MPI Basics

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Logistics

Reading: Grama Ch 6 + 4

- Ch 6: MPI basics
- Ch 4: Communication patterns

Assignments

- A1 Due Soon
  - On-time submission Thu 02-Feb
  - Late Submission Sat 04-Feb
- **Questions?**
- A2 up next week: MPI Programming

Today

- Primitives for Distributed Memory Computing
- MPI Programming

Next Week

- Comm Patterns
- Thu 09-Feb: Mini-Exam 1

Generic Send and Receive

- Distributed memory machines require explicit sharing of data
- Minimum required functionality is:

```
send(void *sendbuf, int nelems, int dest)
receive(void *recvbuf, int nelems, int source)
```

- Referred to as a "point-to-point" communication
- **Sample Use**

```
1  // P0 runs                  // P1 runs
2  a = 100;                   receive(&a, 1, 0)
3  send(&a, 1, 1);            printf("%d\n", a);
4  a=50;
```

- Proc 0 sends a single integer to Proc 1
- Proc 0 then changes that integer
- Proc 1 receives and prints the integer

More typical appearance

- Typically write this as a single program which every processor runs: Single Program, Multiple Data (SPMD)
- Assume availability of a function giving logical Proc Number
- Branching on proc number to take different actions

```
1  void exchange(){
2    int a = 100;
3    int my_proc = get_processor_number();
4    if(my_proc == 0){
5      send(&a, 1, 1);      // send data 100 to Proc 1
6      a=50;
7    }
8    else if(my_proc == 1){
9      receive(&a, 1, 0);  // receive data from Proc 0
10     printf("%d\n", a);
11   }
12 }
```

Flavors Send/Receive

- Hardware+OS may support copying message into a "buffer" space to make allowing program to proceed faster
- Functions usually available to do both blocking `send()` and `send_nonblocking()` with hardware support BUT without OS/hardware support they are the same

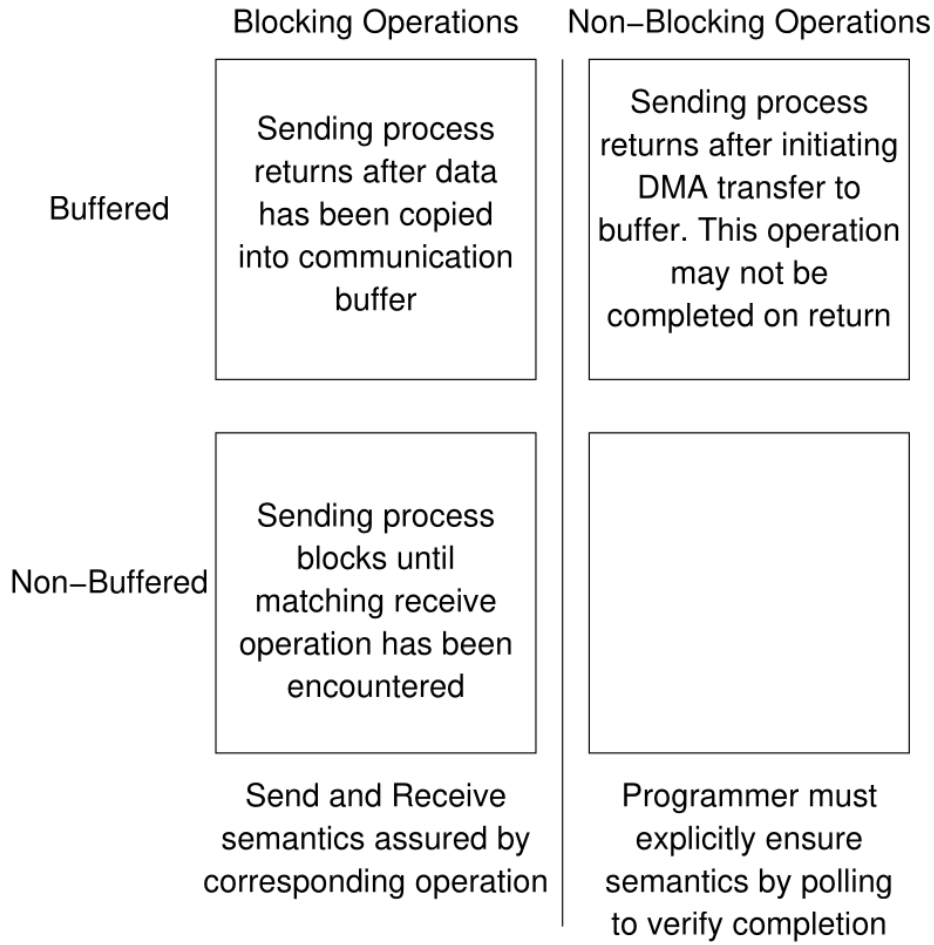


Figure 6.3 Space of possible protocols for send and receive operations.

