Lecture 9 – Basic Communication in MPI

- **Bounce Program to find bandwidth and latency of a computer**
  1. Start an even number of instances of the executable
  2. Pair them up (next and previous in a linear array)
  3. Send/receive a series of messages of increasing size and record the time that it takes to send/receive each message
  4. Repeat a number of times and average results
  5. Report *bandwidth* and *latency*

Definitions of Latency and Bandwidth

- ***Latency*** **is the amount of wall clock time that it takes for a message of zero length to be sent from one processor to another**
  - Latency penalized programs that send/receive a large number of messages
- ***Bandwidth*** **is the number of bytes/sec that can be sent from one processor to another**
  - Low bandwidth penalizes programs that send/receive a large amount of information
- **Ideal network has low latency and high bandwidth and is VERY expensive**

Bounce Program in Fortran 90/95

```
c
c-------------------------------------------------------------------
c     this program times blocking send/receives, and reports the
c     latency and bandwidth of the communication system.  it is
c     designed to run on an even number of nodes.
c
c     AA220 / CS238
c     Juan J. Alonso, October 2001
c
c-------------------------------------------------------------------
c
      program bounce
      parameter (maxcount=1000000)
      parameter (nrepeats=50)
      parameter (nsizes=7)
c
      implicit real*8 (a-h,o-z)
      include "mpif.h"
c
      dimension sbuf(maxcount), rbuf(maxcount)
      dimension length(nsizes)
      integer   status(mpi_status_size)
```

Bounce Program in Fortran 90/95

```
c
c---------------------------------------
c     define an array of message lengths
c---------------------------------------
c
      length(1) = 0
      length(2) = 1
      length(2) = 10
      length(3) = 100
      length(4) = 1000
      length(5) = 10000
      length(6) = 100000
      length(7) = 1000000
c
c---------------------------------------
c     initialize the send buffer to zero
c---------------------------------------
c
      do n=1,maxcount
      sbuf(n) = 0.0d0
      rbuf(n) = 0.0d0
      end do
c
c-------------------------------------
c     set up the parallel environment
c-------------------------------------
c
```

Bounce Program in Fortran 90/95

```
      call mpi_init(ierr)
      call mpi_comm_size(mpi_comm_world,nnodes,ierr)
      call mpi_comm_rank(mpi_comm_world,nodeid,ierr)
c
      if (nodeid.eq.0) write(*,*)'number of processors =',nnodes
c
c     signal error if an odd number of nodes is specified
c
      if (mod(nnodes,2) .ne. 0) then
         if (nodeid .eq. 0) then
            write(6,*) ' you must specify an even number of nodes.'
         end if
         call mpi_finalize(ierr)
      end if
c
c---------------------------------------------------------
c     send or receive messages, and time it.
c     even nodes send, odd nodes receive, then the reverse
c---------------------------------------------------------
c
      do ns=1, nsizes
         time1 = mpi_wtime()
         do nr=1, nrepeats
```

Bounce Program in Fortran 90/95

```
c---------------------------------------------
c           send in one direction i->i+1
c---------------------------------------------
c
         if (mod(nodeid,2) .eq. 0) then
         call mpi_send(sbuf, length(ns), mpi_real8, nodeid+1, 1,
     .                 mpi_comm_world, ierr)
         else
         call mpi_recv(rbuf, length(ns), mpi_real8, nodeid-1, 1,
     .                 mpi_comm_world, status, ierr)
         end if
c
c--------------------------------------------------
c           send in the reverse direction i+1->i
c--------------------------------------------------
c
         if (mod(nodeid,2) .eq. 1) then
         call mpi_send(sbuf, length(ns), mpi_real8, nodeid-1, 1,
     .                 mpi_comm_world, ierr)
         else
         call mpi_recv(rbuf, length(ns), mpi_real8, nodeid+1, 1,
     .                 mpi_comm_world, status, ierr)
         end if
         end do
         time2 = mpi_wtime()
```

