

Introduction to MPI

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Pre-Introduction: Why Use MPI?

- Has been around a longtime (20+ years)
- Dominant
- Will be around a longtime (on all new platforms/roadmaps)
- Lots of libraries
- Lots of algorithms
- Very scalable (3,000,000+ cores right now)
- Portable
- Works with hybrid models
- Explicit parallel routines force the programmer to address parallelization from the beginning, not as an afterthought. Can enable both debugging and memory placement optimization.
- Therefore:
 - A good long term learning investment
 - Good/possible to understand whether you are coder or a manager

Introduction

What is MPI? The Message-Passing Interface Standard(MPI) is a *library* that allows you to do problems in parallel using *message-passing* to *communicate* between *processes*.

•Library

It is not a language (like X10 or UPC), or even an extension to a language. Instead, it is a library that your native, standard, serial compiler (f77, f90, cc, CC, python, etc.) uses.

•Message Passing

Message passing is sometimes referred “paradigm”. But it is really just any method of explicitly passing data between processes and it is flexible enough to implement most other paradigms (Data Parallel, Work Sharing, etc.). It can be defined as having independent processors, with no shared data, communicate through subroutine calls.

•Communicate

This communication may be via a dedicated MPP torus network, or merely an office LAN. To the MPI programmer, it looks much the same.

•Processes

These can be 300,000 cores on Blue Waters, or 4 processes on a single chip. Think “Unix process” and you won’t be far off, although we usually want only 1 process per processor/core/PE so that we actually get a speed up.

Basic MPI

In order to do parallel programming, you require some basic functionality, namely, the ability to:

- Start Processes
- Send Messages
- Receive Messages
- Synchronize

With these four capabilities, you can construct any program. We will look at the basic versions of the MPI routines that implement this. MPI offers over 125 functions. Many of these are more convenient and efficient for certain tasks. However, with the handful that we are about to learn, we will be able to implement just about any algorithm. And many production MPI codes are built using just these routines.

First Example (Starting Processes): Hello World

The easiest way to see exactly how a parallel code is put together and run is to write the classic "Hello World" program in parallel. In this case it simply means that every PE will say hello to us. Something like this:

```
mpirun -n 8 a.out  
Hello from 0.  
Hello from 1.  
Hello from 2.  
Hello from 3.  
Hello from 4.  
Hello from 5.  
Hello from 6.  
Hello from 7.
```

Hello World: C Code

How complicated is the code to do this? Not very:

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

main(int argc, char** argv){
    int my_PE_num;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);
    printf("Hello from %d.\n", my_PE_num);
    MPI_Finalize();
}
```

Hello World: Fortran Code

Here is the Fortran version:

```
program hello
include 'mpif.h'

integer my_pe_num, errcode
call MPI_INIT(errcode)
call MPI_COMM_RANK(MPI_COMM_WORLD, my_pe_num, errcode)
print *, 'Hello from ', my_pe_num, '.'
call MPI_FINALIZE(errcode)
end program hello
```

We will make an effort to present both languages here, but they are really trivially similar in these simple examples, so try to play along on both.

MPI Routine Guidelines

Let's make a few general observations before we go into what is actually happening here:

- We have to include the header file, either `mpif.h` or `mpi.h`. MPI-3 can use the (much better) "USE `mpi_f08`" for Fortran.
- The MPI calls are easy to spot, they always start with `MPI_`. The MPI calls themselves are the same for both languages except that the Fortran routines have an added argument on the end to return the error condition (optional in MPI-3), whereas the C ones return it as the function value.
- We should check these (for `MPI_SUCCESS`) in both cases as it can be very useful for debugging. We don't in these examples for clarity. You probably won't because of laziness.

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

main(int argc, char** argv){
    int my_PE_num;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);
    printf("Hello from %d.\n", my_PE_num);
    MPI_Finalize();
}
```

```
program hello
include 'mpif.h'

integer my_pe_num, errcode
call MPI_INIT(errcode)
call MPI_COMM_RANK(MPI_COMM_WORLD,
                   my_pe_num, errcode)
print *, 'Hello from ', my_pe_num, '.'
call MPI_FINALIZE(errcode)
end
```


MPI_INIT, MPI_FINALIZE and MPI_COMM_RANK

OK, lets look at the actual MPI routines. All three of the ones we have here are very basic and will appear in any MPI code.