Blocked and Unbuffered

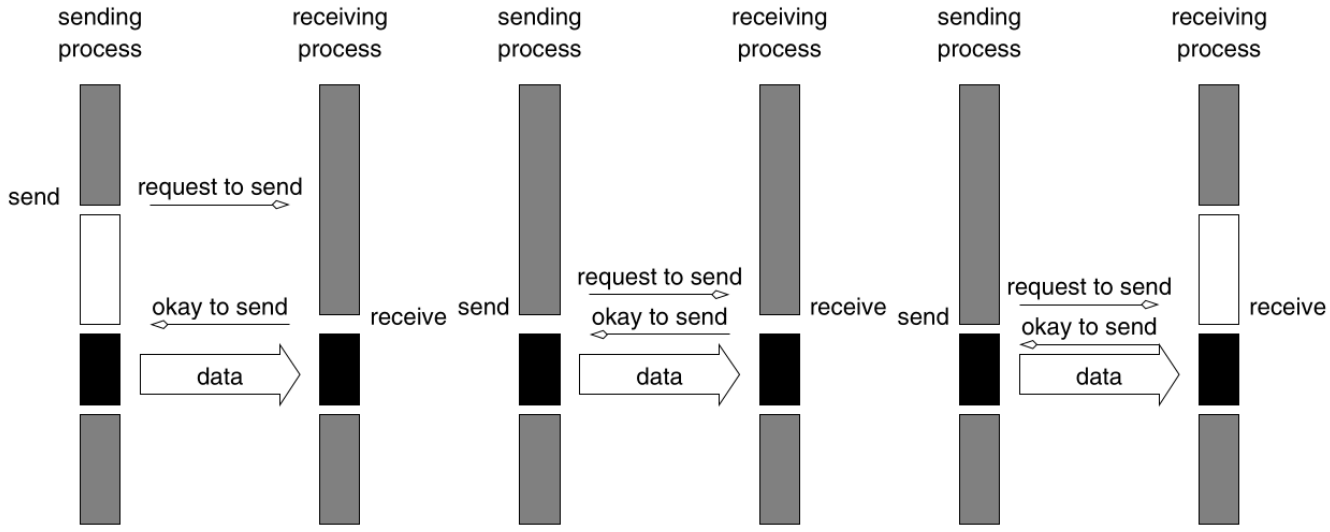


Figure 6.1 Handshake for a blocking non-buffered send/receive operation. It is easy to see that in cases where sender and receiver do not reach communication point at similar times, there can be considerable idling overheads.

Blocking/Unbuffered: no extra buffer available to hold pending sends/receives so must wait until message is sent to proceed
Blocked processors are idle, do no work, which cuts into speedup

Ordering of Send Receive

```
1     P0                          P1
2
3     send(&a, 1, 1);             send(&a, 1, 0);
4     receive(&b, 1, 1);          receive(&b, 1, 0);
```

Assuming `send/receive` blocked/unbuffered, what's wrong with the above code?

