Concurrency, Parallelism and Distributed Systems

Module II: Parallelism

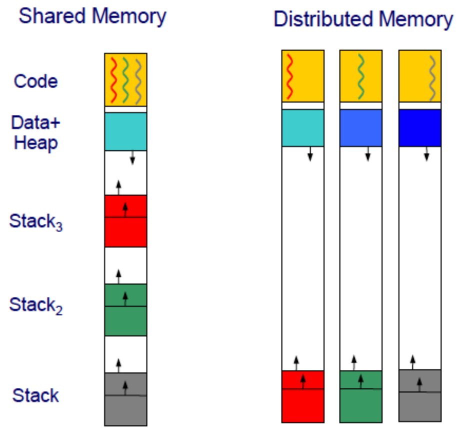
MPI BASICS

MPI Basics

- **Outline**
  - Overview
  - Environment
  - Barrier synchronization
  - Point-to-point communication
  - Collective communication
  - More examples

MPI Basics

- **Message Passing Interface (MPI)**
  - Set of primitives to **communicate** **processes** of different **nodes** in a **distributed memory** architecture
    - ✓ node: machine running his won operating system image with his own physical memory address space
    - ✓ process: set of execution flows (threads) running on a node sharing one unique virtual address space. A process has its own unique virtual address space



MPI Basics

- **Execution Model**
  - Processes are created, one on each node
  - Processes execute always in parallel and exchange data and synchronize at specific points (explicitly indicated by the programmer)
  - Processes finalize execution
- **Programmer must:**
  - Distribute work
  - Distribute data
  - Use communication mechanisms to share data explicitly
  - Use synchronization mechanisms to avoid data races

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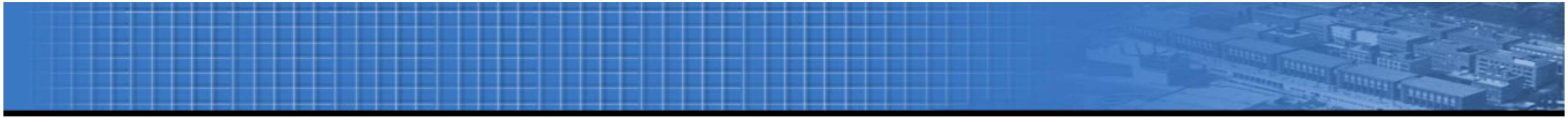

- **Environment**
  - `MPI_INIT`
  - `MPI_COMM_SIZE`
  - `MPI_COMM_RANK`
  - `MPI_FINALIZE`
  - `MPI_ABORT`

Initialization example

```
#include “mpi.h”

int rank;
int nproc;

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

    /* Nothing to do */
    printf("Process: %d out of %d:\\
            Hola mundo!\n",rank,nproc);

    MPI_Finalize();
}
```

MPI_Init

- **Usage**

  -
    ```
    int MPI_Init( int* argc_ptr      /* in */,
                  char** argv_ptr[] /* in */ );
    ```
- **Description**
  - Initialize MPI runtime system

- **All MPI programs must call this routine once and only once before any other MPI routines**

MPI_Comm_size

Usage

```
int MPI_Comm_size( MPI_Comm comm /* in */,
                   int* size     /* out */ );
```

Description

- Return the number of processes (size) in the group associated with a communicator `comm`
- `MPI_Comm` communicator
  - ✓ Context for a communication operation
  - ✓ Messages are always received within the context they were sent
  - ✓ Messages sent in different contexts do not interfere
  - ✓ `MPI_COMM_WORLD`

Process group

- Set of processes that share a communication context

Usage

```
int MPI_Comm_rank ( MPI_Comm comm /* in */,
                    int* rank     /* out */);
```

Description

- Returns the identifier of the local process in the group associated with a communicator `comm`
- The identifier (`rank`) of the process is in the range from `0…size-1`

MPI_Finalize

- **Usage**
  - `int MPI_Finalize (void);`
- **Description**
  - Terminates all MPI processing
  - Make sure this routine is the last MPI call
  - All pending communications involving a process have completed before the process calls `MPI_FINALIZE`

MPI_Abort

- **Usage**

  -
    ```
    int MPI_Abort( MPI_Comm comm   /* in */,
                   int errorcode   /* in */ );
    ```
- **Description**
  - Forces all processes of an MPI job to terminate

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Barrier Synchronization

```
#include “mpi.h”

int rank;
int nproc;

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

    // Ensure that all processes arrive
    // here before crossing this execution point
    MPI_Barrier(MPI_COMM_WORLD);
    /* Something to do in local */

    MPI_Finalize();
}
```

MPI_Barrier

- **Usage**
  - `int MPI_Barrier(MPI_Comm comm);/* in */`
- **Description**
  - Blocks each process in communicator `comm` until all processes have called it

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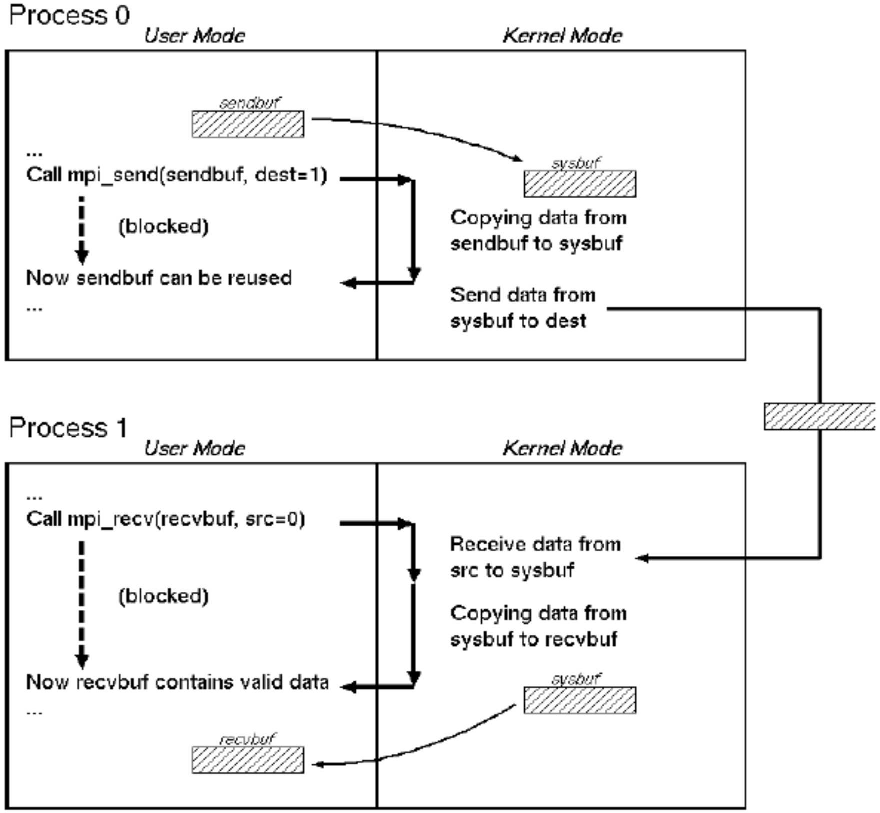
MPI: Point-to-point communication