Bounce Program in Fortran 90/95

```
c---------------------------------------------------
c           timings and report results
c---------------------------------------------------
c
        if (nodeid .eq. 0) then
        write(6,fmt='(a,i9,a,10x,a,f10.4,a)') 'msglen =',8*length(ns),
     &  ' bytes,','elapsed time =',0.5d3*(time2-time1)/nrepeats,' msec'
        call flush(6)
        end if
        if (ns .eq. 1) then
           tlatency = 0.5d6*(time2-time1)/nrepeats
        end if
        if (ns .eq. nsizes) then
           bw = 8.*length(ns)/(0.5d6*(time2-time1)/nrepeats)
        end if
     end do
c
c---------------------------------------------------------
c     report apporximate numbers for bandwidth and latency
c---------------------------------------------------------
c
```

Bounce Program in Fortran 90/95

```
c
c---------------------------------------------------------
c     report apporximate numbers for bandwidth and latency
c---------------------------------------------------------
c
      if (nodeid .eq. 0) then
         write(6,fmt='(a,f6.1,a)') 'latency =',tlatency,' microseconds'
         write(6,*) 'bandwidth =',bw,' mbytes/sec'
c        write(6,fmt='(a,f8.4,a)') 'bandwidth =',bw,' mbytes/sec'
         write(6,fmt='(a)') '(approximate values for mp_send/mp_recv)'
      end if
c
      call mpi_finalize(ierr)
      end
```

Bounce with Scali Cards on Previous Generation Matrx Beowulf Cluster (1.6 GHz Athlons)

```
With scali cards on matrx:
mpimon bounce_pgf -- n01 1 n02 1 n03 1 n04 1 n05 1 n06 1 n07 1 n08 1
  Number of processors = 8
msglen =        0 bytes,          elapsed time =    0.0499 msec
msglen =       80 bytes,          elapsed time =    0.3579 msec
msglen =      800 bytes,          elapsed time =    0.0173 msec
msglen =     8000 bytes,          elapsed time =    0.0620 msec
msglen =    80000 bytes,          elapsed time =    2.5253 msec
msglen =   800000 bytes,          elapsed time =   12.2922 msec
msglen =  8000000 bytes,          elapsed time =   90.0449 msec
latency =  49.9 microseconds
 bandwidth =    88.8445395577 6175       MBytes/sec
(approximate values for mp_send/mp_recv)
```

Bounce with 100BT Ethernet Switch on Previous Generation Matrx Beowulf Cluster

```
With 100BT Switched Ethernet on Beowulf cluster:
n8 3% /usr/local/mpich-1.2.0/bin/mpirun -np 8 ./bounce_eth
 Number of processors = 8
msglen =        0 bytes,          elapsed time =    0.0942 msec
msglen =       80 bytes,          elapsed time =    0.0991 msec
msglen =      800 bytes,          elapsed time =    0.2459 msec
msglen =     8000 bytes,          elapsed time =    0.9316 msec
msglen =    80000 bytes,          elapsed time =    7.1869 msec
msglen =   800000 bytes,          elapsed time =   71.6712 msec
msglen =  8000000 bytes,          elapsed time =  712.2905 msec
latency =  94.2 microseconds
 bandwidth =    11.23137338146257       MBytes/sec
(approximate values for mp_send/mp_recv)
```

Bounce on Previous Generation Multiprocessor Sun

```
With SUNWhpc MPI implementation:
junior:~/bounce /opt/SUNWhpc/bin/mprun -np 8 ./bounce
  Number of processors = 8
 msglen =        0 bytes,          elapsed time =    0.0066 msec
 msglen =       80 bytes,          elapsed time =    0.0102 msec
 msglen =      800 bytes,          elapsed time =    0.0606 msec
 msglen =     8000 bytes,          elapsed time =    0.0781 msec
 msglen =    80000 bytes,          elapsed time =    0.5065 msec
 msglen =   800000 bytes,          elapsed time =    4.7291 msec
 msglen =  8000000 bytes,          elapsed time =   46.0369 msec
 latency =   6.6 microseconds
  bandwidth = 173.77383012979993  MBytes/sec
 (approximate values for mp_bsend/mp_brecv)
```

Bounce with Myrinet on Beowulf Cluster

```
With Myrinet on Beowulf cluster:
n8 3% mpiexec bounce_myr
 Number of processors = 8
msglen =        0 bytes,          elapsed time =    0.0117 msec
msglen =       80 bytes,          elapsed time =    0.0149 msec
msglen =      800 bytes,          elapsed time =    0.0488 msec
msglen =     8000 bytes,          elapsed time =    0.2376 msec
msglen =    80000 bytes,          elapsed time =    1.2652 msec
msglen =   800000 bytes,          elapsed time =   12.3286 msec
msglen =  8000000 bytes,          elapsed time =  122.5315 msec
latency =  11.7 microseconds
 bandwidth =    65.28934971611689       MBytes/sec
(approximate values for mp_bsend/mp_brecv)
```