Blocking with Buffers

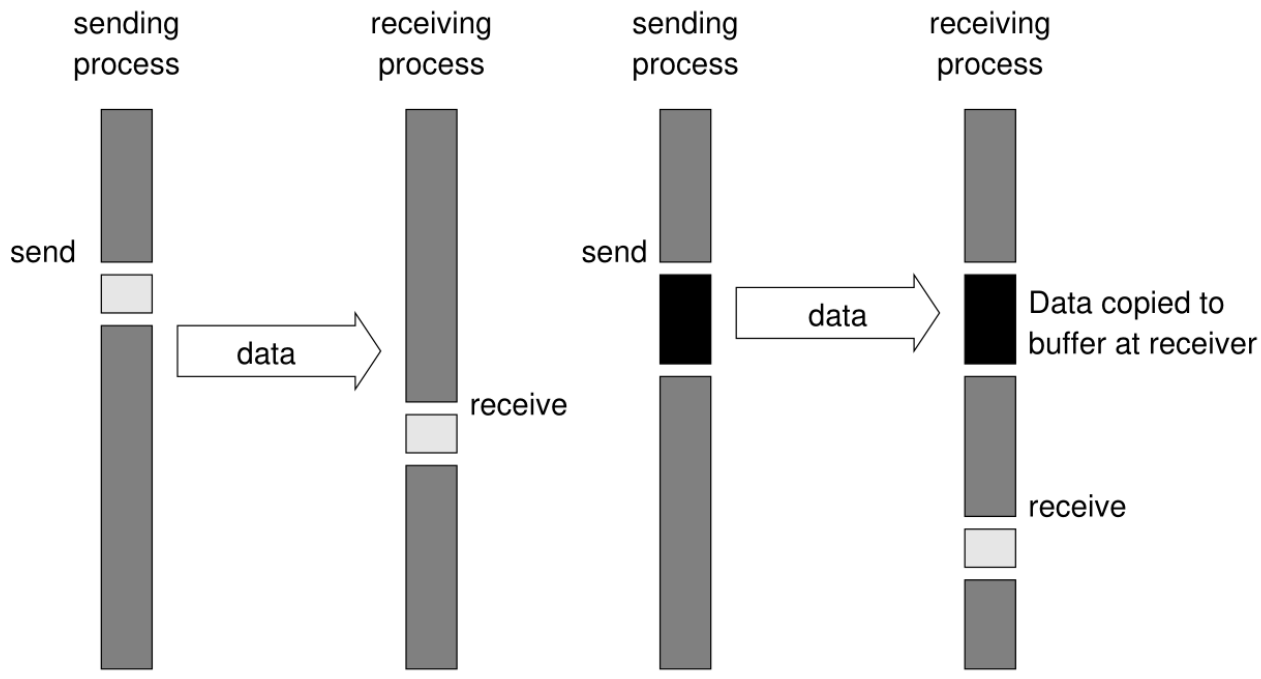


Figure 6.2 Blocking buffered transfer protocols: (a) in the presence of communication hardware with buffers at send and receive ends; and (b) in the absence of communication hardware, sender interrupts receiver and deposits data in buffer at receiver end.

Hardware buffer support, sender and receiver have a memory minion

No buffer support: sender interrupts receiver

The Danger Continues

```
1  P0                          P1
2
3  receive(&a, 1, 1);          receive(&a, 1, 0);
4  send(&b, 1, 1);             send(&b, 1, 0);
```

- `receive()` always blocks until message is obtained
- Does the above code work even in the buffered setting?

Non-blocking Communication

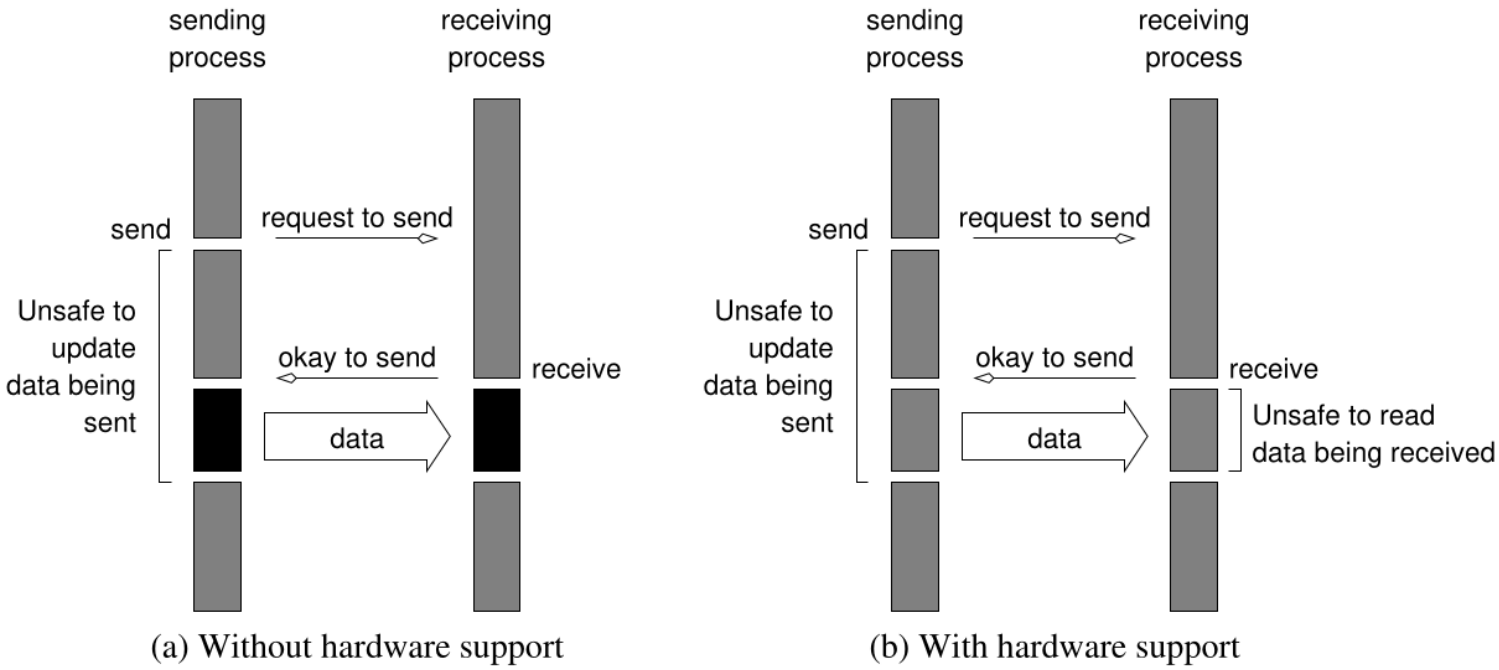
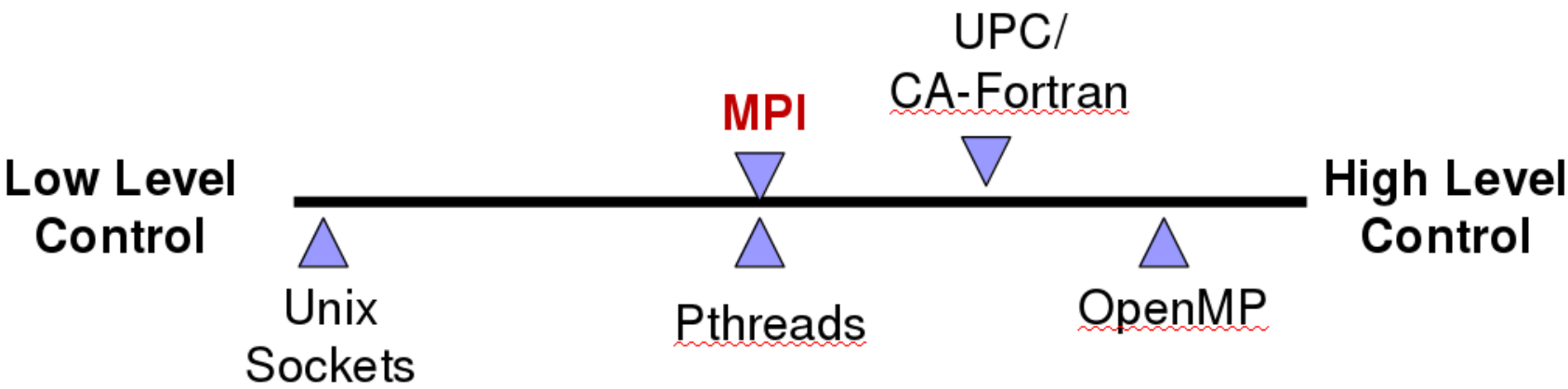