- **Blocking**
  - Return from the procedure indicates the user is allowed to reuse resources specified in the call
- **Non-blocking**
  - The procedure may return before the operation completes, and before the user is allowed to reuse resources specified in the call
- **List of some basic routines:**
  - `MPI_SEND, MPI_RECV`
  - `MPI_ISEND, MPI_IRECV`
  - `MPI_WAIT`
  - `MPI_TEST`
  - `MPI_GET_COUNT`

Message send/receive blocking operations

```
#include “mpi.h”

int rank, nproc;

int main( int argc, char* argv[] ) {
    int isbuf, irbuf;
    MPI_Status status;

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

    if(rank == 0) {
        isbuf = 9;
        MPI_Send( &isbuf, 1, MPI_INTEGER, 1, 1, MPI_COMM_WORLD);
    } else if(rank == 1) {
        MPI_Recv( &irbuf, 1, MPI_INTEGER, 0, 1, MPI_COMM_WORLD,
                            &status);
        printf( “%d\n”, irbuf );
    }
    MPI_Finalize();
}
```

Message send/receive blocking operations


Process 0
User Mode
Kernel Mode
sendbuf
sysbuf
...
Call mpi_send(sendbuf, dest=1)
(blocked)
Now sendbuf can be reused
...
Copying data from sendbuf to sysbuf
Send data from sysbuf to dest
Process 1
User Mode
Kernel Mode
...
Call mpi_recv(recvbuf, src=0)
(blocked)
Now recvbuf contains valid data
...
Receive data from src to sysbuf
Copying data from sysbuf to recvbuf
sysbuf
recvbuf

MPI_Send

- **Usage**

  -
    ```
    int MPI_Send( void* buf,                  /* in */
                  int count,                  /* in */
                  MPI_Datatype datatype,      /* in */
                  int destination,            /* in */
                  int tag,                    /* in */
                  MPI_Comm comm               /* in */ );
    ```

- **Description**
  - Performs a blocking send operation
  - The message can be received by either `MPI_RECV` or `MPI_IRECV`
  - Message envelope
    - ✓ Information used to distinguish messages and selectively receive them
    - ✓ `<destination, tag, comm>`

MPI_Recv

Usage

```
int MPI_Recv( void* buf,              /* out */
              int count,              /* in */
              MPI_Datatype datatype,  /* in */
              int source,             /* in */
              int tag,                /* in */
              MPI_Comm comm,          /* in */
              MPI_Status* status      /* out */ );
```

Description

- Performs a blocking receive operation
- The message received must be less than or equal to the length of the receive buffer `buf`
- `MPI_RECV` can receive a message sent by either `MPI_SEND` or `MPI_ISEND`
- Message envelope: `<source, tag, comm>`

MPI_Sendrecv

Usage

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

Description

- Sends and receives a message
- Blocking exchange

MPI_Datatype

- **`MPI_Datatype` can be one of the following:**
  - `MPI_CHAR`
  - `MPI_SHORT`
  - `MPI_INT`
  - `MPI_LONG`
  - `MPI_UNSIGNED_CHAR`
  - `MPI_UNSIGNED_SHORT`
  - `MPI_UNSIGNED`
  - `MPI_UNSIGNED_LONG`
  - `MPI_FLOAT`
  - `MPI_DOUBLE`
  - `MPI_LONG_DOUBLE`
  - `MPI_BYTE`
  - `MPI_PACKED`

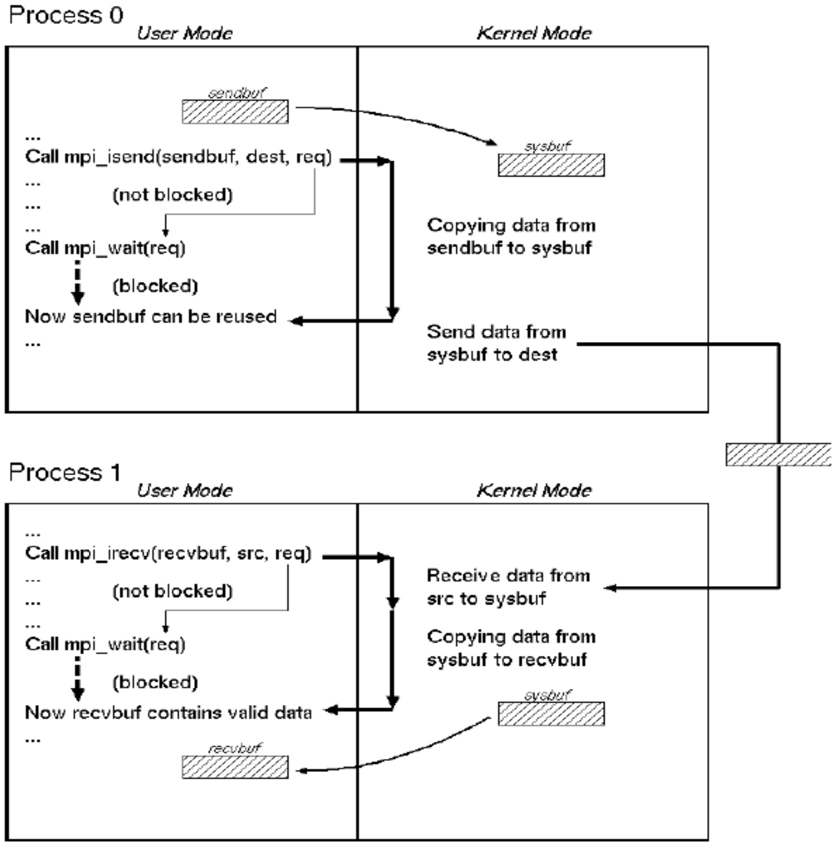
Non-blocking operations (I)

```
#include “mpi.h”

int main( int argc, char* argv[] )
{
    int rank, nproc;
    int isbuf, irbuf, count;
    MPI_Request request;
    MPI_Status status;

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

    if(rank == 0) {
        isbuf = 9;
        MPI_Isend( &isbuf, 1, MPI_INTEGER, 1, 1,
                   MPI_COMM_WORLD, &request );
```

Non-blocking operations (II)

