Not always the best choice to use collective communication
  - There may be forced synchronization, which can be avoided with nonblocking point-to-point communications

MPI Collective Communications Classes

Three classes:

1. Synchronization
   - Barrier synchronization
2. Data movement
   - Broadcast
   - Scatter
   - Gather
   - All-to-all
3. Global computation
   - Reduce
   - Scan

MPI Barrier

```
MPI_Barrier(MPI_Comm comm)
```

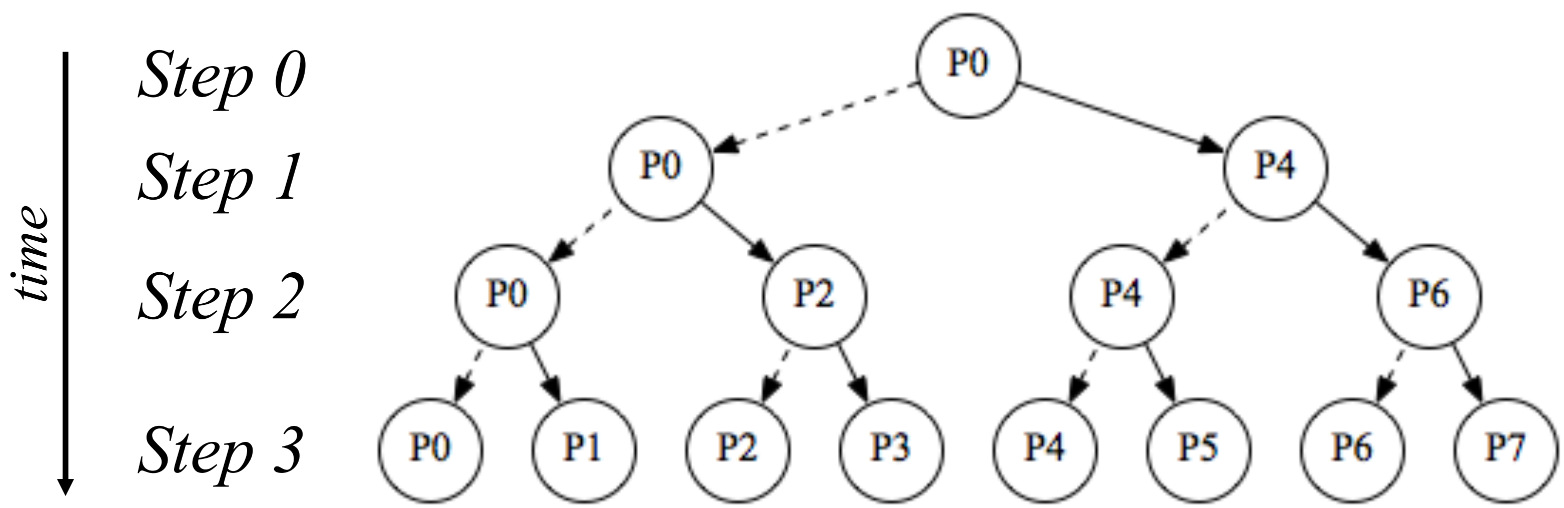
A node invoking the barrier routine will be blocked until all the nodes within the group (communicator) have invoked it

MPI Broadcast

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

Simple broadcast implementation: root sends data to all processes, which is efficient on a bus-based parallel machine

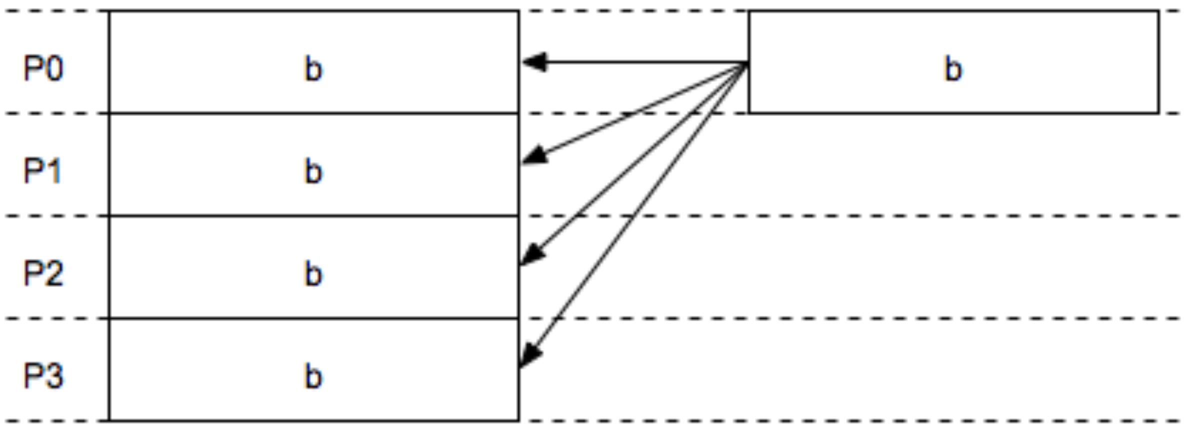
More efficient on a network: broadcast as a tree operation



$Log_2(P)$ steps

Total amount of data transferred: $N(P-1)$

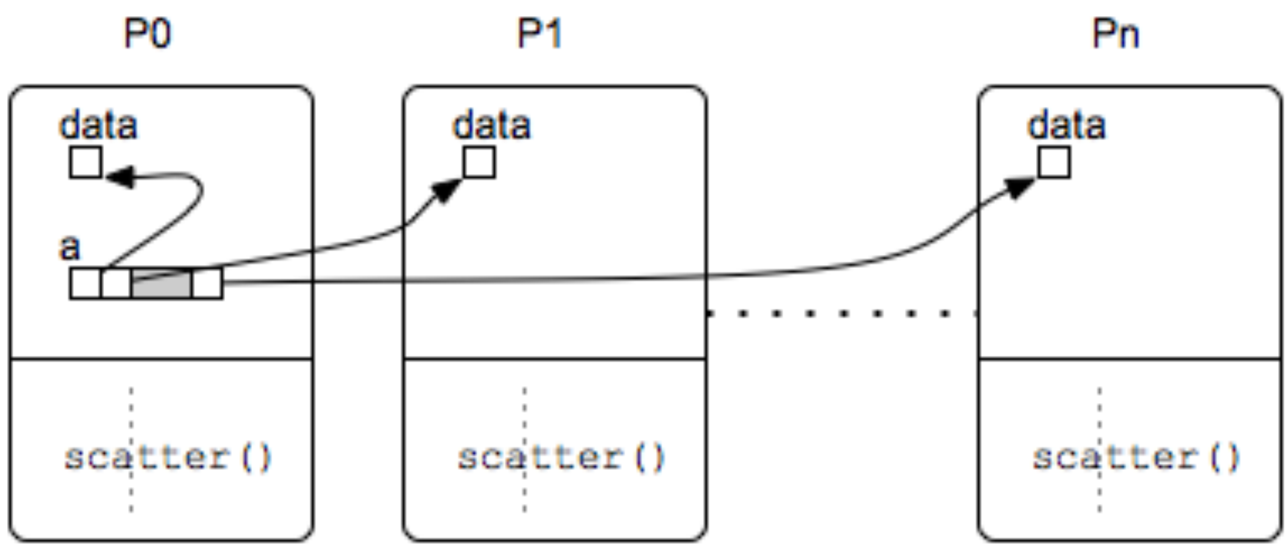
MPI Broadcast Example




```
float A[N][N], Ap[N/P][N], b[N], c[N], cp[N/P];
…
root = 0;
MPI_Broadcast(b, N, MPI_Float, root, MPI_COMM_WORLD);
…
```