Figure 6.4 Non-blocking non-buffered send and receive operations (a) in absence of communication hardware; (b) in presence of communication hardware.

- Takes a bit more work on the programming side
- Must explicitly ensure that transaction completes with function calls
- `isend(data,dest,status)`: send w/o waiting
- `ireceive(data,dest,status)`: receive w/o waiting
- `wait(status)`: wait until a message has been sent or

MPI: Message Passing Interface

- Standardized library of functions for C/C++/Fortran
- Communicate between processors in a distributed memory machine first appearing around 1992
- MPI Version 1.x universally deployed, Version 2.x less so
- Open source implementations: MPICH, Open MPI
- Proprietary: Intel, Platform, IBM, Platform, Cray
- Typically vendor configures MPI for particular architecture / network of a large-scale machine



MPI In a Nutshell: 6 Essential Functions

```
// Initialize and Terminate MPI
int MPI_Init(int *argc, char ***argv) ;
int MPI_Finalize() ;

// Get total number of processors
int MPI_Comm_size(MPI_Comm comm, int *size);

// Get logical proc number of calling process
int MPI_Comm_rank(MPI_Comm comm, int *rank);

// Send a message to dest processor
int MPI_Send(void *buf, int count, MPI_Datatype datatype,
             int dest, int tag, MPI_Comm comm);

// Receive a message from source processor
int MPI_Recv(void *buf, int count, MPI_Datatype datatype,
             int source, int tag, MPI_Comm comm,
             MPI_Status *status);
```

MPI Hello World

```c
// mpi_hello.c: C Example of hello world with MPI.  Compile and run as
// > mpicc -o mpi_hello mpi_hello.c
// > mpirun ./mpi_hello      # use number of processors equal to total machine
// > mpirun -np 2 mpi_hello  # use 2 processors
// > mpirun -np 8 mpi_hello  # use 8 processors

#include <stdio.h>
#include <mpi.h>

int main (int argc, char *argv[]){
  int rank;                    // the id of this processor
  int size;                    // the number of processors being used

  MPI_Init (&argc, &argv);                // starts MPI
  MPI_Comm_rank (MPI_COMM_WORLD, &rank); // get current process id
  MPI_Comm_size (MPI_COMM_WORLD, &size); // get number of processes

  // Say hello from this proc
  printf( "Proc %d of %d says 'Hello world'\n", rank, size );

  MPI_Finalize();
  return 0;
}
```