```
  } else if(rank == 1) {
      MPI_Irecv( &irbuf, 1, MPI_INTEGER, MPI_ANY_SOURCE,
                 MPI_ANY_TAG, MPI_COMM_WORLD, &request);
  /* OTHER WORK TO DO */
      MPI_Wait(&request, &status);
      MPI_Get_count(status, MPI_INTEGER, &count);
      printf( “irbuf = %d source = %d tag = %d
               count = %d\n”, irbuf, status.MPI_SOURCE,
               status.MPI_TAG, count);
  }
  MPI_Finalize();
}
```

Non-blocking operations (II)


Process 0
User Mode
Kernel Mode
sendbuf
...
Call mpi_isend(sendbuf, dest, req)
...
(not blocked)
...
...
Call mpi_wait(req)
(blocked)
Now sendbuf can be reused
...
sysbuf
Copying data from sendbuf to sysbuf
Send data from sysbuf to dest
Process 1
User Mode
Kernel Mode
...
Call mpi_irecv(recvbuf, src, req)
...
(not blocked)
...
...
Call mpi_wait(req)
(blocked)
Now recvbuf contains valid data
...
recvbuf
Receive data from src to sysbuf
Copying data from sysbuf to recvbuf
sysbuf

MPI_Isend

- **Usage**

  -
    ```
    int MPI_Isend( void* buf,                    /* in */
                   int count,                    /* in */
                   MPI_Datatype datatype,        /* in */
                   int dest,                     /* in */
                   int tag,                      /* in */
                   MPI_Comm comm,                /* in */
                   MPI_Request* request          /* out */ );
    ```

- **Description**
  - Performs a non-blocking send operation
  - `request` is an identifier for later enquiry with `MPI_WAIT` or `MPI_TEST`
  - The send buffer `buf` may not be modified until the request has been completed by `MPI_WAIT` or `MPI_TEST`
  - The message can be received by either `MPI_RECV` or `MPI_IRECV`

MPI_Irecv

Usage

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

Description

- Performs a non-blocking receive operation
- Do not access any part of the receive buffer `buf` until the receive is completed by `MPI_WAIT` or `MPI_TEST`
- The message received must be less than or equal to the length of the receive buffer `buf`
- `MPI_IRECV` can receive a message sent by either `MPI_SEND` or `MPI_ISEND`

MPI_Wait

Usage

-
```
int MPI_Wait( MPI_Request* request,   /* inout */
              MPI_Status* status      /* out */ );
```

Description

- Waits for a non-blocking operation to complete, with identifier stored in `request`
- Information on the completed operation is found in `status`
- If wildcards (`MPI_ANY_SOURCE, MPI_ANY_TAG`) were used by the receive for either the `source` or `tag`, the actual source and tag can be retrieved from `status`→`MPI_SOURCE` and `status`→`MPI_TAG`

MPI_Test

Usage

```
● int MPI_Test (MPI_Request* request,   /* inout */
               int *flag,               /* out */
               MPI_Status* status );    /* out */
```

Description

- Test for the completion of a send or receive
- `flag` equals `MPI_SUCCESS` if MPI routine completed successfully

MPI_Get_count

Usage

-
  ```
  int MPI_Get_count( MPI_Status status,    /* in */
                     MPI_Datatype datatype,  /* in */
                     int* count );          /* out */
  ```

Description

- Returns the number of elements in a message (indicated by `status`)
- The `datatype` argument and the argument provided by the call that set the `status` variable should match

MPI_Probe

- **Usage**

```
int MPI_Probe(int source,              /* input */
              int tag,                  /* input */
              MPI_Comm comm,            /* input */
              MPI_Status *status);      /* out */
```

- **Description**
  - Blocking call that returns only after a matching message is found
  - Wildcards can be used to wait for messages coming from any source (`MPI_ANY_SOURCE`) or with any tag (`MPI_ANY_TAG`)
  - There is a non-blocking MPI_Iprobe

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MPI Collective Communication

- **Collective**
  - If all processes in a process group need to invoke the procedure
- **List of some routines:**
  - `MPI_BCAST`
  - `MPI_REDUCE`
  - `MPI_SCATTER`
  - `MPI_SCATTERV`
  - `MPI_GATHER`
  - `MPI_GATHERV`
  - `MPI_ALLGATHER`
  - `MPI_ALLTOALL`
  - `MPI_ALLTOALLV`

Broadcats and Reduce Operations

```
#include <mpi.h>
void main (int argc, char *argv[])
{
   int i, my_id, numprocs, num_steps;
   double x, pi, step, sum = 0.0 ;

   MPI_Init(&argc, &argv) ;
   MPI_Comm_Rank(MPI_COMM_WORLD, &my_id);
   MPI_Comm_Size(MPI_COMM_WORLD, &numprocs) ;
   if (my_id==0) scanf(“%d”,&num_steps);
   MPI_Bcast(&num_steps, 1, MPI_INT, 0, MPI_COMM_WORLD)
   step = 1.0/(double) num_steps ;
   my_steps = num_steps/numprocs ;

   for (i=my_id*my_steps; i<(my_id+1)*my_steps; i++){
    x = (i+0.5)*step;
    sum += 4.0/(1.0+x*x);
    }
   sum *= step ;
   MPI_Reduce(&sum, &pi, 1, MPI_DOUBLE,
       MPI_SUM, 0, MPI_COMM_WORLD) ;
   MPI_Finalize() ;
}
```

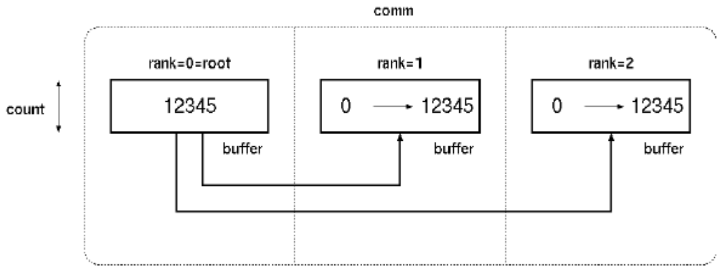
MPI_Bcast

Usage

```
int MPI_Bcast( void* buffer,                  /* inout */
               int count,                     /* in */
               MPI_Datatype datatype,         /* in */
               int root,                      /* in */
              MPI_Comm comm                   /* in */  );
```

Description

- Broadcasts a message from root to all processes in communicator `comm`
- The type signature of `count` and `datatype` on any process must be equal to the type signature of `count` and `datatype` at the `root`