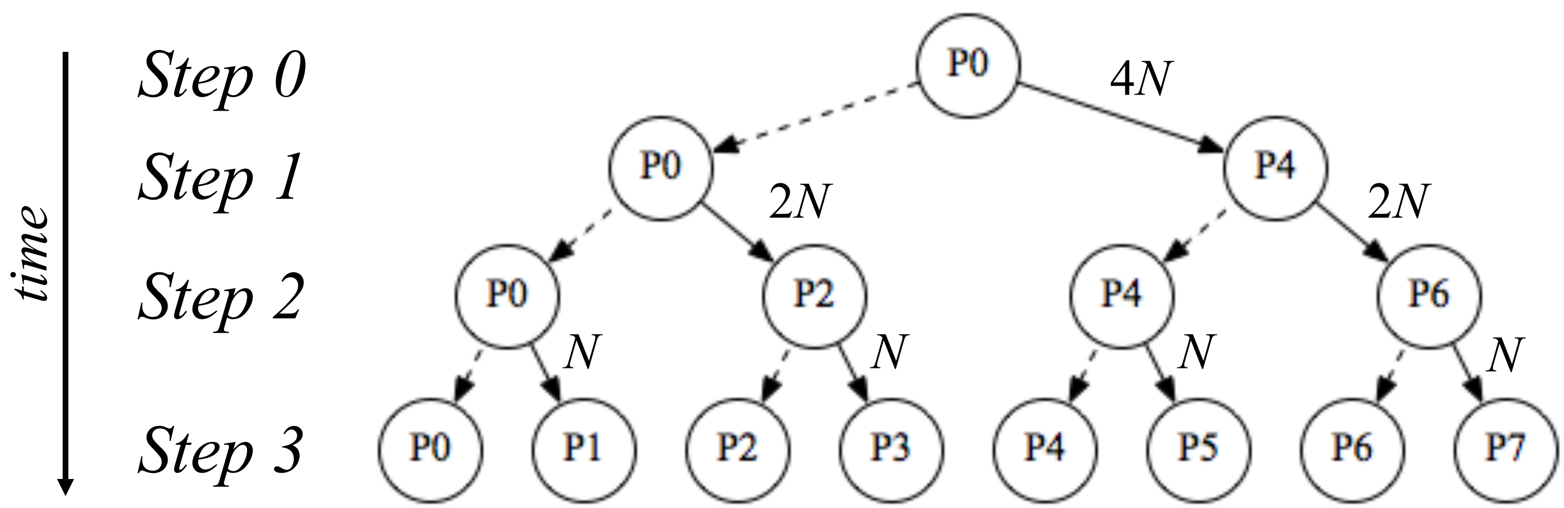
MPI Scatter

```
MPI_Scatter(void *sbuf,
            int scount,
            MPI_Datatype stype,
            void *rbuf,
            int rcount,
            MPI_Datatype rtype,
            int root,
            MPI_Comm comm)
```



MPI Scatter

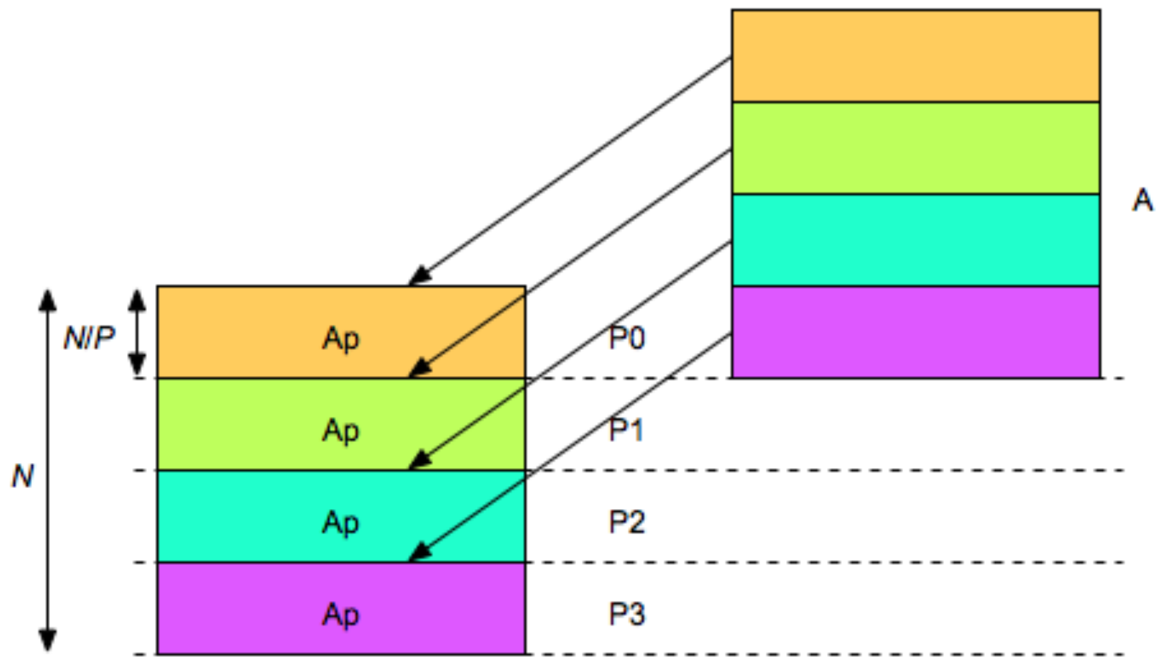
```
MPI_Scatter(void *sbuf,
            int scount,
            MPI_Datatype stype,
            void *rbuf,
            int rcount,
            MPI_Datatype rtype,
            int root,
            MPI_Comm comm)
```



