Lecture 6: Message Passing Interface

- Introduction
- The basics of MPI
- Some simple problems
- More advanced functions of MPI
- A few more examples

When is Parallel Implementation Useful

- In general it is useful for Large problems
- Problems suitable for parallelisation, i.e. you know what speed-up to expect
- You need to be able to recognise them
- Three types of problems are suitable:
  - Parallel Problems
  - Regular and Synchronous Problems
  - Irregular and/or Asynchronous Problems

When is Parallel Implementation Useful: Type I

- Parallel problems:
  - The problem can be broken down into subparts
  - Each subpart is independent of the others
  - No communication is required, except to split up the problem and combine the final results
  - Linear speed-up can be expected

- Example of this is: Monte-Carlo simulations

When is Parallel Implementation Useful: Type II

- Regular and Synchronous Problems:
  - Same instruction set (regular algorithm) applied to all data
  - Synchronous communication (or close to): each processor finishes its task at the same time
  - Local (neighbour to neighbour) and collective (combine final results) communication
- Speed-up based on the computation:communication ratio
- If it is large, expect good speed-up for local communications & ok speed-up for non-local communications
- Ex: Fast Fourier transforms (synchronous), matrix-vector products, sorting (loosely synch.)

When is Parallel Implementation Useful: Type III

- Irregular and/or Asynchronous Problems:
  - Irregular algorithm which cannot be implemented efficiently except with message passing and high communication overhead
  - Communication is usually asynchronous and requires careful coding and load balancing
  - Often dynamic repartitioning of data between processors is required
  - Speed-up is difficult to predict; if the problem can be split up into regular and irregular parts, this makes things easier
- Ex: Melting ice problem (or any moving boundary simulation)

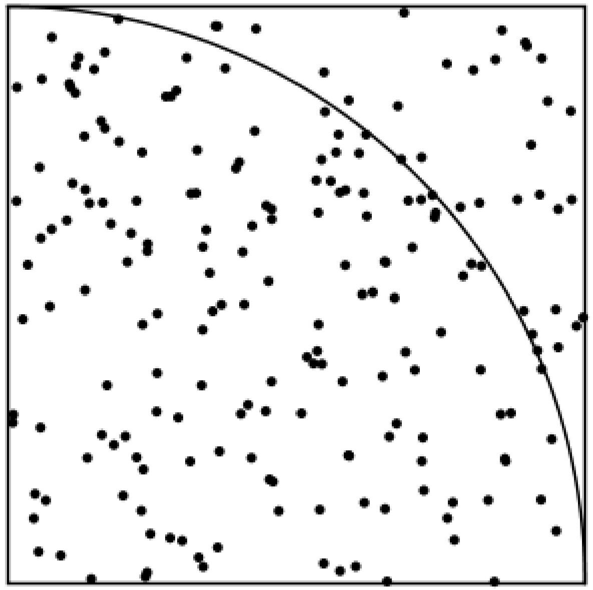
Example 1: matrix-vector product

$$\begin{pmatrix} \boxed{a_{11} & a_{12} & a_{13} & a_{14}} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} \text{X} \begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{pmatrix} = \begin{pmatrix} \boxed{c_1} \\ c_2 \\ c_3 \\ c_4 \end{pmatrix}$$

$$\text{with} \begin{cases} c_1 = a_{11} \times b_1 + a_{12} \times b_2 + a_{13} \times b_3 + a_{14} \times b_4 \\ c_2 = a_{21} \times b_1 + a_{22} \times b_2 + a_{23} \times b_3 + a_{24} \times b_4 \\ c_3 = a_{31} \times b_1 + a_{32} \times b_2 + a_{33} \times b_3 + a_{34} \times b_4 \\ c_2 = a_{41} \times b_1 + a_{42} \times b_2 + a_{43} \times b_3 + a_{44} \times b_4 \end{cases}$$

- A parallel approach:
  - Each element of vector *c* depends on vector *b* and only one line of **A**
  - Each element of *c* can be calculated independently from the others
  - Communication only needed to split up the problem and combine the final results
- => a linear speed-up can be expected for large matrices