MPI_Reduce

- **Usage**

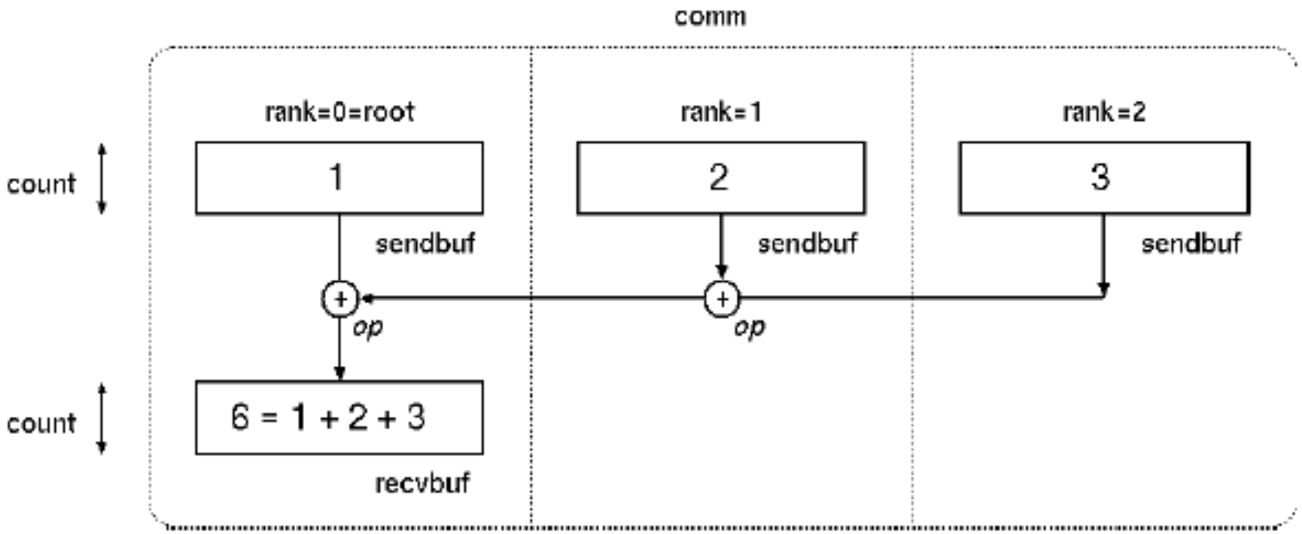
```
int MPI_Reduce(void* sendbuf,             /* in */
               void* recvbuf,             /* out */
               int count,                 /* in */
               MPI_Datatype datatype,     /* in */
               MPI_Op op,                 /* in */
               int root,                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

- **Description**
  - Applies a reduction operation to the vector `sendbuf` over the set of processes specified by communicator `comm` and places the result in `recvbuf` on `root`

MPI_Reduce (cont'd)

