2G1915 Concurrent Programming
Lecture 14

Case Study: Introduction to MPI

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Outline (see also Section 7.8)

- Introduction
  - MPI programming concepts: processes, communicators, etc.
- The MPI library: functions, types
- Basic MPI functions
- Send/receive:
  - Blocking
  - Non-blocking
- Collective operations: barriers, broadcast, gather/scatter, reduce, etc.
- Modularity: working with communicators

MPI: Message Passing Interface

- MPI is a message-passing library specification for multiprocessor, clusters, and heterogeneous networks
  - Not a compiler specification, not a specific product.
  - Message-passing model and API
  - Designed
    - To permit the development of parallel software libraries
    - To provide access to advanced parallel hardware for end users, library writers, and tool developers.
  - MPI is a de facto standard for message passing systems
  - Language bindings: Fortran and C
- MPICH and LAM – the two most popular implementations of MPI today
  - MPICH is more generally usable on various platforms
  - LAM – for TCP/IP networks
- Other common systems: PVM, p4, Parmacs

The MPI Library (API)

- The MPI library is large: about 130 functions
  - extensive functionality and flexibility
    - message passing (point-to-point, collective)
    - process groups and topologies
- The MPI library is small: 6 functions allow writing many programs
    - **`MPI_Init, MPI_Finalize, MPI_Comm_size, MPI_Comm_rank, MPI_Send, MPI_Recv`**
  - or another 6-function set:
    - **`MPI_Init, MPI_Finalize, MPI_Comm_size, MPI_Comm_rank, MPI_ Bcast, MPI_ Reduce`**
- All MPI functions, constants and data types have prefix MPI_

C Data Types Mapping in MPI

- (see **`mpi.h`**)

MPI datatype	C datatype
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 Programming Concepts: Processes

- ***A MPI process***
  - A smallest unit of computation, e.g. a Unix process.
  - Uniquely identified by its rank in a process group.
  - Processes communicate with tagged messages within process groups identified by communicators (communication contexts)
  - A proc can send messages either synchronously or asynchronously.
  - The proc is responsible for receiving messages directed to it.
  - The proc uses either blocking or non-blocking receive/send.
  - The proc can participate in a collective operation such as broadcast, gather, barrier, that involves all processes in a group.
- ***A MPI application***
  - a static set of processes that interact to solve a problem.
  - **`mpirun -np 2 hello`** – starts two **`hello`** processes on two processors.

Communicators. Process groups. Ranks

- ***Communicator***
  - An opaque object that defines a process group and a communication context for the group. Delimits scope of communication.
    - Separate groups of processes working on subproblems each with specific communication context identified by a communicator.
- ***Process group***
  - A virtual set of processes identified by a communicator.
    - Grouped for collective and point-to-point communications.
    - All communication (not just collective operations) takes place in groups.
    - Each process has a unique index (rank) in a given group.
- ***Rank***
  - A unique identifier (index) of a process within a communication (in a proc group).

Programming, Building and Running a MPI Application

- Install one of the MPI implementations, e.g. MPICH
- Develop your application – one program for all processes
  - The number of processes is specified at run time (could be 1)
  - Use the number of proc and proc ranks to determine process tasks
  - In C: `#include <mpi.h>`
- Compile:

```
mpicc -o myprog myprog.c
```

  - For large projects, develop a Makefile (see for example, **mpich/examples/Makefile.in**
- Run:

```
mpirun -np 2 myprog
```

  - The option -help shows all options to mpirun.

Basic MPI Functions

- `int MPI_Init(int *argc, char **argv[])`
  - Start MPI, enroll the process in the MPI application
- `int MPI_Finalize()`
  - Stop (exit) MPI
- `int MPI_Comm_size(MPI_Comm comm, int *size)`
  - Determine the number of processes in the group **`comm`**.
    - **`comm`** – communicator, e.g. **`MPI_COMM_WORLD`**
    - **`size`** – number of processes in group (returned)
- `int MPI_Comm_rank(MPI_Comm comm, int *rank)`
  - Determine the rank of the calling process in the group **`comm`**.
    - **`comm`** – communicator, e.g. **`MPI_COMM_WORLD`**
    - **`rank`** – the rank (returned) is a number between zero and **`size-1`**