Bounce on Previous Generation Davistron Beowulf Cluster using PGI and OpenMPI 2.1 GHz Athlons)

```
With 1Gb Ethernet on davistron:
/share/apps/openmpi-pgi/bin/mpirun bounce_pgi
  Number of processors = 6
msglen =        0 bytes,          elapsed time =    0.0021 msec
msglen =       80 bytes,          elapsed time =    0.0023 msec
msglen =      800 bytes,          elapsed time =    0.0028 msec
msglen =     8000 bytes,          elapsed time =    0.0178 msec
msglen =    80000 bytes,          elapsed time =    0.0877 msec
msglen =   800000 bytes,          elapsed time =    1.1344 msec
msglen =  8000000 bytes,          elapsed time =   10.6623 msec
latency =   2.1 microseconds
 bandwidth =    750.3042635355571       MBytes/sec
```

Bounce on Previous Generation Davistron Beowulf Cluster using Gfortran and OpenMPI (2.1 GHz Athlons)

```
With 1Gb Ethernet on davistron:
/opt/openmpi/bin/mpirun bounce_gnu
  Number of processors = 6
msglen =        0 bytes,          elapsed time =    0.0013 msec
msglen =       80 bytes,          elapsed time =    0.0017 msec
msglen =      800 bytes,          elapsed time =    0.0024 msec
msglen =     8000 bytes,          elapsed time =    0.0120 msec
msglen =    80000 bytes,          elapsed time =    0.0846 msec
msglen =   800000 bytes,          elapsed time =    1.1014 msec
msglen =  8000000 bytes,          elapsed time =   10.3057 msec
latency =    1.3 microseconds
 bandwidth =   776.269240779406       MBytes/sec
```

Bounce on Vortex Beowulf Cluster using PGI and OpenMPI (3.2 GHz Athlons)

```
With 1Gb Ethernet on vortex:
/share/apps/openmpi-1.4.3-pgi-10.9/bin/mpirun bounce_pgi
  Number of processors = 8
msglen =        0 bytes,          elapsed time =    0.0024 msec
msglen =       80 bytes,          elapsed time =    0.0028 msec
msglen =      800 bytes,          elapsed time =    0.0037 msec
msglen =     8000 bytes,          elapsed time =    0.0218 msec
msglen =    80000 bytes,          elapsed time =    0.1253 msec
msglen =   800000 bytes,          elapsed time =    1.8298 msec
msglen =  8000000 bytes,          elapsed time =   18.1576 msec
latency =   2.4 microseconds
 bandwidth =    440.5856717617291       MBytes/sec
```

Bounce on Vortex Beowulf Cluster using Gfortran and OpenMPI (3.2 GHz Athlons)

```
With 1Gb Ethernet on davistron:
/opt/openmpi/bin/mpirun bounce_gnu
  Number of processors = 8
msglen =        0 bytes,          elapsed time =    0.0020 msec
msglen =       80 bytes,          elapsed time =    0.0027 msec
msglen =      800 bytes,          elapsed time =    0.0028 msec
msglen =     8000 bytes,          elapsed time =    0.0179 msec
msglen =    80000 bytes,          elapsed time =    0.1195 msec
msglen =   800000 bytes,          elapsed time =    1.8690 msec
msglen =  8000000 bytes,          elapsed time =   18.7854 msec
latency =   2.0 microseconds
 bandwidth =   425.86171031648576       MBytes/sec
```

Review: Send/Receive Types

- **Standard: similar to Blocking except receive will not allow processor to continue only until its buffer can be reused.**
- **Blocking: receive will not allow processor to continue until it has received its message. Receive acts as a Barrier to that processor.**
- **Synchronous: send (or receive) does not start until a matching receive (or send) is posted indicating it is ready. Send acts as "blocking" until matching receive occurs. In this case, send acts as a Barrier for those processors.**
- **Buffered: either a system or user-defined buffer is made available for send/receive so that communication can proceed.**