$Log_2(P)$ steps

Total amount of data transferred: $N\,P\,log_2(P)/2$

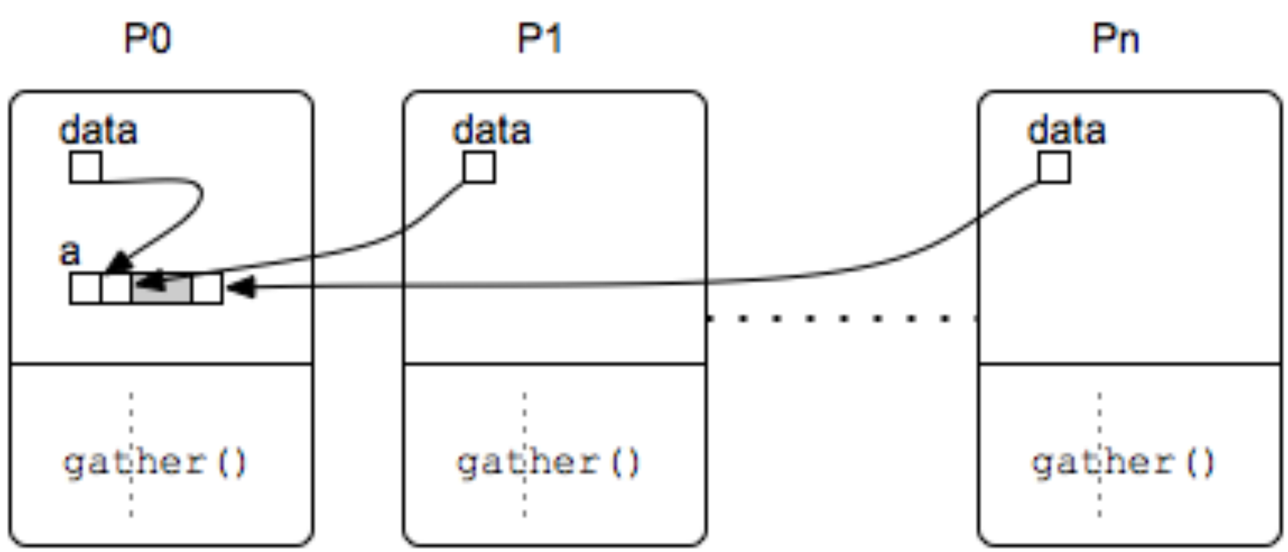
MPI Scatter Example



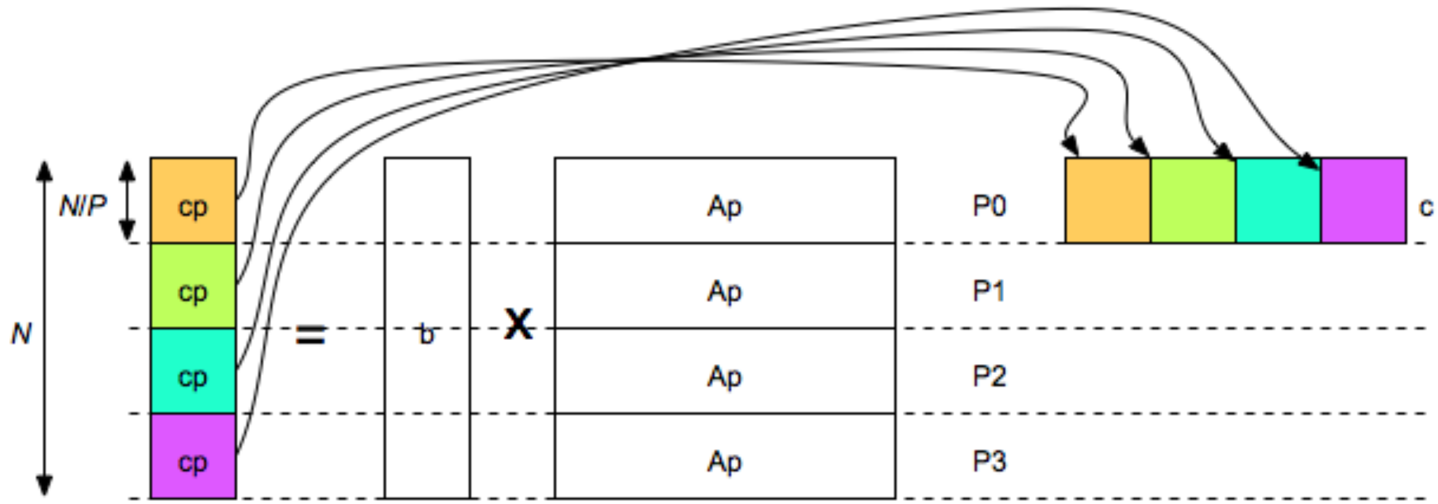

```
float A[N][N], Ap[N/P][N], b[N], c[N], cp[N/P];
…
root = 0;
…
MPI_Scatter(A, N/P*N, MPI_Float, Ap, N/P*N, MPI_Float, root,
            MPI_COMM_WORLD);
…
```

MPI Gather

```
MPI_Gather(void *sbuf,
           int scount,
           MPI_Datatype stype,
           void *rbuf,
           int rcount,
           MPI_Datatype rtype,
           int root,
           MPI_Comm comm)
```