Example: “Hello World”

```
#include "mpi.h"
#include <stdio.h>
int main( argc, argv )
int argc;
char **argv;
{
    int rank, size;
    MPI_Init( &argc, &argv );
    MPI_Comm_rank( MPI_COMM_WORLD, &rank );
    MPI_Comm_size( MPI_COMM_WORLD, &size );
    printf( "Hello world! I'm %d of %d\n", rank, size );
    MPI_Finalize();
    return 0;
}
```

Basic (Blocking) Send

- `int MPI_Send(void *buf, int count, MPI_datatype dt, int dest, int tag, MPI_Comm comm)`
  - Send a message with the given tag to the given destination process in the given communicator
    - **buf** send buffer
    - **count** number of items in buffer
    - **dt** data type of items
    - **dest** destination process rank
    - **tag** message tag
    - **comm** communicator
  - Returns integer result code as for all MPI functions, normally MPI_SUCCESS
  - ***datatype*** can be elementary, continues array of data types, stridden blocks of data types, indexed array of blocks of data types, general structure.

Basic (Blocking) Receive

```
int MPI_Recv(void *buf, int count, MPI_datatype dt,
   int source, int tag, MPI_Comm comm, MPI_Status *status))
```

- Receive a message with the given tag from the given source in the given communicator
  - **`buf`** receive buffer (loaded)
  - **`count`** max number of entries in buffer
  - **`dt`** data type of entries
  - **`source`** source process rank
  - **`tag`** message tag
  - **`comm`** communicator
  - **`status`** status (returned).
- "Wildcard" values are provided for tag (**`MPI_ANY_TAG`**) and source (**`MPI_ANY_SOURCE`**).

Inspecting Received Message

- If wildcard values are used for tag and/or sources, the received message can be inspected via a **MPI_Status** structure that has three components **MPI_SOURCE**, **MPI_TAG**, **MPI_ERROR**

```
MPI_Status status;
MPI_Recv( ..., &status );
int tag_received = status.MPI_TAG;
int rank_of_source = status.MPI_SOURCE;
MPI_Get_count( &status, datatype, &count );
```

  – MPI_Get_count is used to determine how much data of a particular type has been received.

Communication Modes of Blocking Send

- ***Standard*** blocking send (non-local) **`MPI_Send`**
  - Implementation defined buffering: If the message is buffered, the send may complete before a matching receive is invoked.
- ***Buffered*** blocking send (local) **`MPI_Bsend`**
  - Can be started whether or not a matching receive has been posted,
  - may complete before a matching receive is posted.
- ***Synchronous*** blocking send (non-local) **`MPI_Ssend`**
  - Can be started whether or not a matching receive has been posted,
  - complete when a matching receive is posted and has started to receive.
- ***Ready*** blocking send (non-local) **`MPI_Rsend`**
  - may be started only if the matching receive is already posted,
  - Otherwise outcome is undefined.

Example 1: Exchange of Messages (Always Succeeds)

```
MPI_Comm_rank(comm, &rank);
if (rank = 0) {
    MPI_Send(sendbuf, count, MPI_REAL, 1, tag, comm);
    MPI_Recv(recvbuf, count, MPI_REAL, 1, tag, comm, &status);
}
if (rank = 1) {
    MPI_Recv(recvbuf, count, MPI_REAL, 0, tag, comm, &status);
    MPI_Send(sendbuf, count, MPI_REAL, 0, tag, comm);
}
```

– This program will succeed even if no buffer space for data is available.
– The standard send operation can be replaced, in this example, with asynchronous send.

Example 2: Exchange of Messages (Always Deadlocks)

```
MPI_Comm_rank(comm, &rank);
if (rank = 0) {
    MPI_Recv(recvbuf, count, MPI_REAL, 1, tag, comm, &status);
    MPI_Send(sendbuf, count, MPI_REAL, 1, tag, comm);
}
if (rank = 1) {
    MPI_Recv(recvbuf, count, MPI_REAL, 0, tag, comm, &status);
    MPI_Send(sendbuf, count, MPI_REAL, 0, tag, comm);
  }
```

– This program will always deadlock!

– The same holds for any other send mode.

Example 3: Exchange of Messages (Relies on Buffering)

```
MPI_Comm_rank(comm, &rank);
if (rank = 0)
  {
    MPI_Send(sendbuf, count, MPI_REAL, 1, tag, comm);
    MPI_Recv(recvbuf, count, MPI_REAL, 1, tag, comm, &status);
  }
if (rank = 1)
  {
    MPI_Send(sendbuf, count, MPI_REAL, 0, tag, comm);
    MPI_Recv(recvbuf, count, MPI_REAL, 0, tag, comm, &status);
  }
```

- For the program to complete, it is necessary that at least one of the two messages sent has been buffered.
- The program can succeed only if the communication system can buffer at least **`count`** words of data.