Example 2: : Monte-Carlo calculation of Pi



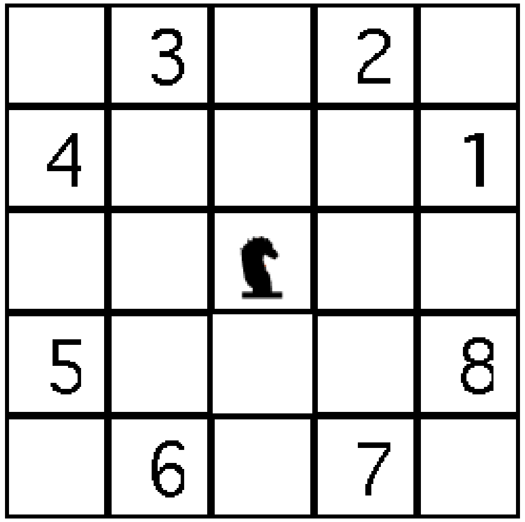
Quadrant of a Unit Circle with Random distribution of points

- π = 3.14159….= area of a circle of radius 1
- π/4 ≈ fraction of the points within the circle quadrant
- The more points, the more accurate the value for π is

Example 2: Monte-Carlo calculation of Pi (Cont'd)

- A parallel approach:
  - Each point is randomly placed within the square
  - The position of each point is independent of the position of the others
  - We can split up the problem by letting each node randomly place a given number of points
  - Communication is only needed to specify the number of points and combine final results
- => a linear speed-up can be expected, allowing for a larger number of points and therefore a greater accuracy in the estimation of π.

Example 3: A More Real Problem



- After each move, the chess software

  must find the best move within a set

  =>This set is large, but finite
- Each move from this set can be evaluated

  independently & the set can be partitioned
- Communication is only needed to split up the problem and combine the final results
- => A linear speed-up can be expected
- => This means that, in a reasonable time, moves can be studied more thoroughly
- => This depth of evaluation is what makes the software more competitive

Some background on MPI

- Developed by MPI forum (made up of Industry, Academia and Govt.)
- They established a standardised Message-Passing Interface (MPI-1) in 1994
- It was intended as an interface to both C and FORTRAN.
- C++ bindings were deprecated in MPI-2. Some Java bindings exist but are not standard yet.
- Aim was to provide a specification which can be implemented on any parallel computer or cluster; hence portability of code was a big aim.

Advantages of MPI

+ Portable, hence protection of software investment
+ A standard, agreed by everybody
+ Designed using optimal features of existing message-passing libraries
+ “Kitchen-sink” functionality, very rich environment (129 functions)
+ Implementations for F77, C and C++ are freely downloadable

…….& It’s Disadvantages

– “Kitchen-sink” functionality, makes it hard to learn all (unnecessary: a bare dozen are needed in most cases)
– Implementations on shared-memory machines is often quite poor, and does not suit the programming model
– Has rivals in other message-passing libraries (e.g. PVM)

MPI Preliminaries…

- MPI provides support for:
  - Point-to-point & collective (i.e. group) communications
  - Inquiry routines to query the environment (how many nodes are there, which node number am I, etc.)
  - Constants and data-types
- We will start with the basics: initialising MPI, and using point-to-point communication

MPI Preliminaries… (Cont'd)

- Naming convention
  - All MPI identifiers are prefixed by '**`MPI_`**'.
  - C routines contain lower case (i.e. '**`MPI_Init`**'),
  - Constants are all in upper case (e.g. '**`MPI_FLOAT`**' is an MPI C data-type).
  - C routines are actually integer functions which return a status code (you are strongly advised to check these for errors!).
- Running MPI
  - Number of processors used is specified in the command line, when running the MPI loader that loads the MPI program onto the processors, to avoid hard-coding this into the program
  - e.g. **`mpirun -np N exec`**

MPI Preliminaries… (Cont'd)

- Writing a program using MPI: what is parallel, what is not
  - Only one program is written. By default, every line of the code is executed by each node running the program.
  - E.g. if the code contains `int result=0`, each node will locally create a variable and assign the value.
- When a section of the code needs to be executed by only a subset of nodes, it has to be explicitly specified.
- E.g., providing that we are using 8 nodes, and that **`MyID`** is a variable storing the rank of the node (from 0 to 7, we will see how to get it later), this section of code assigns to **`result`** to zero for the first half of them, and 1 for the second.

```
    int result;
           if(MyID < 4) result = 0;
    else result = 1;
```

Common MPI Routines

- MPI has a ‘kitchen sink’ approach of 129 different routines
- Most basic programs can get away with using six.
- As usual use #include “mpi.h” in C.