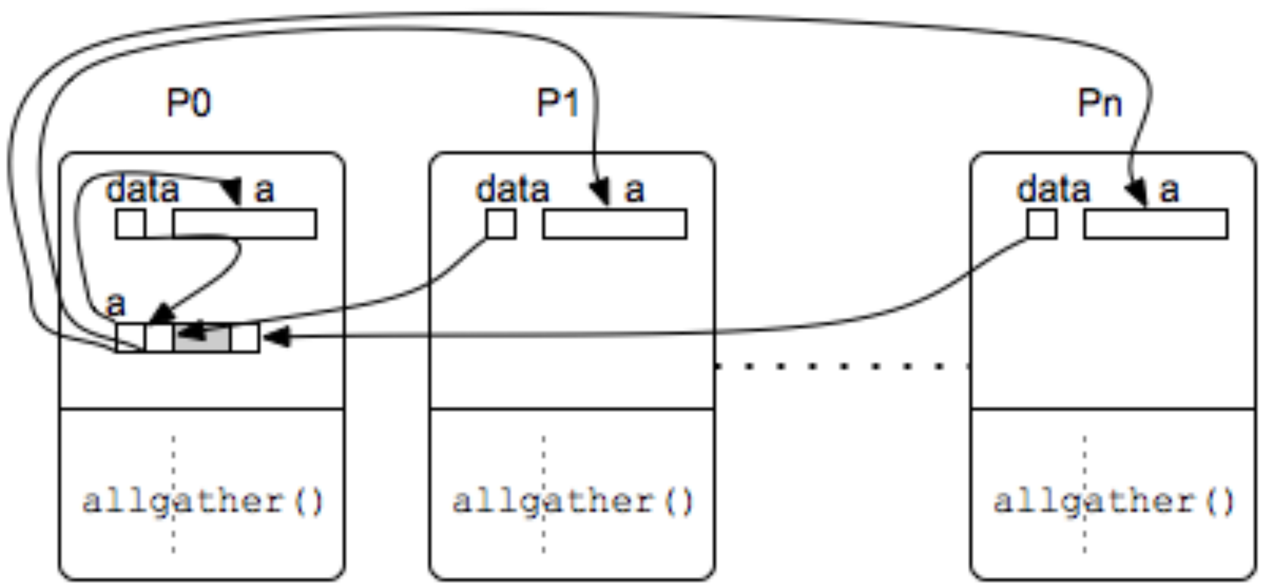
MPI Gather Example



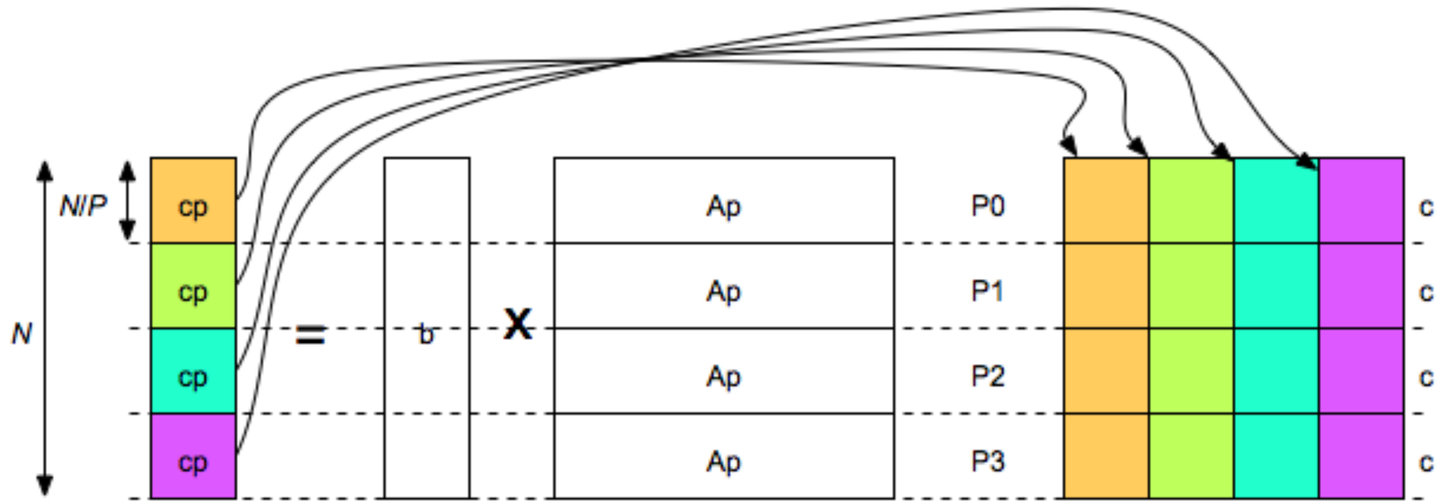

```
float A[N][N], Ap[N/P][N], b[N], c[N], cp[N/P];
…
for (i = 1; i < N/P; i++)
{
   cp[i] = 0;
   for (k = 0; k < N; k++)
     cp[i] = cp[i] + Ap[i][k] * b[k];
}
MPI_Gather(cp, N/P, MPI_Float, c, N/P, MPI_Float, root,
           MPI_COMM_WORLD);
```

MPI AllGather

```
MPI_AllGather(void *sbuf,
              int scount,
              MPI_Datatype stype,
              void *rbuf,
              int rcount,
              MPI_Datatype rtype,
              MPI_Comm comm)
```



MPI AllGather Example



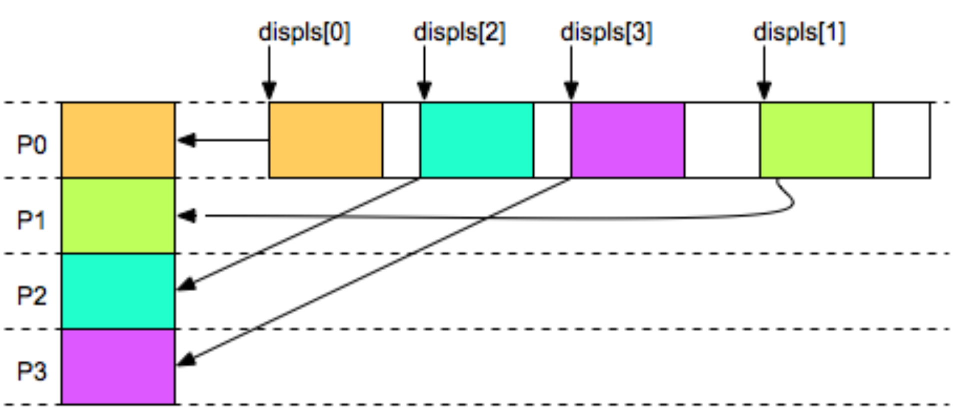

```
float A[N][N], Ap[N/P][N], b[N], c[N], cp[N/P];
…
for (i = 1; i < N/P; i++)
{
    cp[i] = 0;
    for (k = 0; k < N; k++)
      cp[i] = cp[i] + Ap[i][k] * b[k];
}
MPI_AllGather(cp, N/P, MPI_Float, c, N/P, MPI_Float,
              MPI_COMM_WORLD);
```

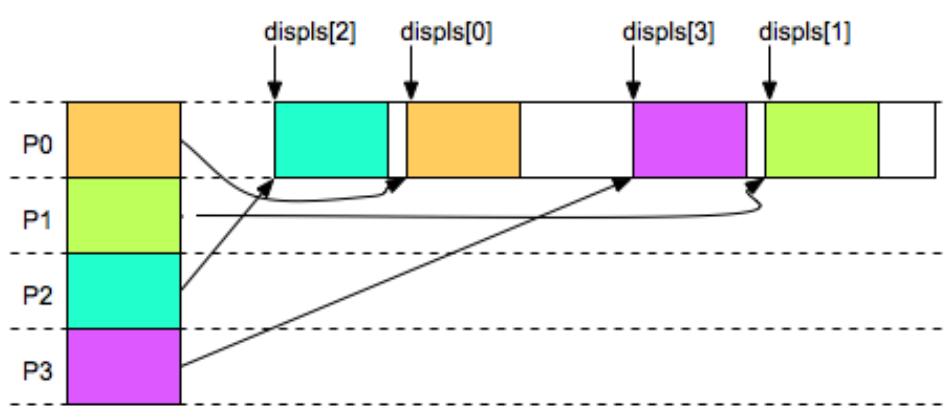
MPI Scatterv and (All)Gatherv

```
MPI_Scatterv(void *sbuf,
             int *scounts,
             int *displs,
             MPI_Datatype stype,
             void *rbuf,
             int rcount,
             MPI_Datatype rtype,
             int root,
             MPI_Comm comm)
```

```
MPI_Gatherv(void *sbuf,
            int scount,
            MPI_Datatype stype,
            void *rbuf,
            int *rcounts,
            int *displs,
            MPI_Datatype rtype,
            int root,
            MPI_Comm comm)
```