Compilation and Running

- Demo using openmpi implementation
- `mpirun` for interactive running
- `mpirun -np 4 progr` sets number of "processors" to 4

```
>> cd 04-mpi-code/
>> mpicc -o mpi_hello mpi_hello.c
>> ./mpi_hello
...
Proc 0 of 1 says 'Hello world'

>> mpirun -np 2 mpi_hello
...
Proc 0 of 2 says 'Hello world'
Proc 1 of 2 says 'Hello world'

>> mpirun mpi_hello
...
Proc 2 of 4 says 'Hello world'
Proc 0 of 4 says 'Hello world'
Proc 1 of 4 says 'Hello world'
Proc 3 of 4 says 'Hello world'
```

MPI Implementations and OpenMPI Warnings

- Several Implementations of MPI:
  - OpenMPI and MPICH are free, open source, widely available
  - HPC Vendors like IBM and Cray provide their own tailored MPI versions
- Recent Versions of OpenMPI can complain a LOT about various items missing
- The many machines with MPI are not configured perfectly leading to additional errors
  - Example: `--mca btl_base_warn_component_unused 0` to warn about missing HPC network components during `mpirun`
  - Example: `--mca opal_warn_on_missing_libcuda 0` if not intending to use GPU libraries
- Exact nature of warnings/errors varies a lot, look at messages which often dictate how to disable them
- Provided `mpiopts.sh` script can be sourced to set suppress common errors

Warning Suppression in OpenMPI

```
>> mpicc mpi_hello_plus.c

>> mpirun -np 2 a.out
--------------------------------------------------------------------------
The library attempted to open the following supporting CUDA
but each of them failed.  CUDA-aware support is disabled.
libcuda.so.1: cannot open shared object file: No such file
libcuda.dylib: cannot open shared object file: No such file
/usr/lib64/libcuda.so.1: cannot open shared object file: No
/usr/lib64/libcuda.dylib: cannot open shared object file: N
If you are not interested in CUDA-aware support, then run w
--mca opal_warn_on_missing_libcuda 0 to suppress this messa
in CUDA-aware support, then try setting LD_LIBRARY_PATH to
of libcuda.so.1 to get passed this issue.
--------------------------------------------------------------------------
P0000 [val]: Hello world from process    0 of 2
P0001 [val]: Hello world from process    1 of 2
[val:558294] 1 more process has sent help message help-mpi-
```

MPI Oversubscribing

Default OpenMPI config uses all processors on a single machine, fails for larger requests unless `--oversubscribe`

```
>> mpirun -np 2 a.out
...
P0001 [val]: Hello world from process    1 of 2
P0000 [val]: Hello world from process    0 of 2

>> mpirun -np 8 a.out
--------------------------------------------------------------------------
There are not enough slots available in the system to satisfy the 8
slots that were requested by the application:

  a.out

Either request fewer slots for your application, or make more slots
available for use.
...
Alternatively, you can use the --oversubscribe option to ignore the
number of available slots when deciding the number of processes to
launch.
--------------------------------------------------------------------------

>> source mpiopts.sh
>> echo $MPIOPTS
--mca opal_warn_on_missing_libcuda 0 --oversubscribe
#                                    ^^^^^^^^^^^^^^^

>> mpirun $MPIOPTS -np 16 a.out
P0009 [val]: Hello world from process    9 of 16
...
P0014 [val]: Hello world from process   14 of 16
P0012 [val]: Hello world from process   12 of 16
```

Hostfiles

- For simple cluster configurations, can pass a **hostfile** to `mpirun` to indicate host names of other machines in cluster
- Simplest form of hostfile is a list of symbolic or IP addresses for machines to recruit for the run
- CSE Labs CUDA cluster[1] has the following machines which can be used for experimentation

  `cuda01.cselabs.umn.edu`
  `cuda02.cselabs.umn.edu`
  `cuda03.cselabs.umn.edu`
  `cuda04.cselabs.umn.edu`
  `cuda05.cselabs.umn.edu`
- 40 physical cores per machine

[1] CUDA cluster is present to support this class, thus MPI is set up for it. We will also use it later for GPU programming.
https://cse.umn.edu/cseit/classrooms-labs#cs