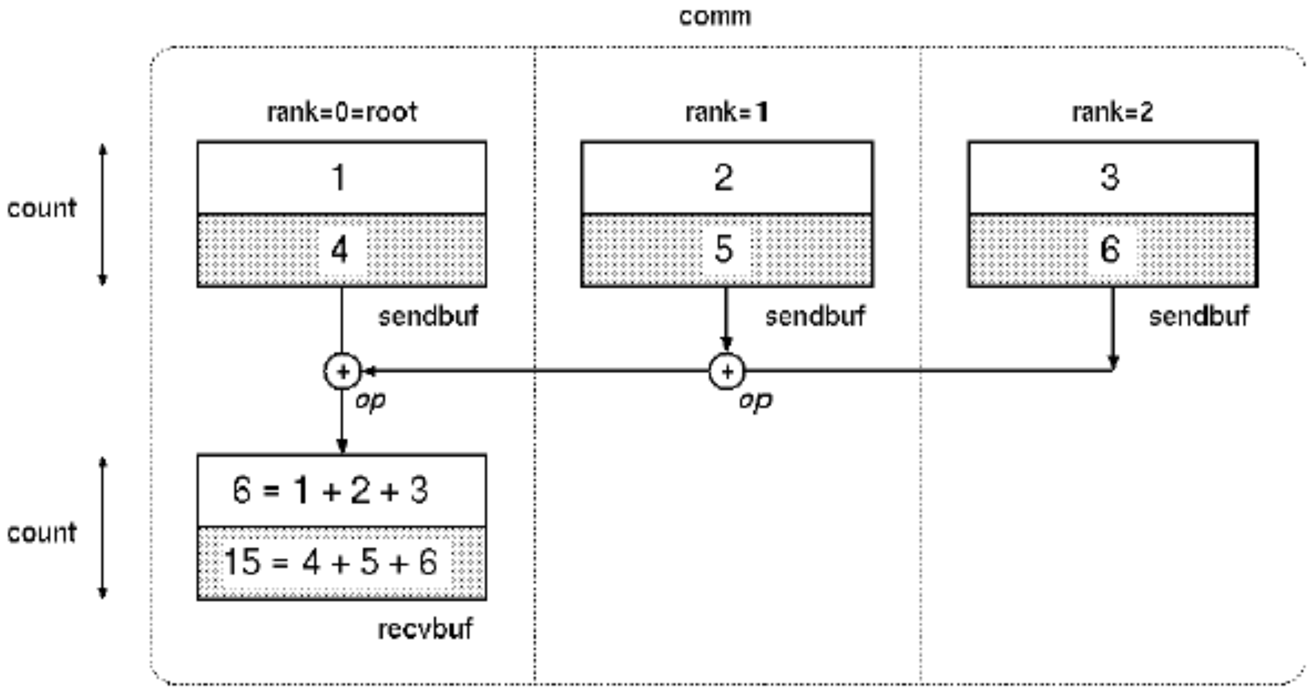
- **Description (Cont'd)**
  - Both the input and output buffers have the same number of elements with the same type
  - Users may define their own operations or use the predefined operations provided by MPI
- **Predefined operations**
  - `MPI_SUM, MPI_PROD`
  - `MPI_MAX, MPI_MIN`
  - `MPI_MAXLOC, MPI_MINLOC`
  - `MPI_LAND, MPI_LOR, MPI_LXOR`
  - `MPI_BAND, MPI_BOR, MPI_BXOR`

MPI_Reduce (cont'd)



`MPI_REDUCE` for scalars

MPI_Reduce (cont'd)

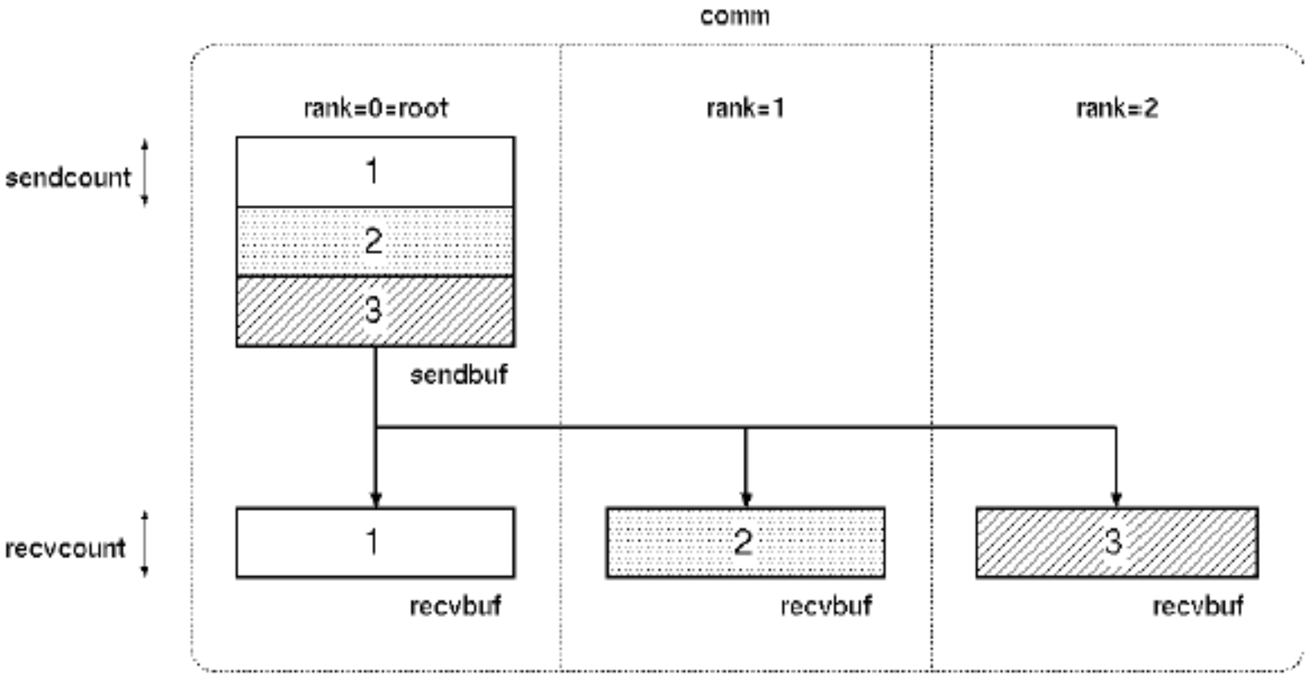


`MPI_REDUCE` for arrays

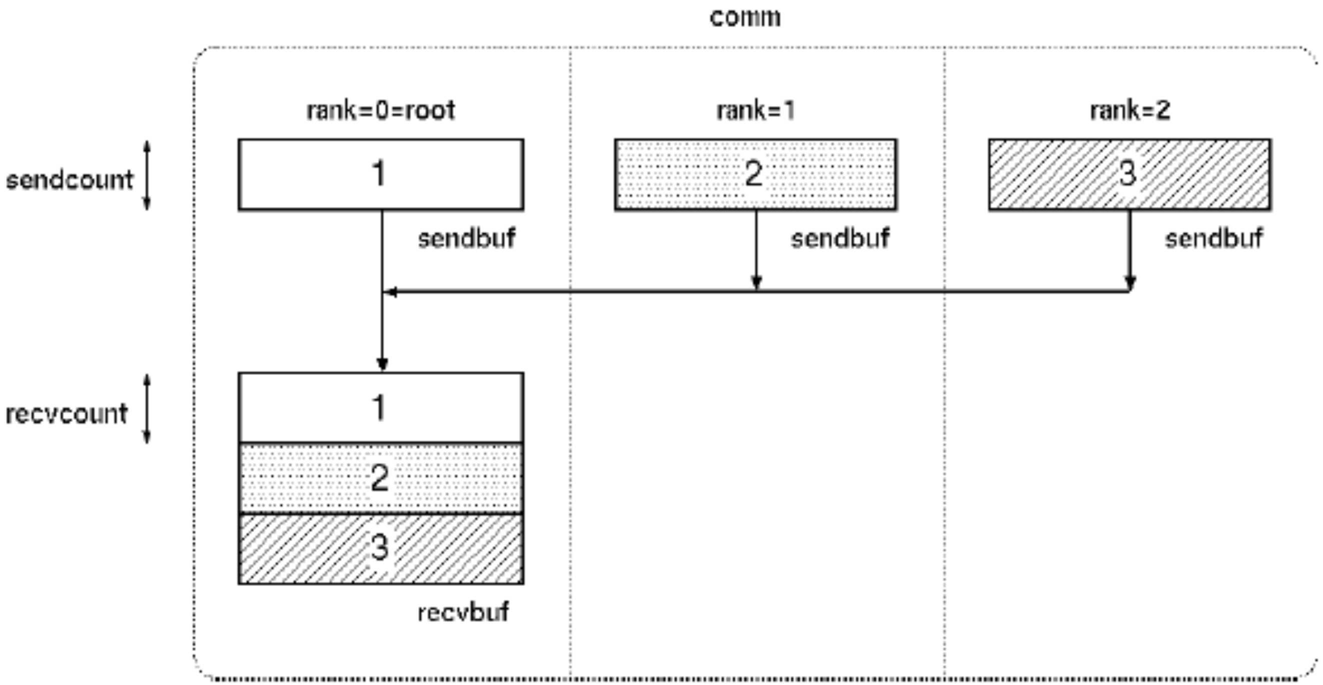
Scatter and Gather Operations