Adds displacements to scatter/gather operations and counts may vary per process



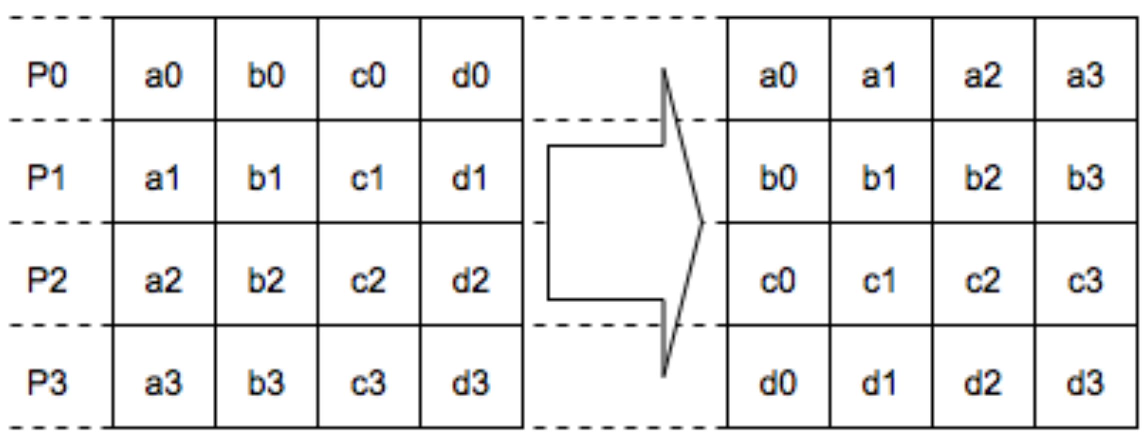


Note: counts are same in this example

MPI All to All

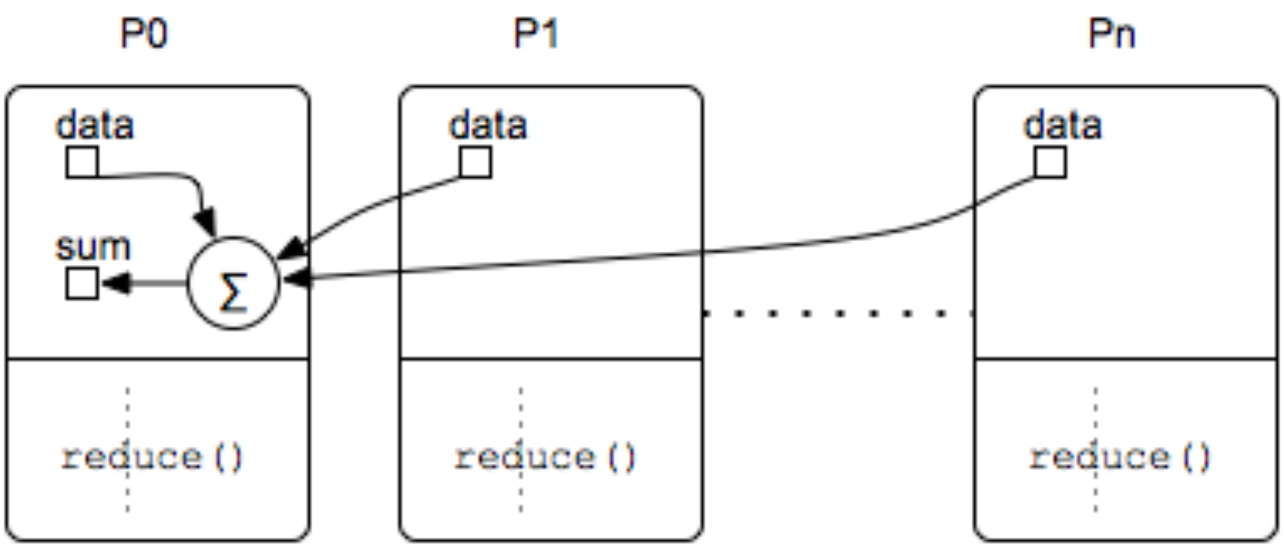
```
MPI_Alltoall(void *sbuf,
             int scount,
             MPI_Datatype stype,
             void *rbuf,
             int rcount,
             MPI_Datatype rtype,
             MPI_Comm comm)
```

Global transpose: the jth block from processor i is received by processor j and stored in ith block

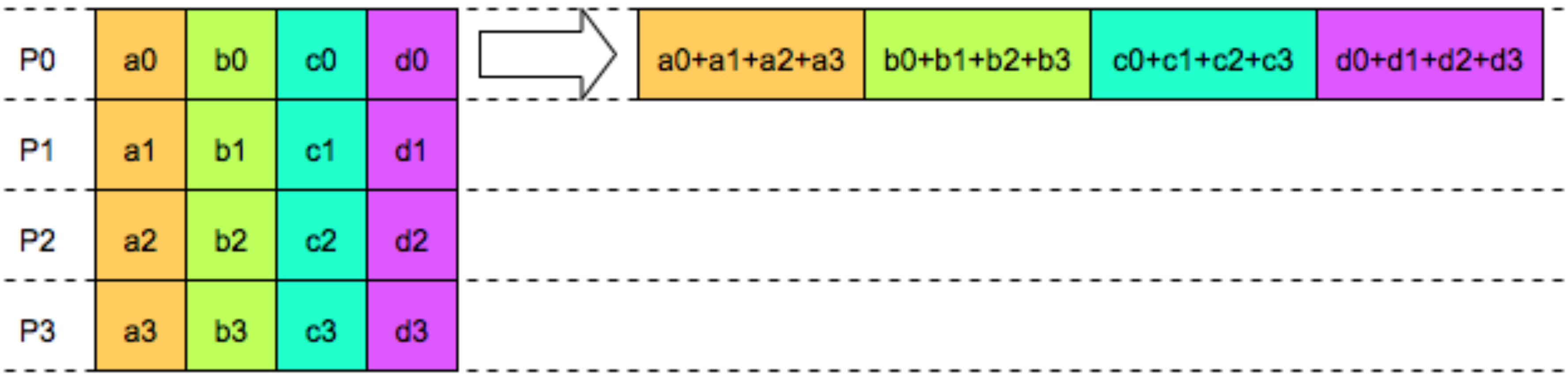


MPI Reduce

```
MPI_Reduce(void *sbuf,
           void *rbuf,
           int count,
           MPI_Datatype stype,
           MPI_Op op,
           int root,
           MPI_Comm comm)
```