Extended Example on CUDA cluster 1/2

```
### log in to lab machines
>> ssh cuda01.cselabs.umn.edu
...
csel-cuda-01>> cat hostfile-cuda-full.txt
cuda01.cselabs.umn.edu
cuda02.cselabs.umn.edu
cuda03.cselabs.umn.edu
cuda04.cselabs.umn.edu
cuda05.cselabs.umn.edu

### compile + run mpi program
csel-cuda-01>> mpicc mpi_hello_plus.c
csel-cuda-01>> mpirun -hostfile hostfile-cuda-full.txt -np 32 ./a.out
No protocol specified
No protocol specified
P0023 [csel-cuda-01]: Hello world from process   23 of 32
P0024 [csel-cuda-01]: Hello world from process   24 of 32
...
P0002 [csel-cuda-01]: Hello world from process    2 of 32
P0013 [csel-cuda-01]: Hello world from process   13 of 32

### 40 processors per machine
csel-cuda-01>> mpirun -hostfile hostfile-cuda-full.txt -np 64 ./a.out
...
P0011 [csel-cuda-01]: Hello world from process   11 of 64
P0020 [csel-cuda-01]: Hello world from process   20 of 64
..
P0039 [csel-cuda-01]: Hello world from process   39 of 64
P0041 [csel-cuda-02]: Hello world from process   41 of 64
P0045 [csel-cuda-02]: Hello world from process   45 of 64
P0046 [csel-cuda-02]: Hello world from process   46 of 64
...
```

Extended Example on CUDA cluster 2/2

```
### utilize whole cluster
csel-cuda-01>> mpirun -hostfile hostfile-cuda-full.txt -np 200 ./a.out
...
P0003 [csel-cuda-01]: Hello world from process    3 of 200
...
P0089 [csel-cuda-03]: Hello world from process   89 of 200
...
P0190 [csel-cuda-05]: Hello world from process  190 of 200
P0123 [csel-cuda-04]: Hello world from process  123 of 200
...
P0077 [csel-cuda-02]: Hello world from process   77 of 200


### 200 processors total in CUDA cluster; going over this errors out
csel-cuda-01 [04-mpi-code]% mpirun -hostfile hostfile-cuda-full.txt -np 201 ./a.out
--------------------------------------------------------------------------
There are not enough slots available in the system to satisfy the 201
slots that were requested by the application:

  ./a.out

Either request fewer slots for your application, or make more slots
available for use.

A "slot" is the Open MPI term for an allocatable unit where we can
launch a process.  The number of slots available are defined by the
environment in which Open MPI processes are run:

  1. Hostfile, via "slots=N" clauses (N defaults to number of
     processor cores if not provided)
  2. The --host command line parameter, via a ":N" suffix on the
     hostname (N defaults to 1 if not provided)
  3. Resource manager (e.g., SLURM, PBS/Torque, LSF, etc.)
  4. If none of a hostfile, the --host command line parameter, or an
     RM is present, Open MPI defaults to the number of processor cores
```

Distributed Memory (MPI) Systems at UMN

CUDA Cluster

- `csel-cuda01.cselabs.umn.edu` to `csel-cuda05.cselabs.umn.edu`
- Have OpenMPI installed, honor hostfile
- Hostfile in `04-mpi-code.zip` as `hostfile-cuda-full.txt`
- Good for experimentation but not a true HPC system
- Requires setting up SSH keys / Known Hosts[2]

MSI Systems

- Will use MSI to evaluate scalability of program performance for A2
- Usually no need to use a hostfile as MPI jobs are run in batch and number of nodes is requested as part of job
- Requires use of job scheduling system SLURM, discuss later

[2] See Accessing Unix/Linux Programming Environments Section 3 for instructions on setting up keys for password/Duo free login to CSE Labs

MPI Send and Recieve

Most basic functionality is point-to-point message transfer via `MPI_Send()` / `MPI_Recv()`

```
1  int count = 5;
2  int a[count]={10,20,30,40,50};
3  int b[count];
4  int partner = 1;
5  int tag = 1;
6
7  // Send contents of a to partner proc with tag=1
8  MPI_Send(a, count, MPI_INT, partner, tag, MPI_COMM_WORLD);
9
10 // Receive message into b from partner proc
11 MPI_Recv(b, count, MPI_INT, partner, tag, MPI_COMM_WORLD,
12           MPI_STATUS_IGNORE);  // ignore status of receipt
```

- Analyze the program `send_receive_test.c`
- Compare with `send_bugs.c` which demos stall problems
- Note `MPI_ANY_SOURCE` may be used for recv's source

Tags Make Messages Unique

```
int a[10], b[10], myrank;
MPI_Status status;
...
MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
if (myrank == 0) {
  MPI_Send(a, 10, MPI_INT, 1, 1, MPI_COMM_WORLD);
  MPI_Send(b, 10, MPI_INT, 1, 2, MPI_COMM_WORLD);
}
else if (myrank == 1) {
  MPI_Recv(b, 10, MPI_INT, 0, 2, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
  MPI_Recv(a, 10, MPI_INT, 0, 1, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
}
```

- Tags must be honored on receive
- Above code may deadlock if not buffered due to the misordering of tags
- Mostly we will use `tag=1` for simplicity
- Alternatively `MPI_ANY_TAG`, possible to query what tag was received later on (though we won't have cause to do this)