```
int gsize, localbuf[100];
int root=0, rank, *rootbuf;
...
MPI_Comm_size( MPI_COMM_WORLD, &nproc );
MPI_Comm_rank( MPI_COMM_WORLD, &rank );

if (rank == root)
     rootbuf = (int *)malloc(nproc*100*sizeof(int));

/* MATRIX INITIALIZED IN ROOT */
MPI_Scatter (rootbuf, 100, MPI_INT, localbuf, 100,
             MPI_INT, root, comm);

/* DO WORK WITH DATA */

MPI_Gather (localbuf, 100, MPI_INT, rootbuf, 100,
            MPI_INT, root, comm);
/* RESULTS BACK IN ROOT */
```

MPI_Scatter


comm
rank=0=root
rank=1
rank=2
sendcount
1
2
3
sendbuf
recvcount
1
recvbuf
2
recvbuf
3
recvbuf

MPI_Gather


comm
rank=0=root
rank=1
rank=2
sendcount
1
2
3
sendbuf
sendbuf
sendbuf
recvcount
1
2
3
recvbuf

MPI_Scatter

- **Usage**

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

- **Description**
  - Distribute individual messages from `root` to each process in communicator
  - Inverse operation to `MPI_GATHER`

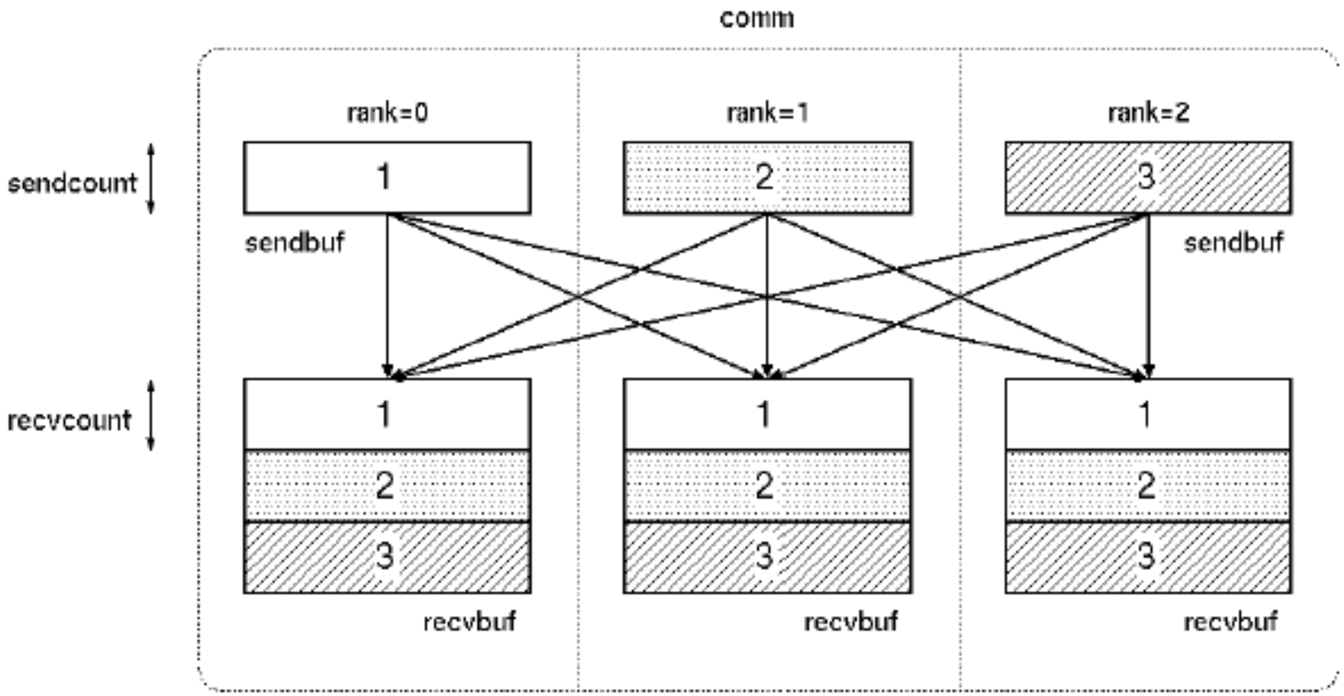
MPI_Gather

- **Usage**

```
int MPI_Gather( void* sendbuf,      /* in */
            int sendcount,          /* in */
            MPI_Datatype sendtype,  /* in */
            void* recvbuf,          /* out */
            int recvcount,          /* in */
            MPI_Datatype recvtype,  /* in */
            int root,               /* in */
            MPI_Comm comm           /* in */ );
```

- **Description**
  - Collects individual messages from each process in communicator `comm` to the `root` process and store them in rank order

MPI_Allgather



MPI_Allgather

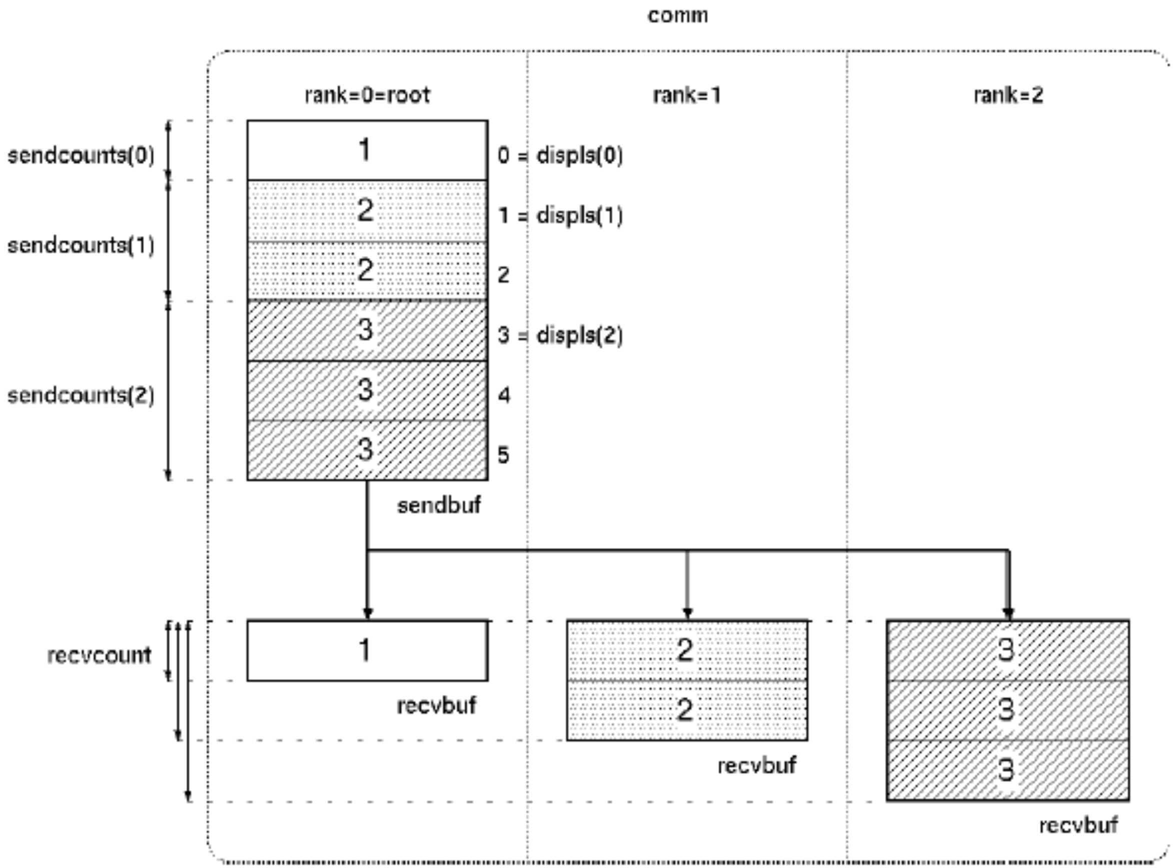
Usage