Review: Buffered/Non-buffered Communications

- **No-buffering (phone calls)**
  - Proc 0 initiates the send request and rings Proc 1. It waits until Proc 1 is ready to receive. The transmission starts.
  - Synchronous communication – completed only when the message was received by the receiving proc
- **Buffering (beeper)**
  - The message to be sent (by Proc 0) is copied to a system-controlled block of memory (buffer)
  - Proc 0 can continue executing the rest of its program
  - When Proc 1 is ready to receive the message, the system copies the buffered message to Proc 1
  - Asynchronous communication – may be completed even though the receiving proc has not received the message

Review: Buffered Communication

- **Buffering requires system resources, e.g. memory, and can be slower if the receiving proc is ready at the time of requesting the send**
- **Application buffer: address space that holds the data**
- **System buffer: system space for storing messages. In buffered communication, data in application buffer is copied to/from system buffer**
- **MPI allows communication in buffered mode:**

  MPI_Bsend, MPI_Ibsend
- **User allocates the buffer by:**

  MPI_Buffer_attach(buffer, buffer_size)
- **Free the buffer by MPI_Buffer_detach**

Review: Blocking / Non-blocking Communication

- **Blocking Communication (old McDonald's)**
  - The receiving proc has to wait if the message is not ready
  - Different from synchronous communication
    - Standard blocking occurs until buffer can be reused
    - Synchronous mode blocking occurs until receive has occurred
  - Proc 0 may have already buffered the message to system and Proc 1 is ready, but the interconnection network is busy
- **Non-blocking Communication (In & Out)**
  - Proc 1 checks with the system if the message has arrived yet. If not, it continues doing other stuff. Otherwise, get the message from the system.
- **Useful when computation and communication can be performed at the same time**
- **MPI allows both non-blocking send and receive**

MPI_Isend and MPI_Irecv

- **In non-blocking send, program identifies an area in memory to serve as a send buffer. Processing continues immediately without waiting for message to be copied out from the application buffer**
- **The program *should not* modify the application buffer until the non-blocking send has completed**
- **Non-blocking communication can be combined with non-buffering: MPI_Issend, or buffering: MPI_Ibsend**
- **Use MPI_Wait or MPI_Test to determine if the non-blocking send or receive has completed**

Non-Blocking Send Syntax

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

[IN buf] initial address of send buffer (choice)

[IN count] number of elements in send buffer (integer)

[IN datatype] datatype of each send buffer element (handle)

[IN dest] rank of destination (integer)

[IN tag] message tag (integer)

[IN comm] communicator (handle)

[OUT request] communication request (handle)

C:

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

Fortran 90/95:

```
MPI_ISEND(BUF, COUNT, DATATYPE, DEST, TAG, COMM, REQUEST,
                IERROR)
<type> BUF(*)
INTEGER COUNT, DATATYPE, DEST, TAG, COMM, REQUEST, IERROR
```

Non-Blocking Receive Syntax

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

[OUT buf] initial address of receive buffer (choice)

[IN count] number of elements in receive buffer (integer)

[IN datatype] datatype of each receive buffer element (handle)

[IN source] rank of source (integer)

[IN tag] message tag (integer)

[IN comm] communicator (handle)

[OUT request] communication request (handle)

C:

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

Fortran 90/95:

```
MPI_IRECV(BUF, COUNT, DATATYPE, SOURCE, TAG, COMM,
             REQUEST, IERROR)
<type> BUF(*)
INTEGER COUNT, DATATYPE, SOURCE, TAG, COMM, REQUEST,
   IERROR
```

Communication Completion

- Wait until the communication operation associated with the specified request is completed. Note that for a send operation, this simply means that the message has been sent, and the send buffer is ready for reuse. This does NOT mean that the corresponding receive operation has also completed.
- Used with MPI_Isend and MPI_Irecv non-synchronous sends and receives

MPI_WAIT(request, status)

[INOUT request] request (handle)

[OUT status] status object (Status)

C:

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

Fortran 90/95:

```
MPI_WAIT(REQUEST, STATUS, IERROR)
INTEGER REQUEST, STATUS(MPI_STATUS_SIZE), IERROR
```

Communication Completion

- Test if the communication operation specified by REQUEST has completed or not. Status is returned in FLAG. If the communication request has not completed, you can go do something else and test again later.
- Again, used with MPI_Isend and MPI_Irecv non-synchronous communications

MPI_TEST(request, flag, status)