`MPI_Init`	Initialise MPI computation
`MPI_Finalize`	Terminate MPI computation
`MPI_Comm_size`	Determine number of processes
`MPI_Comm_rank`	Determine my process number
`MPI_Send, MPI_Isend`	Blocking, non-blocking send
`MPI_Recv, MPI_Irecv`	Blocking, non-blocking

Common MPI Routines (Cont'd): MPI Initialisation, Finalization

- In all MPI-written programs, MPI must be initialised before use, and finalised at the end.
- All MPI-related commands and types must be handled within this section of code:

`MPI_Init`	Initialise MPI computation
⋮	
`MPI_Finalize`	Terminate MPI computation

- `MPI_Init` takes two parameters as input (`argc` and `argv`),
  - It is used to start the MPI environment, create the default communicator (more later) and assign a rank to each node.
- `MPI_Finalize` cleans up all MPI state. Once this routine is called, no MPI routine (even `MPI_INIT`) may be called.
- The user must ensure that all pending communications involving a process completes before the process calls `MPI_Finalize`.

Common MPI Routines (Cont'd): Basic Inquiry Routines

- At various stages in a parallel-implemented function, it may be useful to know how many nodes the program is using, or what the rank of the current node is.
- The **`MPI_Comm_size`** function returns the number of processes/ nodes as an integer, taking only one parameter, a communicator.
- In most cases you will only use the default Communicator: **`MPI_COMM_WORLD`**.
- The **`MPI_Comm_rank`** function is used to determine what the rank of the current process/node on a particular communicator.
- E.g. if there are two communicators, it is possible, and quite usual, that the ranks of the same node would differ.
- Again, in most cases, this function will only be used with the default communicator as an input (**`MPI_COMM_WORLD`**), and it will return (as an integer) the rank of the node on that communicator.

Common MPI Routines (Cont'd): Point-to-Point communications in MPI

- This involves communication between two processors, one sending, and the other receiving.
- Certain information is required to specify the message:
  - Identification of sender processor
  - Identification of destination/receiving processor
  - Type of data (**`MPI_INT`**, **`MPI_FLOAT`** etc)
  - Number of data elements to send (i.e. array/vector info)
  - Where the data to be sent is in memory (pointer)
  - Where the received data should be stored in (pointer)

Common MPI Routines (Cont'd): Sending data **`MPI_Send`**, **`MPI_Isend`**

- **`MPI_Send`** is used to perform a blocking send, (i.e. process waits for the communication to finish before going to the next command).

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

- This functions takes six parameters:
  - the location of the data to be sent i.e. a pointer (*input parameter*)
  - the number of data elements to be sent (*input parameter*)
  - the type of data e.g. **`MPI_INT`**, **`MPI_FLOAT`**, etc. (*input parameter*)
  - the rank of the receiving/destination node (*input parameter*)
  - a tag for identification of the communication (*input parameter*)
  - the communicator to be used for transmission (*input parameter*)
- **`MPI_Isend`** is non-blocking, so an additional parameter, to allow for verification of communication success is needed.
- It is a pointer to an element of type **`MPI_Request`**.

Common MPI Routines (Cont'd): Receiving data **`MPI_Recv`**, **`MPI_Irecv`**

- **`MPI_Recv`** is used to perform a blocking receive, (i.e. process waits for the communication to finish before going to the next command).

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

- This functions takes seven parameters:
  - the location of the receive buffer i.e. a pointer (*output parameter*)
  - the max number of data elements to be received (*input parameter*)
  - the type of data e.g. **`MPI_INT`**, **`MPI_FLOAT`**, etc. (*input parameter*)
  - the rank of the source/sending node (*input parameter*)
  - a tag for identification of the communication (*input parameter*)
  - the communicator to be used for transmission (*input parameter*)
  - a pointer to a structure of type **`MPI_Status`**, contains source processor's rank, communication tag, and error status (*output parameter*)
- For the non-blocking **`MPI_Irecv`**, **`MPI_Request`** replaces **`MPI_Status`**.