Non-Blocking Communication Operations

- ***Non-blocking send*** initiates sending:

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

- ***Non-blocking receive*** initiates receiving:

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

  - A request object is returned in **`request`** to identify the operation.

- To query the status of communication or to wait for its completion:

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

  - Returns immediately with flag = true if the operation identified by **`request`** has completed, otherwise returns immediately with flag = false.

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

  - Returns when the operation identified by **`request`** completes.

Example: Non-Blocking Send/Receive

```
MPI_Comm_rank(comm, &rank);
if (rank = 0)
  {
    MPI_Isend(a, 10, MPI_REAL, 1, tag, comm, request);
    /**** do some computation to mask latency ****/
    MPI_Wait(request, &status);
  }
if (rank = 1)
  {
    MPI_Irecv(a, 10, MPI_REAL, 0, tag, comm, request);
    /**** do some computation to mask latency ****/
    MPI_Wait(request, &status);
  }
}
```

Probing for Pending Messages

```
MPI_Iprobe(source, tag, comm, flag, status)
```

– polls for pending messages

```
MPI_Probe(source, tag, comm, status)
```

– returns when a message is pending

- Non-blocking/blocking check for an incoming message without receiving it

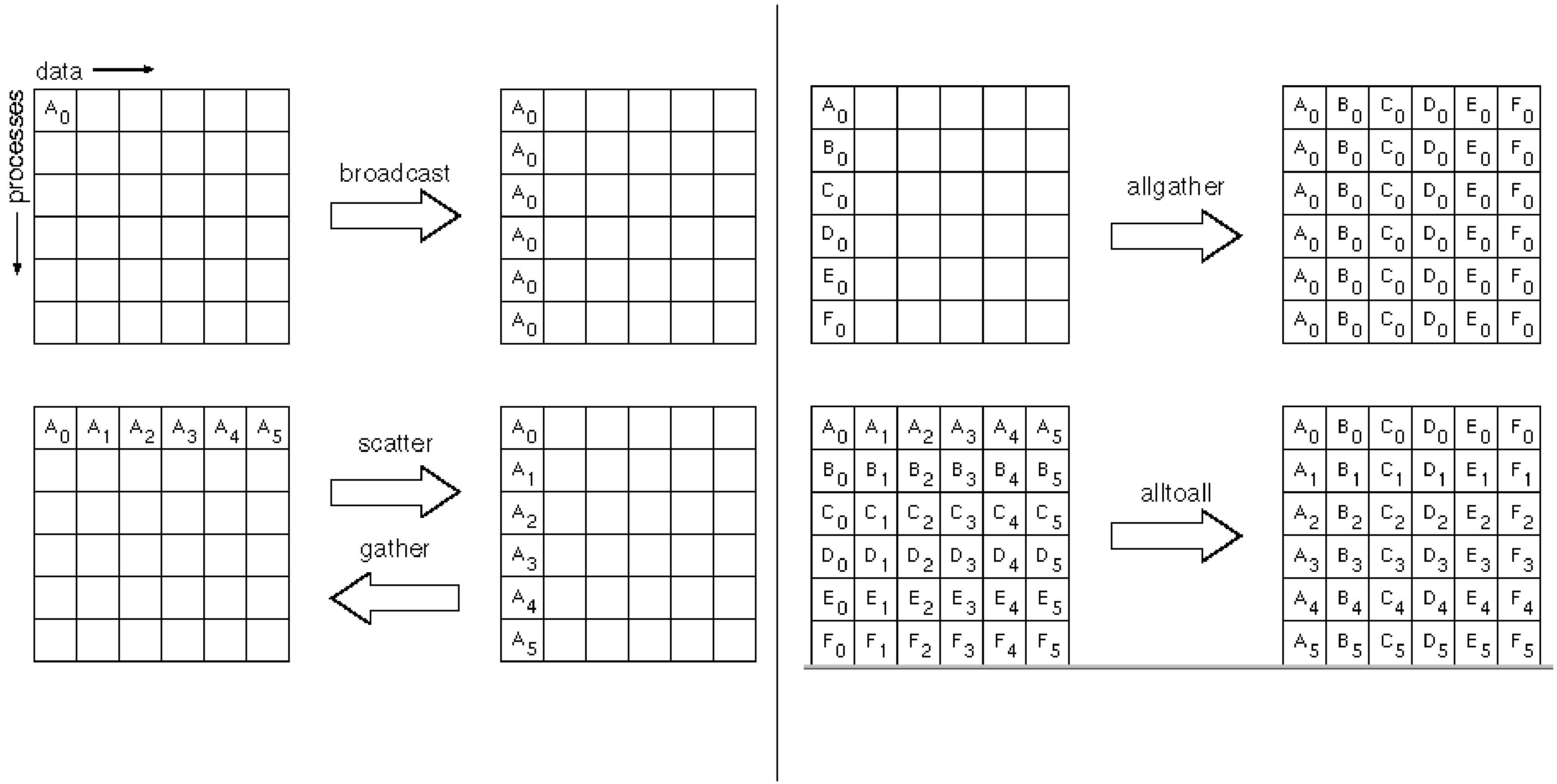
Collection Operations

- A ***collective operation*** is executed by having all processes in the communicator call the same communication routine with matching arguments.
  - Several collective routines have a single originating or receiving process – the ***root***.
  - Some arguments in the collective functions are specified as “significant only at root”, and are ignored for all participants except the root.

Collective Communication

- Collective synchronization (barrier):
```
int MPI_Barrier(MPI_Comm comm)
```
- Broadcast from **buf** of **root** to all processes:
```
int MPI_Bcast(void *buf, int count, MPI_datatype dt,
              int root, MPI_Comm comm)
```
- Collective data transfer:
```
int MPI_Gather( void *sendbuf, int sendcount,
                MPI_datatype sendtype, void *recvbuf,
                int recvcount, MPI_datatype recvtype,
                int root, MPI_Comm comm)
int MPI_Scatter(void *sendbuf, int sendcount,
                MPI_datatype sendtype, void *recvbuf,
                int recvcount, MPI_datatype recvtype,
                int root, MPI_Comm comm)
```

Collective Move Operations



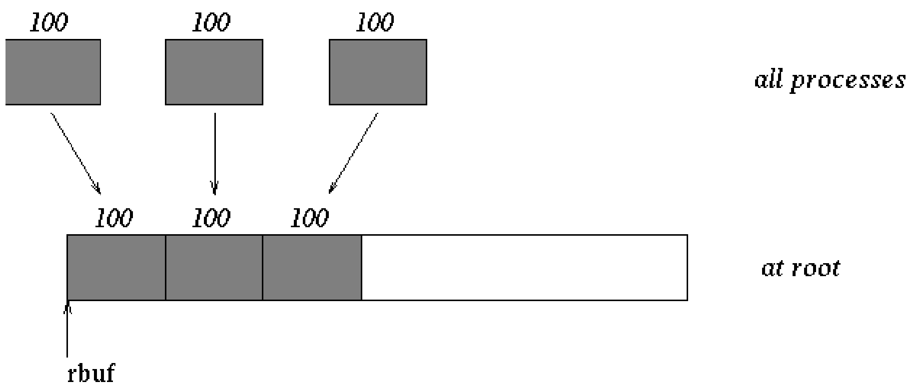
Example 1: Broadcast

- 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);
}
```

Example 2: Gather

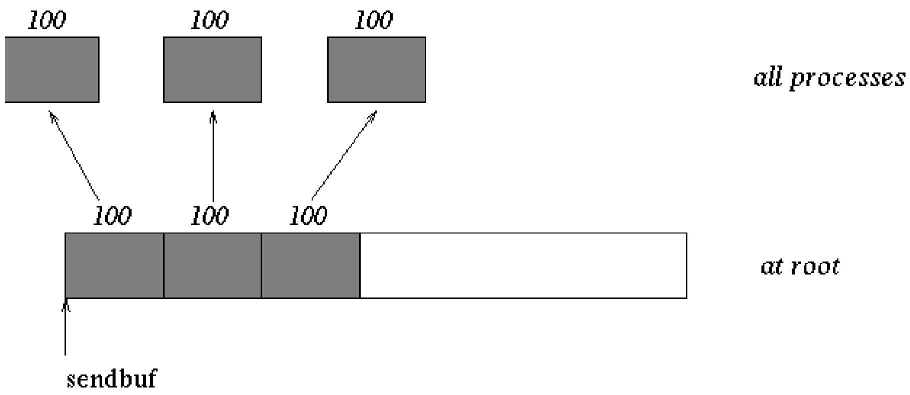
- Gather 100 integers from every process in group to root.