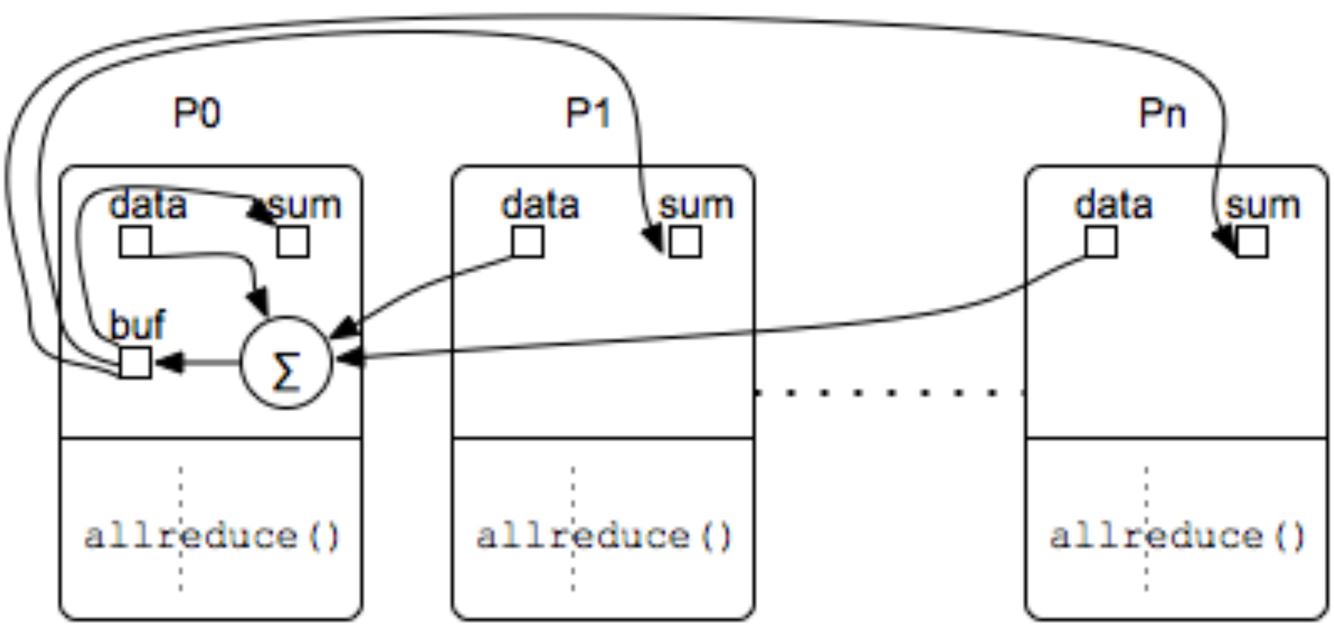
MPI Reduce Example



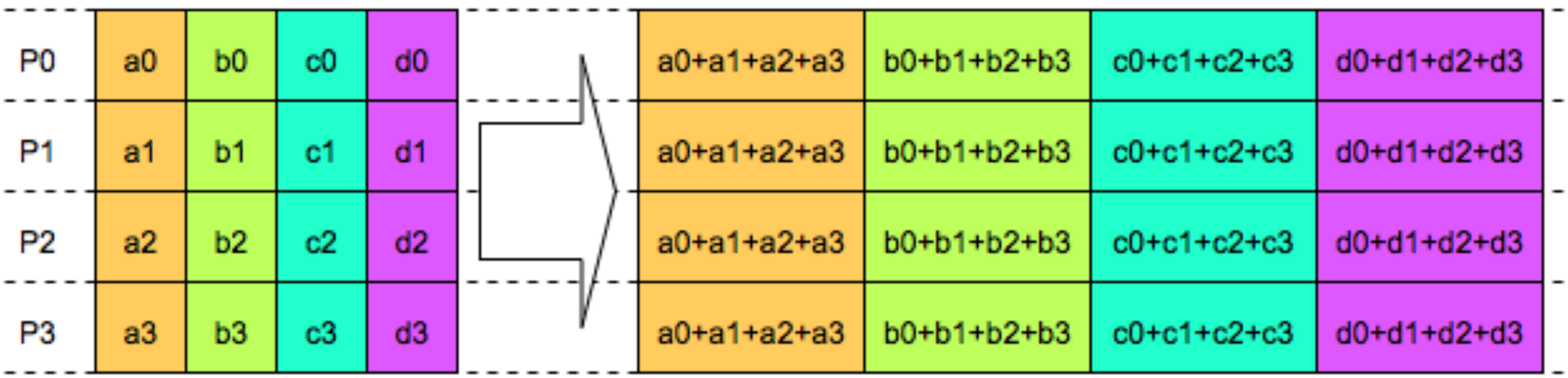

```
float abcd[4], sum[4];
…
MPI_Reduce(abcd, sum, 4, MPI_Float, root, MPI_SUM,
           MPI_COMM_WORLD);
```

MPI AllReduce

```
MPI_AllReduce(void *sbuf,
              void *rbuf,
              int count,
              MPI_Datatype stype,
              MPI_Op op,
              MPI_Comm comm)
```



MPI AllReduce Example

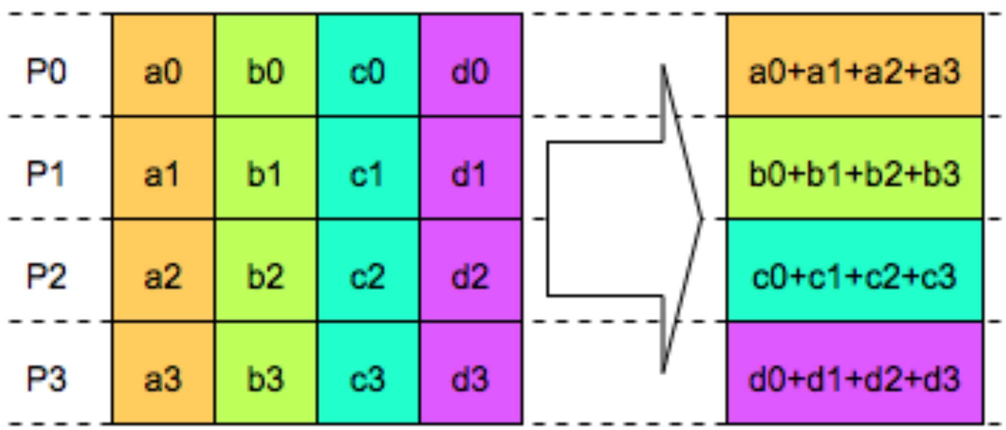



```
float abcd[4], sum[4];
…
MPI_AllReduce(abcd, sum, 4, MPI_Float, MPI_SUM,
              MPI_COMM_WORLD);
```

MPI Reduce_scatter

```
MPI_Reduce_scatter(void *sbuf,
                   void *rbuf,
                   int *rcounts,
                   MPI_Datatype stype,
                   MPI_Op op,
                   MPI_Comm comm)
```

Same as Reduce followed by Scatter



Note: rcounts = number of elements received, which is >1 when N>P

MPI Scan

```
MPI_Scan(void *sbuf,
         void *rbuf,
         int count,
         MPI_Datatype stype,
         MPI_Op op,
         MPI_Comm comm)
```

P0	a0	b0	c0	d0
P1	a1	b1	c1	d1
P2	a2	b2	c2	d2
P3	a3	b3	c3	d3

a0	b0	c0	d0
a0+a1	b0+b1	c0+c1	d0+d1
a0+a1+a2	b0+b1+b2	c0+c1+c2	d0+d1+d2
a0+a1+a2+a3	b0+b1+b2+b3	c0+c1+c2+c3	d0+d1+d2+d3