A first MPI example: Hello World.

```
#include <mpi.h>
int main(int argc, char *argv[]) {
    int myid, size;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &myid);
    MPI_Comm_size(MPI_COMM_WORLD, &size);
    printf("process %d out of %d says Hello\n", myid, size);
    MPI_Finalize();
    return 0;
 }
```

First "real" MPI program: Exchanging 2 Values

```
#include <mpi.h>
int main(int argc, char *argv[]) {
    int rank, value, size, length = 1, tag = 1;
    MPI_Status status;
        /* initialize MPI and get own id (rank) */
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &myid);
    MPI_Comm_size(MPI_COMM_WORLD, &size);
    if (size!=2) {
        printf("use exactly two processes\n");
        exit(1);
    }
    if (myid == 0) {
        otherid = 1; myvalue = 14;
    }
    else {
        otherid = 0; myvalue = 25;
    }
        printf("process %d sending %d to process %d\n", myid, myvalue, otherid);
        /* Send one integer to the other node (i.e. "otherid") */
        MPI_Send(&myvalue,1,MPI_INT,otherid,tag,MPI_COMM_WORLD);
        /* Receive one integer from any other node */
        MPI_Recv(&othervalue,1,MPI_INT,MPI_ANY_SOURCE,
                MPI_ANY_TAG,MPI_COMM_WORLD, &status);
        printf("process %d received a %d\n", myid, othervalue);
        MPI_Finalize();             /* Terminate MPI */
    return 0;
 }
```

Compiling and Running MPI Programmes

- To compile programs using MPI, you need an “MPI-enabled” compiler.
- On our cluster, we use `mpicc` to compile C programs containing MPI commands or `mpicxx` for C++.
- Before running an executable using MPI, you need to make sure the "multiprocessing daemon" (MPD) is running.
- It makes the workstations into "virtual machines" to run MPI programs.
- When you run an MPI program, requests are sent to MPD daemons to start up copies of the program.
- Each copy can then use MPI to communicate with other copies of the same program running in the virtual machine. Just type “mpd &” in the terminal.
- To run the executable, type “`mpirun -np N./executable_file`”, where N is the number to be used to run the program.
- This value is then used in your program by `MPI_Init` to allocate the nodes and create the default communicator.

Example 3:“Ring” Communication

```
#include <mpi.h>
int main(int argc, char *argv[]) {

    int rank, value, size;
    MPI_Status status;
        /* initialize MPI and get own id (rank) */
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &rank);
    MPI_Comm_size(MPI_COMM_WORLD, &size);
    do  {
        if (rank == 0) {
           scanf("%d", &value );
           /* Master Node sends out the value */
           MPI_Send( &value, 1, MPI_INT, rank + 1, 0, MPI_COMM_WORLD);
        }
        else {
        /* Slave Nodes block on receive the send on the value */
           MPI_Recv( &value, 1, MPI_INT, rank - 1, 0, MPI_COMM_WORLD, &status);
           if (rank < size - 1) {
                 MPI_Send( &value, 1, MPI_INT, rank + 1, 0, MPI_COMM_WORLD);
           }
        printf("process %d got %d\n", rank, value);
        } while (value >= 0);
        /* Terminate MPI */
    MPI_Finalize();
    return 0;
 }
```

Example 4: Matrix-Vector Product Implementation

```
#include <mpi.h>
int main(int argc, char *argv[]) {
    int A[4][4], b[4], c[4], line[4],temp[4], local_value, myid;
    MPI_Init(&argc, &argv); MPI_Comm_rank(MPI_COMM_WORLD, &myid);
    if (myid == 0) {
          for (int i=0; i<4; i++) {
              b[i] = 4 - i;
              for (int j=0; j<4; j++)
                    A[i][j] = i + j; /* set some notional values for A, b */
          }
          line[0]=A[0][0]; line[1]=A[0][1];
          line[2]=A[0][2]; line[3]=A[0][3];
    }
    if (myid == 0) {
          for (int i=1; i<4; i++) {/* slaves do most of the multiplication */
              temp[0]=A[i][0];temp[1] = A[i][1];temp[2] = A[i][2];temp[3] = A[i][3];
              MPI_Send( temp, 4, MPI_INT, i, i, MPI_COMM_WORLD);
              MPI_Send( b, 4, MPI_INT, i, i, MPI_COMM_WORLD);
          }
    }
    else {
              MPI_Recv( line, 4, MPI_INT, 0, myid, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
              MPI_Recv( b, 4, MPI_INT, 0, myid, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
    }                  {/* master node does its share of multiplication too*/
    c[myid] = line[0] * b[0] + line[1] * b[1] + line [2] * b[2] + line[3] * b[3];
    if (myid != 0) {
          MPI_Send(&c[myid], 1, MPI_INT, 0, myid, MPI_COMM_WORLD);
    }
    else {
          for (int i=1; i<4; i++) {
              MPI_Recv( &c[i], 1, MPI_INT, i, i, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
              }
    }
    MPI_Finalize();
    return 0;
}
```