[INOUT request] communication request (handle)

[OUT flag] true if operation completed (logical)

[OUT status] status object (Status)

C:

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

Fortran 90/95:

```
MPI_TEST(REQUEST, FLAG, STATUS, IERROR)
LOGICAL FLAG
INTEGER REQUEST, STATUS(MPI_STATUS_SIZE), IERROR
```

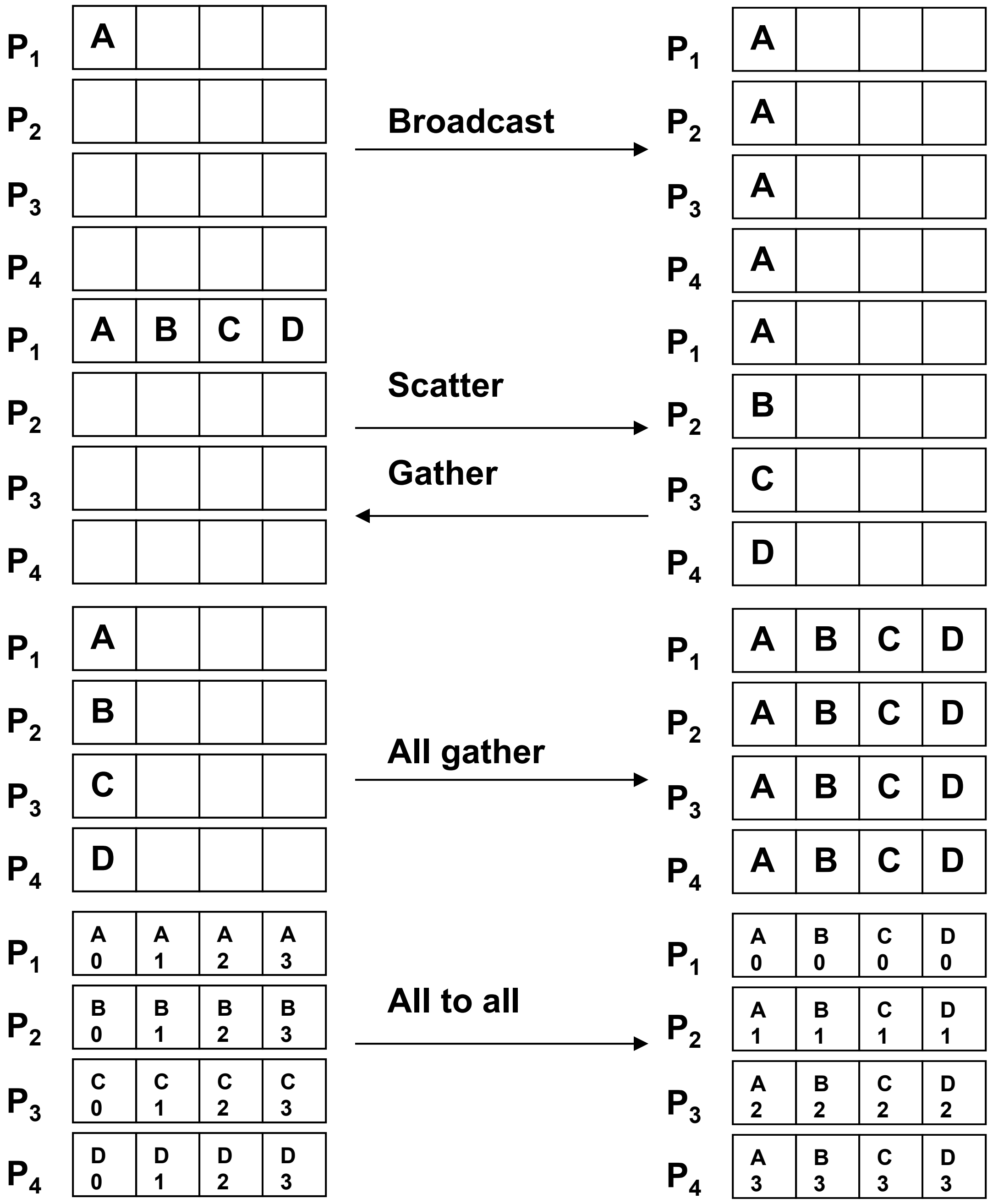
Review: Collective Communication

- **Communication pattern involving a group of procs; usually more than 2**
- **MPI_Barrier: Synchronize all procs**
- **Broadcast (MPI_Bcast)**
  - A single proc sends the same data to every proc
- **Reduction (MPI_Reduce)**
  - All of the procs contribute data that is combined using a binary operation
  - Example: max, min, sum, etc.
  - One proc obtains the final answer
- **Allreduce (MPI_Allreduce)**
  - Same as MPI_Reduce but every proc contains the final answer
  - Effectively as MPI_Reduce + MPI+Bcast, but more efficient