MPI Reduce and Scan Reduction Operators

MPI_OP	Operation	C	Fortran
MPI_MAX	maximum	integer, float	integer, real, complex
MPI_MIN	minimum	integer, float	integer, real, complex
MPI_SUM	sum	integer, float	integer, real, complex
MPI_PROD	product	integer, float	integer, real, complex
MPI_LAND	logical and	integer	logical
MPI_BAND	bit-wise and	integer, MPI_BYTE	integer, MPI_BYTE
MPI_LOR	logical or	integer	logical
MPI_BOR	bit-wise or	integer, MPI_BYTE	integer, MPI_BYTE
MPI_LXOR	logical xor	integer	logical
MPI_BXOR	bit-wise xor	integer, MPI_BYTE	integer, MPI_BYTE
MPI_MAXLOC	max val and loc	float, double, long double	real, complex,double precision
MPI_MINLOC	min val and loc	float, double, long double	real, complex,double precision

MPI Groups and Communicators

- A group is an ordered set of processes
  - Each process in a group is associated with a unique integer rank between 0 and P-1, with P the number of processes in the group
- A communicator encompasses a group of processes that may communicate with each other
  - Communicators can be created for specific groups
  - Processes may be in more than one group/communicator
- Groups/communicators are dynamic and can be setup and removed at any time
- From the programmer's perspective, a group and a communicator are the same

MPI Groups and Communicators

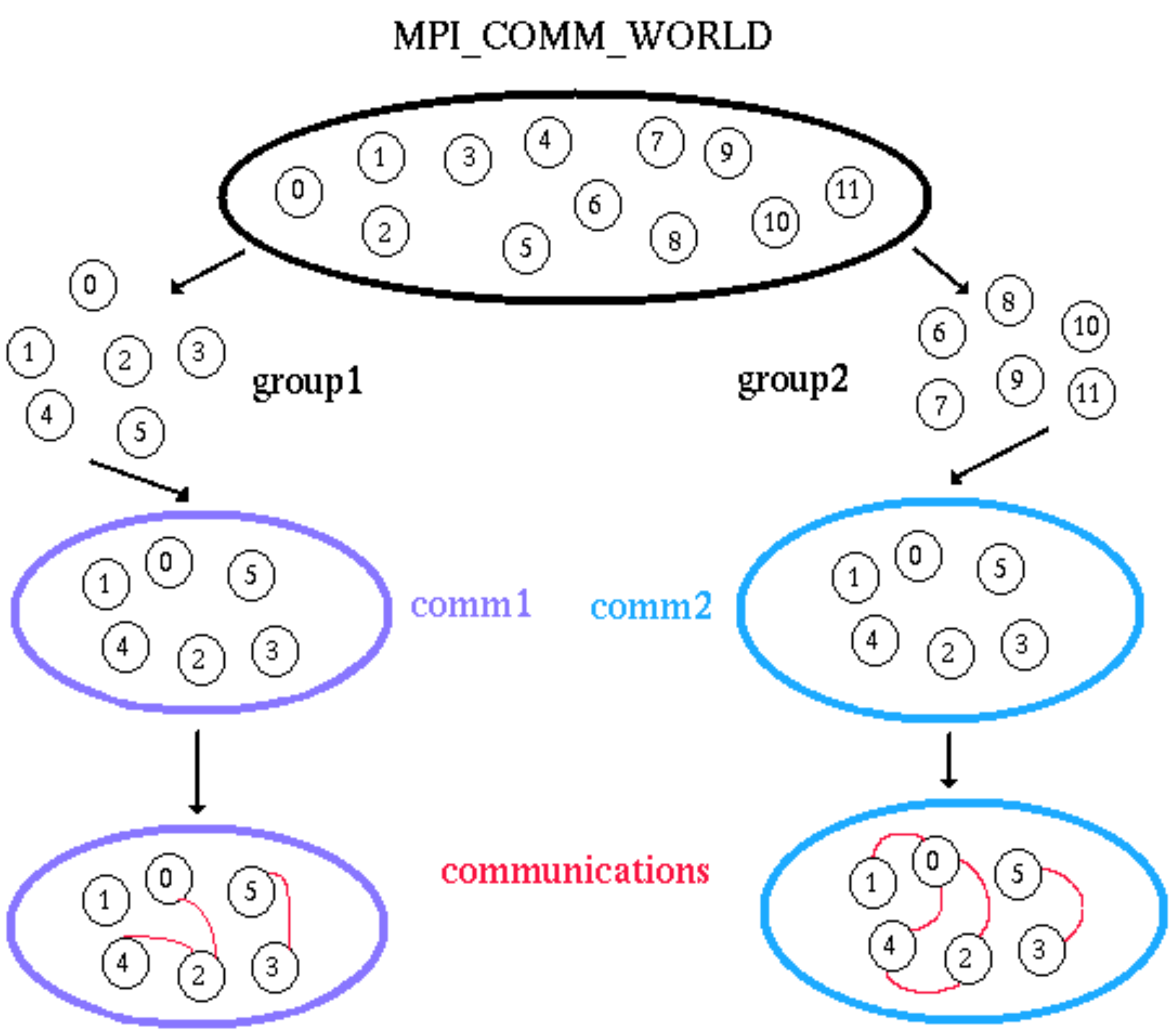


Image source: Lawrence Livermore National Labs

MPI Group Operations

`MPI_Comm_group`
returns the group associated with a communicator
`MPI_Group_union`
creates a group by combining two groups
`MPI_Group_intersection`
creates a group from the intersection of two groups
`MPI_Group_difference`
creates a group from the difference between two groups
`MPI_Group_incl`
creates a group from listed members of an existing group
`MPI_Group_excl`
creates a group excluding listed members of an existing group
`MPI_Group_range_incl`
creates a group according to first rank, stride, last rank
`MPI_Group_range_excl`
creates a group by deleting according to first rank, stride, last rank
`MPI_Group_free`
marks a group for deallocation

MPI Communicator Operations

`MPI_Comm_size`
returns number of processes in communicator's group
`MPI_Comm_rank`
returns rank of calling process in communicator's group
`MPI_Comm_compare`
compares two communicators
`MPI_Comm_dup`
duplicates a communicator
`MPI_Comm_create`
creates a new communicator for a group
`MPI_Comm_split`
splits a communicator into multiple, non-overlapping communicators
`MPI_Comm_free`
marks a communicator for deallocation

MPI Virtual Topologies

- A *virtual topology* can be associated with a communicator
- Two types of topologies supported by MPI
  - Cartesian (grid)
  - Graph
- Increases efficiency of communications
  - Some MPI implementations may use the physical characteristics of a given parallel machine
  - Introduces locality: low communication overhead with nodes that are "near" (few message hops), while distant nodes impose communication penalties (many hops)

MPE and Jumpshot

```
MPE_Log_get_state_eventIDs(int *startID, int *finalID)
```
Get a pair of event numbers to describe a state (see next)

```
MPE_Describe_state(int startID, int finalID, const char *name
                   const char *color)
```
Describe the state with a name and color (e.g. "red", "blue", "green")

```
MPE_Log_get_solo_eventID(int *eventID)
```
Get an event number to describe an event (see next)

```
MPE_Describe_event(int eventID, const char *name, const char *color)
```
Describe the event with a name and color (e.g. "red", "blue", "green")

```
MPE_Log_event(int event, int data, const char *bytebuf)
```
Record event in the log, data is unused and bytebuf carries informational data are should be NULL. Use two calls, one with the startID and the other with the finalID to log the time of a state.