Example 5: Pi Calculation Implementation

All nodes do this part

```
int main(int argc, char *argv[]) {
    MPI_Init(&argc, &argv);
    #define INT_MAX_ 1000000000
    int myid, size, inside=0, outside=0, points=10000;
    double x,y, Pi_comp, Pi_real=3.141592653589793238462643;
    MPI_Comm_rank(MPI_COMM_WORLD, &myid);
    MPI_Comm_size(MPI_COMM_WORLD, &size);
    if (myid == 0) {
          for (int i=1; i<size; i++)    /* send out the value of points to all slaves */
              MPI_Send(&points, 1, MPI_INT, i, i, MPI_COMM_WORLD);
    }
    else
          MPI_Recv(&points, 1, MPI_INT, 0, i, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
    rands=new double[2*points];
    for (int i=0; i<2*points; i++ ){
          rands[i]=random();
          if (rands[i]<=INT_MAX_) i++   /* this random is within range */
    }
    for (int i=0; i<points;i++ ){
          x=rands[2*i]/INT_MAX_;
          y=rands[2*i+1]/INT_MAX_;
          if((x*x+y*y)<1) inside++      /* point is inside unit circle so incr var inside */
    }
    delete[] rands;
    if (myid == 0) {
          for (int i=1; i<size; i++) {
              int temp;                 /* master receives all inside values from slaves */
              MPI_Recv(&temp, 1, MPI_INT, i, i, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
              inside+=temp;    }        /* master sums all insides sent to it by slaves */
    }
    else
          MPI_Send(&inside, 1, MPI_INT, 0, i, MPI_COMM_WORLD); /* send inside to master  */
    if (myid == 0) {
          Pi_comp = 4 * (double) inside / (double)(size*points);
          cout << "Value obtained: " << Pi_comp << endl << "Pi:" << Pi_real << endl;}
    MPI_Finalize(); return 0;
}
```

Collective communications in MPI

- Groups are sets of processors that communicate with each other in a certain way.
- Such communications permit a more flexible mapping of the language to the problem (allocation of nodes to subparts of the problem etc).
- MPI implements Groups using data objects called Communicators.
- A special Communicator is defined (called '**`MPI_COMM_WORLD`**') for the group of all processes.
- Each Group member is identified by a number (its Rank 0..n-1).
- There are three steps to create new communication structures:
  – accessing the group corresponding to MPI_COMM_WORLD,
  – using this group to create sub-groups,
  – allocating new communicators for this group.
- We will see this in more detail in the last examples.

Some Sophisticated MPI Routines

- The advantage of the global communication routines below is that the MPI system can implement them more efficiently than the programmer, involving far less function calls.
- Also the system will have more opportunity to overlap message transfers with internal processing and to exploit parallelism that might be available in the communications network.

`MPI_Barrier`	Synchronise
`MPI_Bcast`	Broadcast same data to all procs
`MPI_Gather`	Get data from all procs
`MPI_Scatter`	Send different data to all procs
`MPI_Reduce`	Combine data from all onto one proc
`MPI_Allreduce`	Combine data from all procs onto all procs

Sophisticated MPI Routines: `MPI_Barrier`

- `MPI_Barrier` is used to synchronise a set of nodes.

```
int MPI_Barrier( MPI_Comm comm )
```

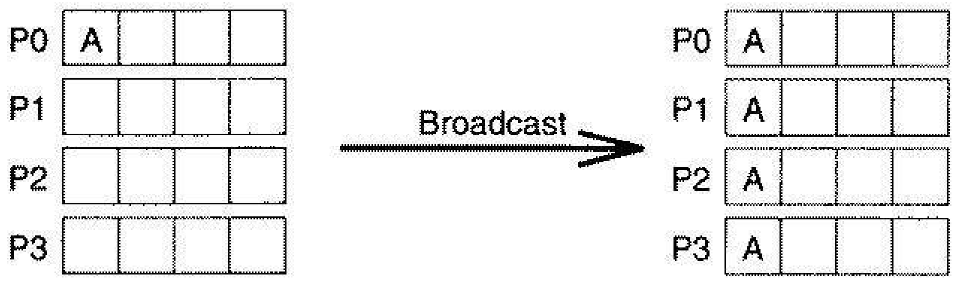
- It blocks the caller until all group members have called it.
- ie call returns at any process only after all group members have entered the call.
- This functions takes only parameter, the communicator (i.e. group of nodes) to be synchronised.
- As we previously saw with other functions, it will most of the times be used with the default communicator, `MPI_COMM_WORLD`.