Review: Other Collective Communicators

- **Scatter (MPI_Scatter)**
  - Split the data on the root processor into p segments
  - The 1st segment is sent to proc 0, the 2nd to proc 1, etc.
  - Similar to but more general than MPI_Bcast
- **Gather (MPI_Gather)**
  - Collect the data from each processor and store the data on root processor
  - Similar to but more general than MPI_Reduce
- **Can collect and store the data on all procs using MPI_Allgather**

Review: Comparison of Collective Communicators



Barrier Synchronization

MPI_Barrier(comm)

[IN comm] communicator (handle)

C:

Int MPI_Barrier(MPI_Comm comm)

Fortran 90/95:

MPI_BARRIER(COMM, IERROR)

INTEGER COMM, IERROR

- **MPI_BARRIER blocks the caller until all group members have called it. The call returns at any process only after all group members have entered the call**
- **Use this only where needed since there is high overhead associated with synching processors**

Broadcast

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

[INOUT buffer] starting address of buffer (choice)

[IN count] number of entries in buffer (integer)

[IN datatype] data type of buffer (handle)

[IN root] rank of broadcast root (integer)

[IN comm] communicator (handle)

C:

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

Fortran 90/95:

```
MPI_BCAST(BUFFER, COUNT, DATATYPE, ROOT,
          COMM, IERROR)
```

Broadcast

- **MPI_BCAST broadcasts a message from the process with rank *root* to all processes of the group, itself included. It is called by all members of group using the same arguments for comm, root. On return, the contents of root's communication buffer has been copied to all processes.**
- **For example: Broadcast 100 integers from process 0 to every process in the group.**

```
MPI_Comm comm;
    int array[100];
    int root=0;
    ...
    MPI_Bcast( array, 100, MPI_INT, root, comm);
```

- **As in many of our example code fragments, we assume that some of the variables (such as comm in the above) have been assigned appropriate values. Broadcasting is costly, so use Bcast only when needed.**

Gather

MPI_GATHER(sendbuf, sendcount, sendtype, recvbuf, recvcount, recvtype, root, comm)

[IN sendbuf] starting address of send buffer (choice)

[IN sendcount] number of elements in send buffer (integer)

[IN sendtype] data type of send buffer elements (handle)

[OUT recvbuf] address of receive buffer (choice, significant only at root)

[IN recvcount] number of elements for any single receive (integer, significant only at root)

[IN recvtype] data type of recv buffer elements (significant only at root) (handle)

[IN root] rank of receiving process (integer)

[IN comm] communicator (handle)

C:

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

Fortran 90/95:

```
MPI_GATHER(SENDBUF, SENDCOUNT, SENDTYPE, RECVBUF,
           RECVCOUNT, RECVTYPE, ROOT, COMM, IERROR)
<type> SENDBUF(*), RECVBUF(*)
INTEGER SENDCOUNT, SENDTYPE, RECVCOUNT, RECVTYPE, ROOT, COMM,
   IERROR
```

Gather

- Each process (root process included) sends the contents of its send buffer to the root process. The root process receives the messages and stores them in rank order. The outcome is as if each of the n processes in the group (including the root process) had executed a call to MPI_SEND and the root had executed n calls to MPI_RECV.