MPE and Jumpshot

```
int event1, state1s, state1f;
int myrank;

MPI_Comm_rank(MPI_COMM_WORLD, &myrank);

MPE_Log_get_solo_eventIDs(&event1);
MPE_Log_get_state_eventIDs(&state1s, &state1f);

if (myrank == 0)
{ MPE_Describe_event(event1, ”Start", ”green");
  MPE_Describe_state(state1s, state1f, ”Computing", "red");
}

MPE_Log_event(event1, 0, NULL);
MPI_Bcast(…);
…
MPE_Log_event(state1s, 0, NULL);
doComputation();
MPE_Log_event(state1f, 0, NULL);
MPI_Barrier();
```

MPI+MPE Compilation, Linking, and Run

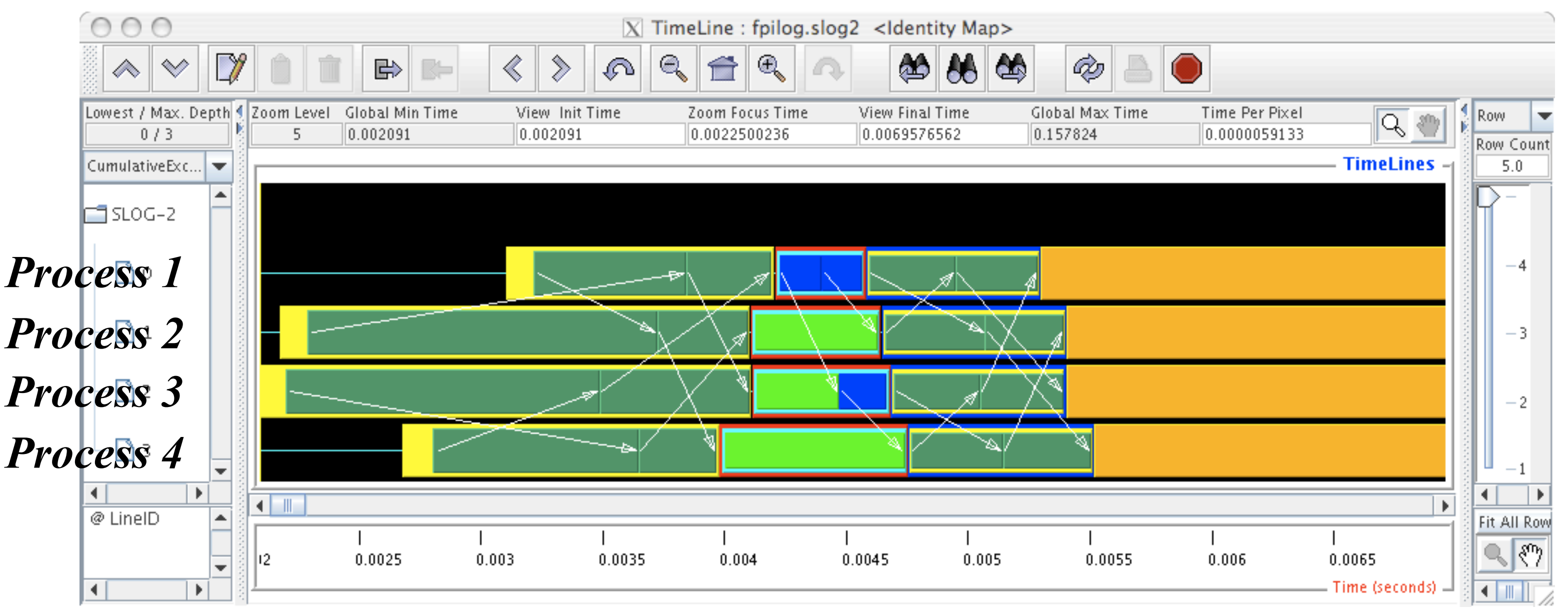
- Compilation with MPE requires **`mpe`** and **`lmpe`** libs:
  - **`mpicc -o myprog myprog.c -lmpe -llmpe`**
  - Note: without **`-llmpe`** you must init and finalize the logs
- Run directly…
  - **`mpirun -np 4 ./myprog`**
- … or in batch mode (e.g. with SGE)
  - **`qsub runmyprog.sh`**
- This generates the log file (typically in home dir)
  - **`myprog.clog2`**
- Display log file with
  - **`jumpshot`**

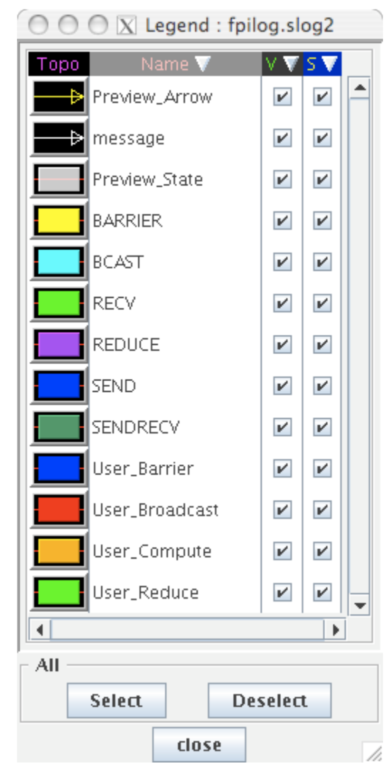
```
#!/bin/bash
# All environment variables active within the qsub
# utility to be exported to the context of the job:
#$ -V
# use openmpi with 4 nodes
#$ -pe openmpi_4 4
# use current directory
#$ -cwd
mpirun -np $NSLOTS ./myprog
```

Jumpshot

- Jumpshot generates a space-time diagram from a log file
  - Supports clog2 (through conversion) and newer slog2 formats
  - Shows user-defined states (start-end) and single point events
    - www.cs.fsu.edu/~engelen/courses/HPC/cpilog.c
    - www.cs.fsu.edu/~engelen/courses/HPC/fpilog.f

Space-time diagram





Further Reading

- [PP2] pages 52-61
- Optional:
  Lawrence Livermore National Laboratories MPI Tutorial
  `http://www.llnl.gov/computing/tutorials/mpi/`