Sophisticated MPI Routines: `MPI_Bcast`

- `MPI_Bcast` used to send data from one node to all the others in one single command.

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

- This functions takes five parameters: -
  - location of data to be sent i.e. a pointer (*input/output* parameter)
  - number of data elements to be sent (*input* parameter)
  - type of data (*input* parameter)
  - rank of the broadcast node (*input* parameter)
  - communicator to be used (*input* parameter)

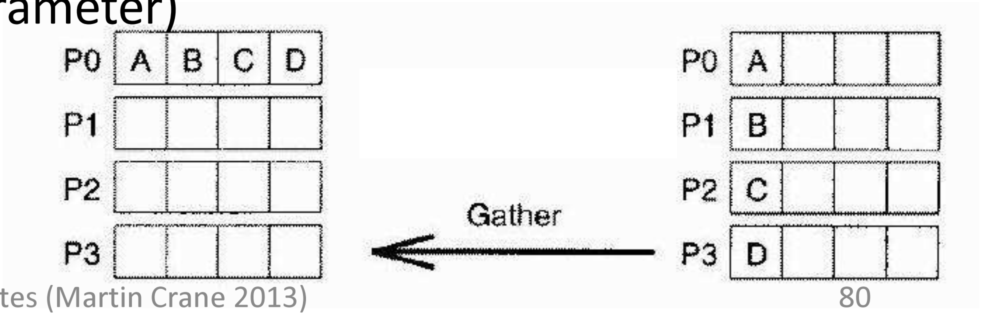


Sophisticated MPI Routines: `MPI_Gather`

- `MPI_Gather` is used to gather on a single node data scattered over a group of nodes.

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

- This functions takes eight parameters: -
  - location of data to be sent i.e. a pointer (*input* parameter)
  - number of data elements to be sent (*input* parameter)
  - type of data to be sent (*input* parameter)
  - location of the receive buffer i.e. a pointer (*output parameter*)
  - number of elements to be received (*input* parameter)
  - type of data to be received (*input* parameter)
  - rank of the sending node (*input* parameter)
  - communicator to be used for transmission. (*input* parameter)

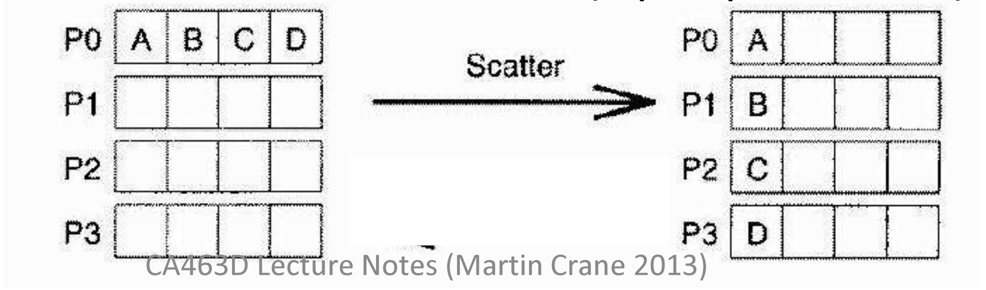


Sophisticated MPI Routines: `MPI_Scatter`

- `MPI_Scatter` used to scatter data from single node to a group

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

- This function takes eight parameters: -
  - location of data to be sent i.e. a pointer (*input* parameter)
  - number of data elements to be sent (*input* parameter)
  - type of data to be sent (*input* parameter)
  - location of the receive buffer i.e. a pointer (*output parameter*)
  - number of elements to be received (*input* parameter)
  - type of data to be received (*input* parameter)
  - rank of the sending node (*input* parameter)
  - communicator to be used for transmission. (*input* parameter)