Scatter

MPI_SCATTER(sendbuf, sendcount, sendtype, recvbuf, recvcount, recvtype, root, comm)

[IN sendbuf] address of send buffer (choice, significant only at root)

[IN sendcount] number of elements sent to each process (integer, significant only at root)

[IN sendtype] data type of send buffer elements (significant only at root) (handle)

[OUT recvbuf] address of receive buffer (choice)

[IN recvcount] number of elements in receive buffer (integer)

[IN recvtype] data type of receive buffer elements (handle)

[IN root] rank of sending process (integer)

[IN comm] communicator (handle)

C:

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

Fortran 90/95:

```
MPI_SCATTER(SENDBUF, SENDCOUNT, SENDTYPE, RECVBUF,
            RECVCOUNT, RECVTYPE, ROOT, COMM, IERROR)
<type> SENDBUF(*), RECVBUF(*)
INTEGER SENDCOUNT, SENDTYPE, RECVCOUNT, RECVTYPE, ROOT, COMM,
    IERROR
```

Scatter

- MPI_SCATTER is the inverse operation to MPI_GATHER.
- The outcome is as if the root executed n send operations, and each process executed a receive.

All-to-All

MPI_ALLTOALL(sendbuf, sendcount, sendtype, recvbuf, recvcount, recvtype, comm)

[IN sendbuf] starting address of send buffer (choice)

[IN sendcount] number of elements sent to each process (integer)

[IN sendtype] data type of send buffer elements (handle)

[OUT recvbuf] address of receive buffer (choice)

[IN recvcount] number of elements received from any process (integer)

[IN recvtype] data type of receive buffer elements (handle)

[IN comm] communicator (handle)

C:

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

Fortran 90/95:

```
MPI_ALLTOALL(SENDBUF, SENDCOUNT, SENDTYPE, RECVBUF,
             RECVCOUNT, RECVTYPE, COMM, IERROR)
<type> SENDBUF(*), RECVBUF(*)
INTEGER SENDCOUNT, SENDTYPE, RECVCOUNT, RECVTYPE, COMM,
   IERROR
```

All-to-All

- **MPI_ALLTOALL is an extension of MPI_ALLGATHER to the case where each process sends distinct data to each of the receivers. The jth block sent from process i is received by process j and is placed in the ith block of recvbuf.**

Reduce

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

[IN sendbuf] address of send buffer (choice)

[OUT recvbuf] address of receive buffer (choice, significant only at root)

[IN count] number of elements in send buffer (integer)

[IN datatype] data type of elements of send buffer (handle)

[IN op] reduce operation (handle)

[IN root] rank of root process (integer)

[IN comm] communicator (handle)

C:

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

Fortran 90/95:

```
MPI_REDUCE(SENDBUF, RECVBUF, COUNT, DATATYPE, OP, ROOT,
                   COMM, IERROR)
<type> SENDBUF(*), RECVBUF(*)
INTEGER COUNT, DATATYPE, OP, ROOT, COMM, IERROR
```

Reduce

- MPI_REDUCE combines the elements provided in the input buffer of each process in the group, using the operation *op*, and returns the combined value in the output buffer of the process with rank root.
- The input buffer is defined by the arguments sendbuf, count and datatype; the output buffer is defined by the arguments recvbuf, count and datatype; both have the same number of elements, with the same type.
- The routine is called by all group members using the same arguments for count, datatype, op, root and comm. Thus, all processes provide input buffers and output buffers of the same length, with elements of the same type.
- Each process can provide one element, or a sequence of elements, in which case the combine operation is executed element-wise on each entry of the sequence.

Reduce

- **There are a series of pre-defined operations**
  - [MPI_MAX] maximum
  - [MPI_MIN] minimum
  - [MPI_SUM] sum
  - [MPI_PROD] product
  - [MPI_LAND] logical and
  - [MPI_BAND] bit-wise and
  - [MPI_LOR] logical or
  - [MPI_BOR] bit-wise or
  - [MPI_LXOR] logical xor
  - [MPI_BXOR] bit-wise xor
  - [MPI_MAXLOC] max value and location
  - [MPI_MINLOC] min value and location
- **The user can also define global operations to perform on distributed data with MPI_OP_CREATE.**

Homework 4 (Reading Only)

- **Read Chapters 4-6 in <u>Using MPI</u> by Gropp et al. and review the more advanced MPI routines**
  - The OpenMPI manual can also be used
- **Read Chapter 6 of <u>Introduction to Parallel Computing</u> by Grama et al. if you purchased the book.**
- **Exercise (not for credit)**
  - Write a routine that uses MPI_Send and MPI_Receive to find the minimum and maximum of a set of 100 random numbers
  - Write another routine that uses MPI_Reduce to find the minimum and maximum instead of MPI_Send and MPI_Receive
  - Compare the wall clock time for the two routines using MPI_Wtime.