```
MPI_Comm comm;
int gsize, sendarray[100];
int root, myrank, *rbuf;
...
MPI_Comm_rank( comm, myrank);
MPI_Comm_size( comm, &gsize);
...
if ( myrank == root)
     rbuf = (int *)malloc(gsize*100*sizeof(int));
MPI_Gather( sendarray, 100, MPI_INT, rbuf, 100, MPI_INT, root,
   comm);
```

Example 3: Scatter

- The reverse of Example 2 (previous slide): Scatter sets of 100 integers from the root to each process in the group.




```
MPI_Comm comm;
int gsize,*sendbuf;
int root, rbuf[100];
...
MPI_Comm_rank( comm, myrank);
MPI_Comm_size( comm, &gsize);
if ( myrank == root) {
    sendbuf = (int *)malloc(gsize*100*sizeof(int));
    ... // fill the send buffer with data to be scattered
}
MPI_Scatter( sendbuf, 100, MPI_INT, rbuf, 100, MPI_INT, root,
   comm);
```

Global Reduction Operations

- Reduce from send buffers of all participating processes into a receive buffer of the root proc using operation op

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

- Reduce from send buffers of all participating processes into receive buffers of all the processes using operation op

```
int MPI_Allreduce(void * sendbuf, void * recvbuf,
               int count, MPI_datatype dt,
                MPI_Op op, int root, MPI_Comm comm)
```

- Available operations include:

  MPI_MAX, **MPI_MIN**, **MPI_SUM**, **MPI_LAND**, **MPI_BOR**, ...

Timing Functions

- **`double MPI_Wtime(void)`**
  - Returns a floating-point number of seconds, representing elapsed wall-clock time since some time in the past. The time is “local” on the host.
- **`double MPI_Wtick(void)`**
  - Returns the resolution of MPI_WTIME in seconds, the number of seconds between successive clock ticks.
- Example of usage:

```
{
   double starttime, endtime;
   starttime = double MPI_Wtime();
    ....  stuff to be timed  ...
   endtime   = double MPI_Wtime();
   printf("That took %f seconds\n",
                      endtime-starttime);
}
```

Modularity: Communicators

- A ***communicator*** identifies a process group and provides a context for all communication within the group
  - Communicator acts as an extra tag on messages
- The communicator **`MPI_COMM_WORLD`** identifies all running processes of the MPI application

Create/Destroy Communicators

- Create new communicator: same group, new context:

```
int MPI_Comm_dup(MPI_Comm comm, MPI_Comm *newcomm)
```

- Create new communicators based on colors, ordered by keys:

```
int MPI_Comm_split(MPI_Comm comm, int color, int key,
     MPI_Comm *newcomm)
```

  - **`color`** identifies a group, **`key`** – rank in the group

- Create an inter-communicator from two intra-communicators

```
int MPI_Intercomm_create( MPI_Comm local_comm,int local_leader,
     MPI_Comm peer_comm, int remoteleader,
     int tag, MPI_Comm *inter_comm)
```

- Destroy a communicator

```
int MPI_Comm_free(MPI_Comm *comm)
```

Communicators (cont'd)

- One use of communicators is for calling parallel library routines in different context:

```
MPI_Comm *newcomm;
...
MPI_Comm_dup(comm, newcomm);
transpose(newcomm, matrix);  /* call library function */
MPI_Comm_free(newcomm);
```

Example: Compute PI

```
#include "mpi.h"
#include <math.h>
int main(int argc,char *argv[]) {
    int done = 0, n, myid, numprocs, i, rc;
    double PI25DT = 3.141592653589793238462643;
    double mypi, pi, h, sum, x, a;
    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);
    while (!done) {
       if (myid == 0) {
          printf("Enter the number of intervals: (0 quits) ");
          scanf("%d",&n);
       }
       MPI_Bcast(&n, 1, MPI_INT, 0, MPI_COMM_WORLD);
       if (n == 0) break;
       h  = 1.0 / (double) n;
       sum = 0.0;
       for (i = myid + 1; i <= n; i += numprocs) {
          x = h * ((double)i - 0.5);
          sum += 4.0 / (1.0 + x*x);
       }
       mypi = h * sum;
       MPI_Reduce(&mypi, &pi, 1, MPI_DOUBLE, MPI_SUM, 0,
                  MPI_COMM_WORLD);
       if (myid == 0) printf("pi is approximately %.16f,
                              Error is %.16f\n",  pi,
                              fabs(pi - PI25DT));
    }
  MPI_Finalize();
}
```