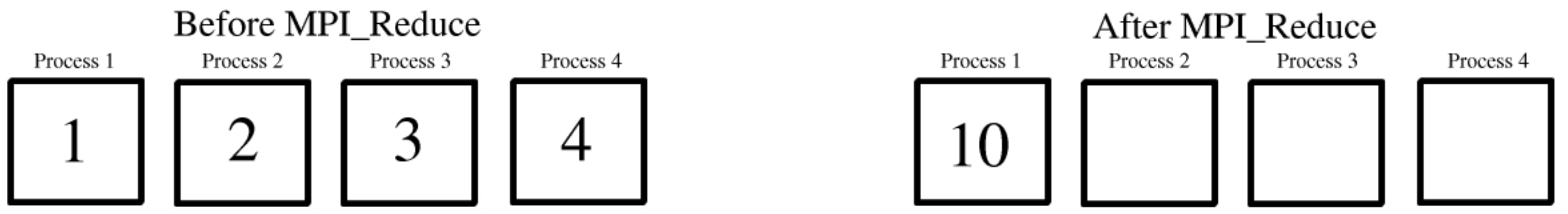


Sophisticated MPI Routines: **MPI_Reduce**

- **MPI_Reduce** used to reduce values on all nodes of a group to a single value on one node using some reduction operation (sum etc).

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

- This functions takes six parameters: -
  - location of the data to be sent i.e. a pointer (*input* parameter)
  - location of the receive buffer i.e. a pointer (*output parameter*)
  - number of elements to be sent (*input* parameter)
  - type of data e.g. **MPI_INT,MPI_FLOAT**, etc. (*input* parameter)
  - operation to combine the results e.g. **MPI_SUM** (*input* parameter)
  - communicator used for transmission (*input* parameter)

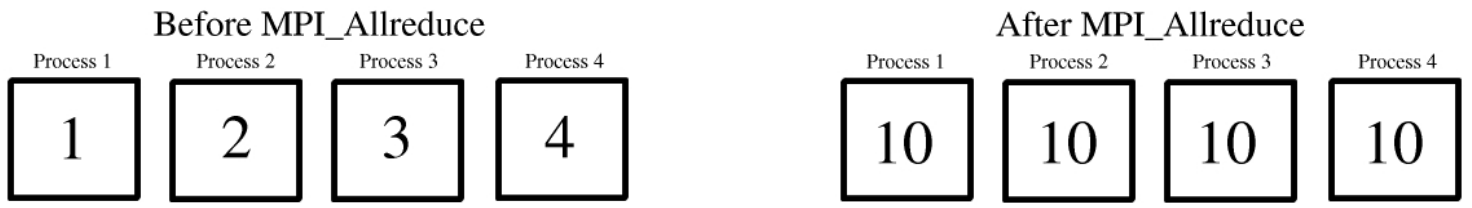


Sophisticated MPI Routines: `MPI_Allreduce`

- `MPI_Allreduce` is used to reduce values on all group nodes to a one value, and send it back to all (i.e. equals `MPI_Reduce+MPI_Bcast`)

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

- This functions takes six parameters: -
  - location of the data to be sent i.e. a pointer (*input* parameter)
  - location of the receive buffer i.e. a pointer (*output parameter*)
  - number of elements to be sent (*input* parameter)
  - type of data e.g. `MPI_INT`,`MPI_FLOAT`, etc. (*input* parameter)
  - operation to combine the results e.g. `MPI_SUM` (*input* parameter)
  - communicator used for transmission (*input* parameter)



Example 6: A New Matrix-Vector Product

```
#include <mpi.h>
int main(int argc, char *argv[]) {
    int A[4][4], b[4], c[4], line[4],temp[4], local_value, myid;
    MPI_Init(&argc, &argv); MPI_Comm_rank(MPI_COMM_WORLD, &myid);
    if (myid == 0) {
          for (int i=0; i<4; i++) {
              b[i] = 4 - i;
              for (int j=0; j<4; j++)
                    A[i][j] = i + j; /* set some notional values for A, b */
          }
          line[0]=A[0][0]; line[1]=A[0][1];
          line[2]=A[0][2]; line[3]=A[0][3];
    }
    MPI_Bcast(b,4,MPI_INT,0,MPI_COMM_WORLD)
    if (myid == 0) {
          for (int i=0; i<4; i++) {/* slaves do most of the multiplication */
              temp[0]=A[i][0];temp[1] = A[i][1];temp[2] = A[i][2];temp[3] = A[i][3];
              MPI_Send( temp, 4, MPI_INT, i, i, MPI_COMM_WORLD);
              /* No need to send vector b here */
          }
    }
    else {
              MPI_Recv( line, 4, MPI_INT, 0, myid, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
              /* No need to receive vector b here */
    }               {/* master node does its share of multiplication too*/
    c[myid] = line[0] * b[0] + line[1] * b[1] + line [2] * b[2] + line[3] * b[3];
    if (myid != 0) {
          MPI_Send(&c[myid], 1, MPI_INT, 0, myid, MPI_COMM_WORLD);
    }
    else {
          {
          for (int i=1; i<4; i++) {
              MPI_Recv( &c[i], 1, MPI_INT, i, i, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
              }
    }
    MPI_Finalize(); return 0;
}
```