MPI Data Types Supported

```
// Sends a message.
int MPI_Send(void *buf, int count, MPI_Datatype datatype,
             int dest, int tag, MPI_Comm comm);

// Receives a message.
int MPI_Recv(void *buf, int count, MPI_Datatype datatype,
             int source, int tag, MPI_Comm comm,
             MPI_Status *status);
```

- Type of buffer is always untyped (`void* buf`)
- To try to get at slightly better safety, MPI has standard datatypes

`MPI_CHAR`	signed char
`MPI_INT`	signed int
`MPI_LONG`	signed long int
`MPI_FLOAT`	float
`MPI_DOUBLE`	double
`MPI_BYTE`	Last two used for sending
`MPI_PACKED`	structure arrays

Unsigned types also available

Exercise: Heat Transfer in MPI

- Discuss conversion of the following A1 code to an MPI version
- How is data in `H` divided up?
- Is communication required?
- How would one arrange `MPI_Send / MPI_Recv` calls?
- How much data needs to be transferred and between who?
- When the computation is finished, how can all data be displayed?

```
// Simulate the temperature changes for internal cells
for(t=0; t<max_time-1; t++){
  for(p=1; p<width-1; p++){
    double left_diff  = H[t][p] - H[t][p-1];
    double right_diff = H[t][p] - H[t][p+1];
    double delta = -k*( left_diff + right_diff );
    H[t+1][p] = H[t][p] + delta;
  }
}
```

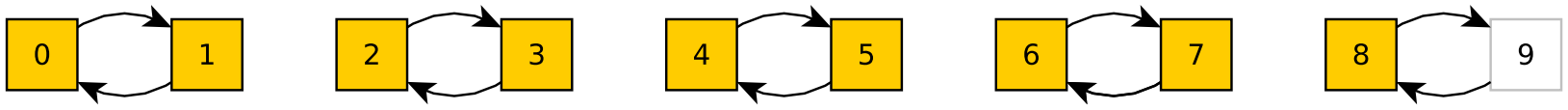
Some Patterns that occur in the problem

- Pair exchange of items: made easier with `MPI_sendrecv`
- Collecting final output for display: `MPI_Gather`
  - Previewed here
  - Discussed in following lectures

Exchange: Sendrecv for exchanging data between pairs

```
{
  double send[10], recv[10]; int partner;
  if(procid % 2 == 1 ){ // odd procs send left, receive left
    partner = procid-1;
    MPI_Send(send, 10, MPI_DOUBLE, partner, 1, MPI_COMM_WORLD);
    MPI_Recv(recv, 10, MPI_DOUBLE, partner, 1, MPI_COMM_WORLD,
             MPI_STATUS_IGNORE);
  }
  else{                    // even procs receive right, send right
    partner = procid+1;
    MPI_Recv(recv, 10, MPI_DOUBLE, partner, 1, MPI_COMM_WORLD,
             MPI_STATUS_IGNORE);
    MPI_Send(send, 10, MPI_DOUBLE, partner, 1, MPI_COMM_WORLD);
  }
}
{ // Sendrecv simplifies this pattern
  double send[10], recv[10]; int partner;
  partner = (procid % 2 == 1) ? procid-1 : procid+1;
  MPI_Sendrecv(send, 10, MPI_DOUBLE, partner, 1,
               recv, 10, MPI_DOUBLE, partner, 1,
               MPI_COMM_WORLD, MPI_STATUS_IGNORE);
}
```