```
int MPI_Allgather( void* sendbuf,          /* in */
                   int sendcount,          /* in */
                   MPI_Datatype sendtype,  /* in */
                   void* recvbuf,          /* out */
                   int recvcount,          /* in */
                   MPI_Datatype recvtype,  /* in */
                   MPI_Comm comm);         /* in */
```

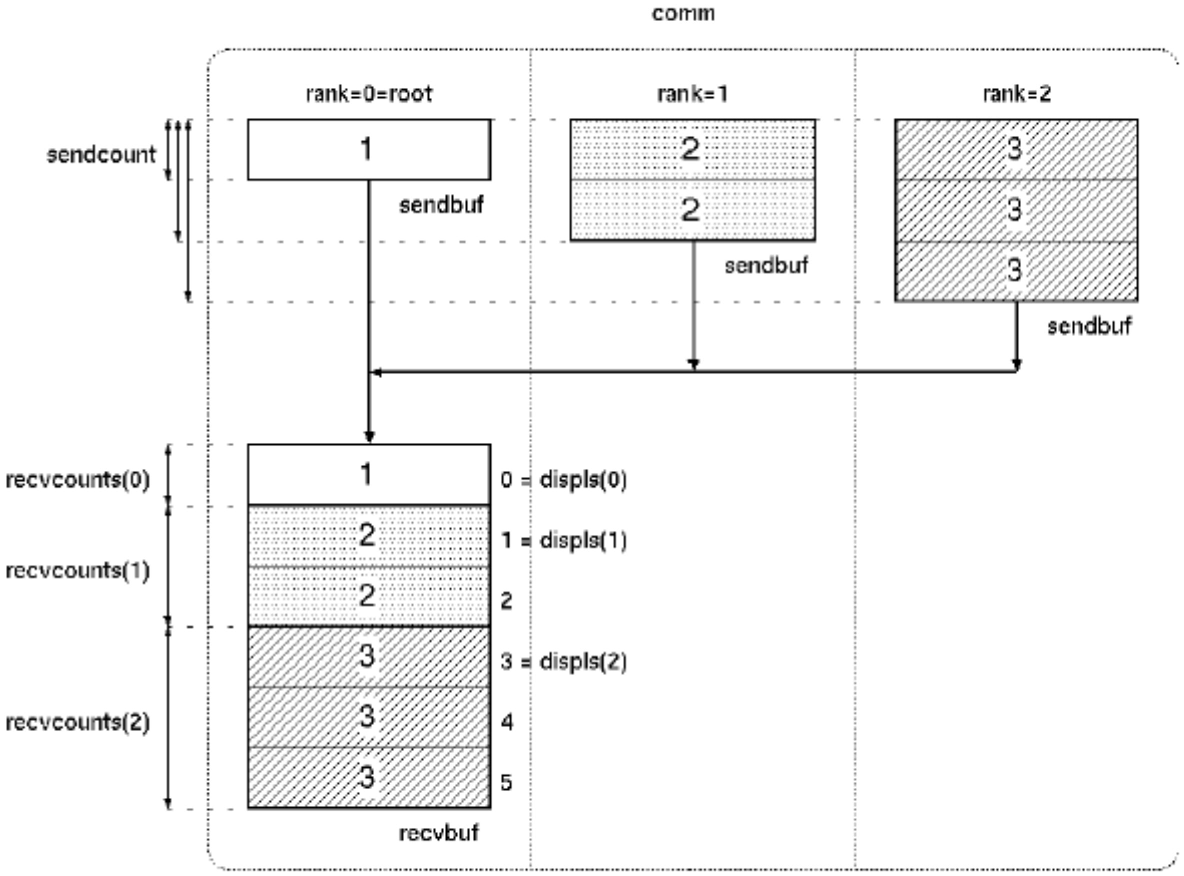
Description

- Gathers individual messages from each process in communicator `comm` and distributes the resulting message to each process
- Similar to `MPI_GATHER` except that all processes receive the result

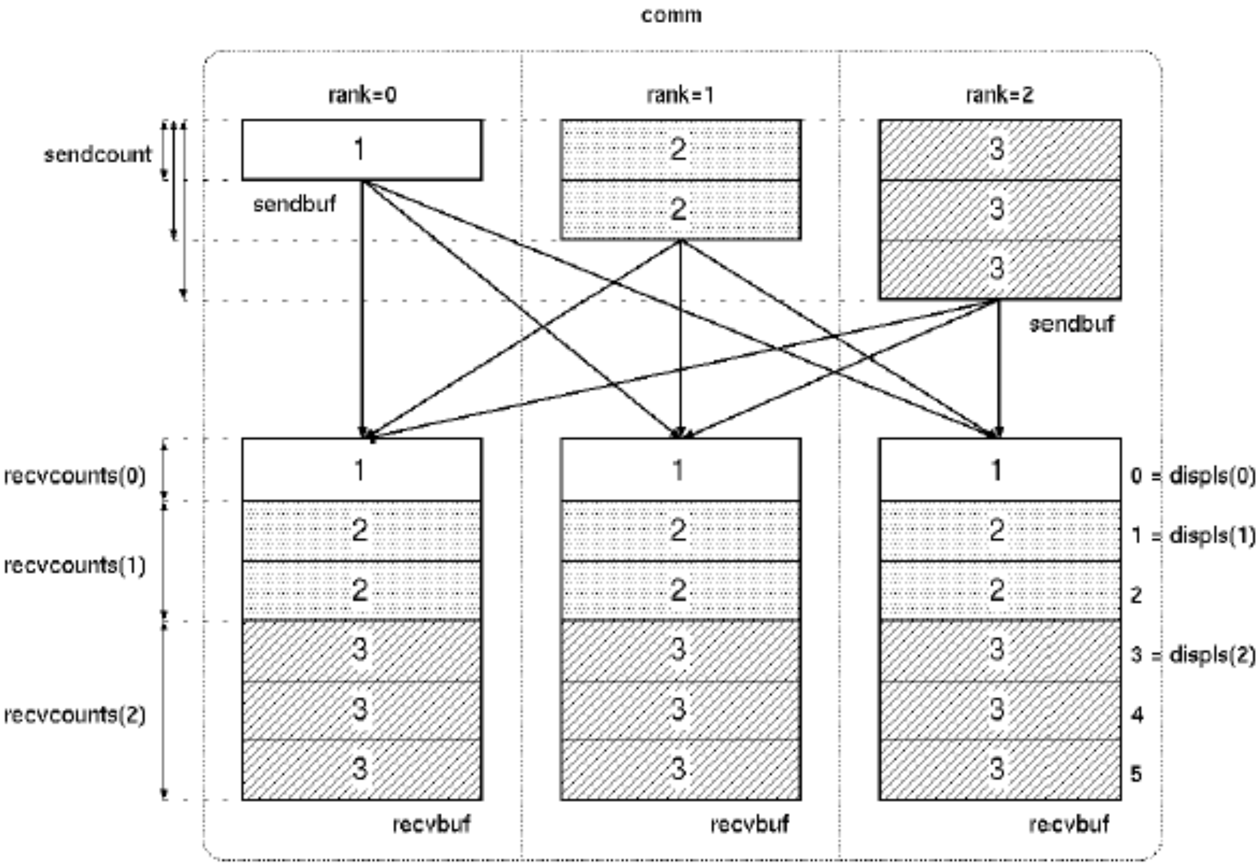
MPI_Scatterv



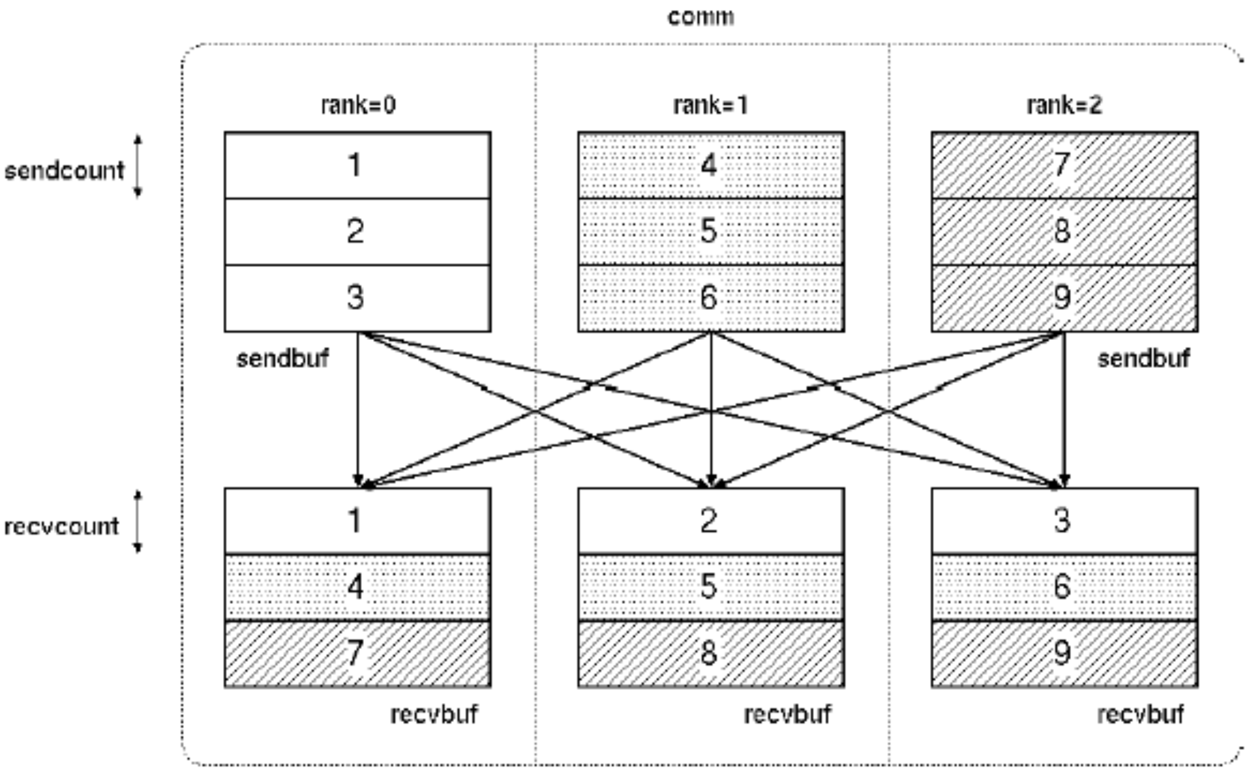
MPI_Gatherv


comm
rank=0=root
rank=1
rank=2
sendcount
1
2
2
3
3
3
sendbuf
sendbuf
sendbuf
recvcounts(0)
recvcounts(1)
recvcounts(2)