Example 5: A New Pi Calculation Implementation

```
int main(int argc, char *argv[]) {
    MPI_Init(&argc, &argv);
    #define INT_MAX_ 1000000000
    int myid, size, inside=0, outside=0, points=10000;
    double x,y, Pi_comp, Pi_real=3.141592653589793238462643;
    MPI_Comm_rank(MPI_COMM_WORLD, &myid);
    MPI_Comm_size(MPI_COMM_WORLD, &size);
          /* Again send/receive replaced by MPI_Bcast */
    MPI_Bcast(&points,1,MPI_INT, 0, MPI_COMM_WORLD);
    rands=new double[2*points];
    for (int i=0; i<2*points; i++ ){
          rands[i]=random();
          if (rands[i]<=INT_MAX_) i++   /* this random is within range */
    }
    for (int i=0; i<points;i++ ){
          x=rands[2*i]/INT_MAX_;
          y=rands[2*i+1]/INT_MAX_;
          if((x*x+y*y)<1) inside++      /* point is inside unit circle so incr var inside */
    }
    delete[] rands;
    if (myid == 0) {
          for (int i=1; i<size; i++) {
              int temp;                 /* master gets all inside values from slaves */
              MPI_Recv(&temp, 1, MPI_INT, i, i, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
              inside+=temp;    }        /* master sums all insides sent to it by slaves */
    }
    else
          MPI_Send(&inside, 1, MPI_INT, 0, i, MPI_COMM_WORLD); /* send inside to master */

    MPI_Reduce(&inside,&total,1,MPI_INT,MPI_SUM,0, MPI_COMM_WORLD);
    if (myid == 0) {
          Pi_comp = 4 * (double) inside / (double)(size*points);
          cout << "Value obtained: " << Pi_comp << endl << "Pi:" << Pi_real << endl;}
    MPI_Finalize(); return 0;
}
```

Using Communicators

- Creating a new group (and communicator) by excluding the first node:

```
#include <mpi.h>
int main(int argc, char *argv[]) {
        .
        .
        .
        .
    MPI_Comm comm_world, comm_worker;
    MPI_Group group_world, group_worker;
    comm_world = MPI_COMM_WORLD;
    MPI_Comm_group(comm_world, &group_world);
    MPI_Group_excl(group_world, 1, 0, &group_worker);
                /* process 0 not member */
    MPI_Comm_create(comm_world, group_worker, &comm_worker);
        .
        .
        .
        .
}
```

- **Warning:**

`MPI_Comm_create()` is a collective operation, so all processes in the old communicator must call it - even those not going in the new communicator.

Example 8: Using Communicators

```
#include <mpi.h>
#include <stdio.h>
#define NPROCS 8
int main(int argc, char *argv[]) {

    int rank, newrank, sendbuf, recvbuf;
    ranks1[4]={0,1,2,3}, ranks2[4]={4,5,6,7};
    MPI_Group orig_group, new_group;
    MPI_Comm new_comm

    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &rank);
    sendbuf = rank;
                /* Extract the original group handle */
    MPI_Comm_group(MPI_COMM_WORLD, &orig_group);
    if (rank < NPROCS/2) {/* Split tasks into 2 distinct groups based on rank */
      MPI_Group_incl(orig_group, NPROCS/2, ranks1, &new_group);
    else
      MPI_Group_incl(orig_group, NPROCS/2, ranks2, &new_group);
    /* Create new communicator and then perform collective communications */
    MPI_Comm_create(MPI_COMM_WORLD, new_group, &new_comm);
    MPI_Allreduce(&sendbuf, &recvbuf, 1, MPI_INT, MPI_SUM, new_comm);
    MPI_Group_rank (new_group, &new_rank);

    printf(“rank= %d newrank= %d recvbuf= %d\n", rank, newrank, recvbuf);

    MPI_Finalize();
}
```

Final Reminder

- MPI programs need specific compilers (e.g. `mpicc`), `MPD` and `mpirun`.
- MPI programs start with `MPI_Init` and finish with `MPI_Finalize`,
- Four functions for point-to-point communication,
- Six more advanced functions, for synchronise, and perform collective communication,
- Nine functions (at least three!) to create new groups and communicators,
- Too many examples to remember everything.