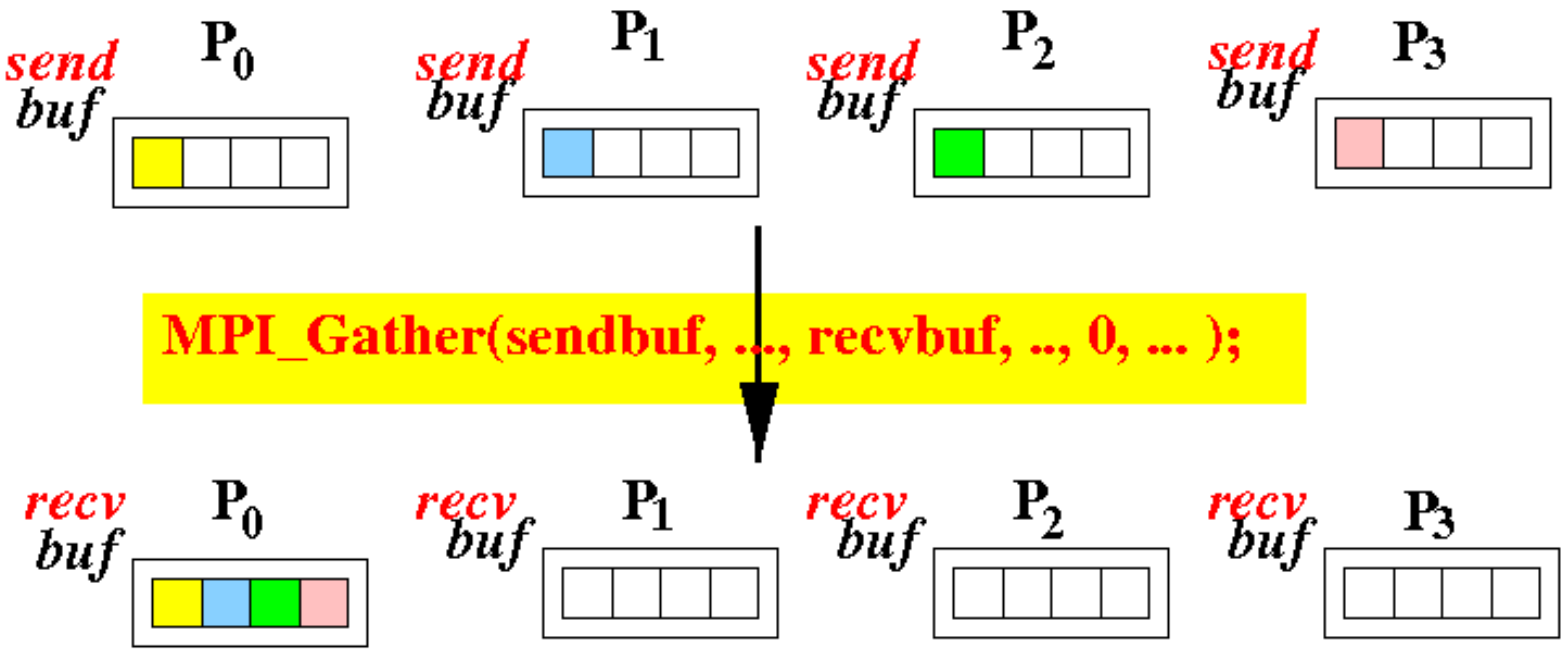
Take Care: Pair exchange can hang




```
{
  double send[10], recv[10]; int partner;
  partner = (procid % 2 == 1) ? procid-1 : procid+1;
  MPI_Sendrecv(send, 10, MPI_DOUBLE, partner, 1,
               recv, 10, MPI_DOUBLE, partner, 1,
               MPI_COMM_WORLD, MPI_STATUS_IGNORE);
}
```

- With 9 processors, logic is broken
- Proc 8 will wait to communicate with a partner that doesn't exist
- Program never terminates

Gather Preview



Source: Shun Yan Cheung Notes on MPI

- Every processor has computed columns
- One processor (usually `procid 0`) needs to gather all of the data
- Everyone calls `MPI_Gather()`

MPI_Gather Sample

Use of Gather

```
// Preamble for any code
MPI_Comm comm = MPI_COMM_WORLD;
int sendarray[100];
int procid, total_procs, *rbuf;
...;
// Only proc 0 needs space for all
// data
if(procid == 0) {
  rbuf = malloc(total_procs*100*
                sizeof(int));
}

// Everyone calls gather
// proc 0 gets all data eventually
MPI_Gather(sendarray, 100, MPI_INT,
           rbuf, 100, MPI_INT,
           0, comm);
```

Equivalent Non-Gather Code

```
if(rank == 0){
  for(i=0; i<100; i++){
    rbuf[i] = sendarray[i];
  }
  for(i=1; i<total_procs; i++){
    int *rloc = &rbuf[i*100];
    MPI_Recv(rloc, 100,
             MPI_INT, i,
             tag, MPI_COMM_WORLD,
             MPI_STATUS_IGNORE);
  }
}
else{
  MPI_Send(sendarray, 100,
           MPI_INT, 0,
           tag, MPI_COMM_WORLD);
}
```

Collective Communication Patterns Next

- `gather` is an example of a class of **Collective Communication Patterns**
- Will study more of these in subsequent lectures
- Using built-in collective comm. patterns simplifies programs and allows MPI implementation to exploit network as much as possible

Sending Structs

Sending structs can be done via the `MPI_BYTE` type

```
{                                          // from send_structs.c
  typedef struct {
    double x;
    int a, b;
  } dint_t;
  ...;
  dint_t mine[10];
  // calculate data sizes "manually" just as is done in a malloc()
  MPI_Send(mine,  10*sizeof(dint_t), MPI_BYTE,
           partner, 1, MPI_COMM_WORLD);
}
```

- Simple and effective if all compute nodes **use the same binary layout**
- MPI also provides a (complex) method for situations where struct layout differs between nodes
- Must Dictate # of struct fields, types, and ordering into a `MPI_Datatype` and use `MPI_Type_create_struct()`
- Likely hurts performance if struct layout differs so will not discuss in detail