1
2
2
3
3
3
0 = displs(0)
1 = displs(1)
2
3 = displs(2)
4
5
recvbuf

MPI_Allgatherv



MPI_Alltoall



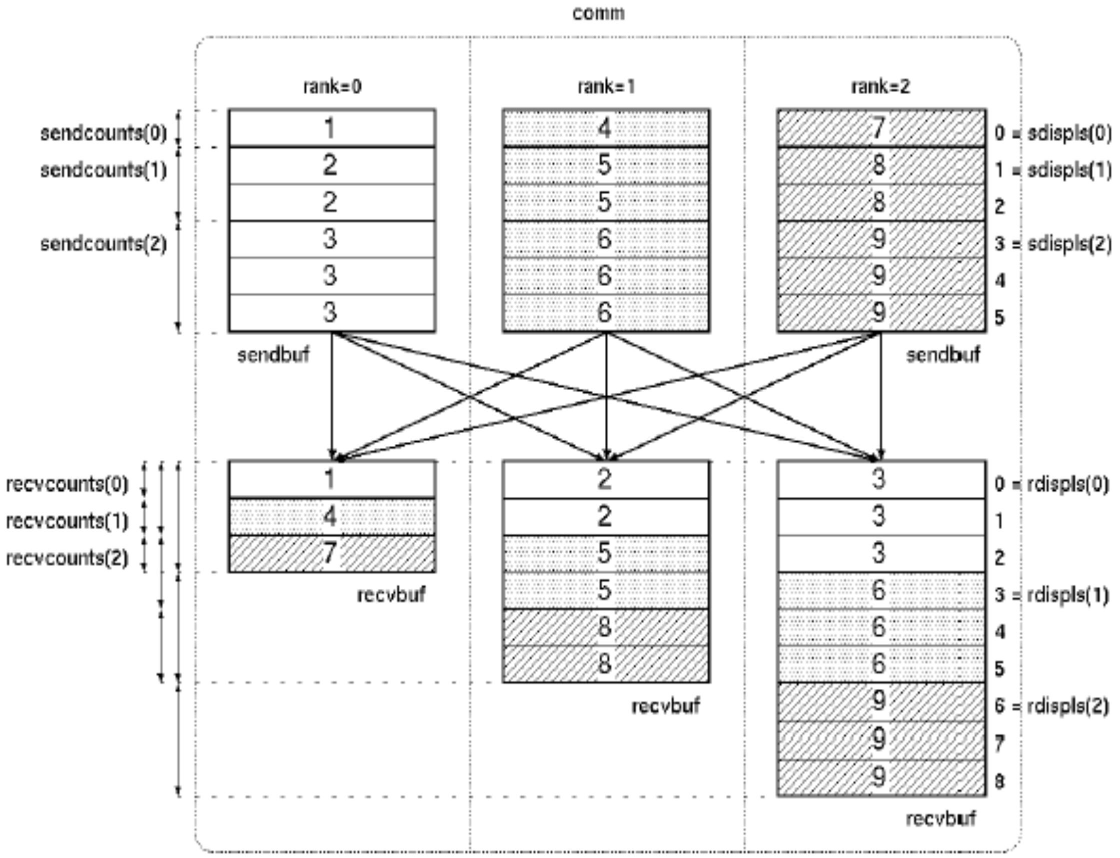
MPI_Alltoall

- **Usage**

```
int MPI_Alltoall( void* sendbuf,           /* in */
                  int sendcount,           /* in */
                   MPI_Datatype sendtype,  /* in */
                   void* recvbuf,          /* out */
                   int recvcount,          /* in */
                   MPI_Datatype recvtype,  /* in */
                   MPI_Comm comm);         /* in */
```

- **Description**
  - Sends a distinct message from each process to every other process
  - The j-th block of data sent from process `i` is received by process `j` and placed in the `i-th` block of the buffer `recvbuf`
  - Useful to implement, for example, transpositions

MPI_Alltoallv



MPI BASICS