MPI_INIT

This routine must be the first MPI routine you call (it does *not* have to be the first statement). It sets things up and might do a lot of behind-the-scenes work on some cluster-type systems (like start daemons and such). On most dedicated MPPs, it won't do much. We just have to have it. In C, it is common to to pass along the command line arguments. These are very standard C variables that contain anything entered on the command line when the executable was run. You may have used them before in normal serial codes. You can usually use NULL for both of these arguments, but we will stick with the normal convention.

MPI_FINALIZE

This is the companion to MPI_Init. It must be the last MPI_Call. It may do a lot of housekeeping, or it may not. Your code won't know or care.

MPI_COMM_RANK

Now we get a little more interesting. This routine returns to every PE its rank, or unique address from 0 to PEs-1. This is the only thing that sets each PE apart from its companions. In this case, the number is merely used to have each PE print a slightly different message. In general, though, the PE number will be used to load different data files or take different branches in the code. It has another argument, the communicator, that we will ignore for a few slides.

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

main(int argc, char** argv){
    int my_PE_num;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);
    printf("Hello from %d.\n", my_PE_num);
    MPI_Finalize();
}
```

Compiling

Before we think about what *exactly* is happening when this executes, let's compile and run this thing - just so you don't think we are skipping any magic. We compile using a normal ANSI C or Fortran 90 compiler (many other languages are also available). While logged in to Bridges:

For C codes:

```
mpicc hello.c
```

For Fortran codes:

```
mpif90 hello.f
```

We now have an executable called `a.out` (the default).

Running

To run an MPI executable we must tell the machine how many copies we wish to run at runtime. On Bridges you can choose any number up to the size of your job request. We'll try 8. The command is `mpi run`:

```
mpirun -n 8 a.out  
Hello from 5.  
Hello from 3.  
Hello from 1.  
Hello from 2.  
Hello from 7.  
Hello from 0.  
Hello from 6.  
Hello from 4.
```

Which is (almost) what we desired when we started.

What's Happening?

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

main(int argc, char** argv){
    int my_PE_num;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);
    printf("Hello from %d.\n", my_PE_num);
    MPI_Finalize();
}
```

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

main(int argc, char** argv){
    int my_PE_num;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);
    printf("Hello from %d.\n", my_PE_num);
    MPI_Finalize();
}
```

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

main(int argc, char** argv){
    int my_PE_num;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);
    printf("Hello from %d.\n", my_PE_num);
    MPI_Finalize();
}
```

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

main(int argc, char** argv){
    int my_PE_num;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);
    printf("Hello from %d.\n", my_PE_num);
    MPI_Finalize();
}
```

```
Hello from 5.
Hello from 3.
Hello from 1.
Hello from 2.
Hello from 7.
Hello from 0.
Hello from 6.
Hello from 4.
```

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

main(int argc, char** argv){
    int my_PE_num;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);
    printf("Hello from %d.\n", my_PE_num);
    MPI_Finalize();
}
```

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

main(int argc, char** argv){
    int my_PE_num;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);
    printf("Hello from %d.\n", my_PE_num);
    MPI_Finalize();
}
```

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

main(int argc, char** argv){
    int my_PE_num;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);
    printf("Hello from %d.\n", my_PE_num);
    MPI_Finalize();
}
```

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

main(int argc, char** argv){
    int my_PE_num;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);
    printf("Hello from %d.\n", my_PE_num);
    MPI_Finalize();
}
```

What Actually Happened...

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

main(int argc, char** argv){
    int my_PE_num;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);
    printf("Hello from %d.\n", my_PE_num);
    MPI_Finalize();
}
```

```
Hello from 5.
Hello from 3.
Hello from 1.
Hello from 2.
Hello from 7.
Hello from 0.
Hello from 6.
Hello from 4.
```

There are two issues here that may not have been expected. The most obvious is that the output might seem out of order. The response to that is "what order were you expecting?" Remember, the code was started on all nodes practically simultaneously. There was no reason to expect one node to finish before another. Indeed, if we rerun the code we will probably get a different order. Sometimes it may seem that there is a very repeatable order. But, one important rule of parallel computing is don't assume that there is any particular order to events unless there is something to guarantee it. Later on we will see how we could force a particular order on this output.

The second question you might ask is "how does the output know where to go?" A good question. In the case of a cluster, it isn't at all clear that a bunch of separate unix boxes printing to standard out will somehow combine them all on one terminal. Indeed, you should appreciate that a dedicated MPP environment will automatically do this for you – even so you should expect a lot of buffering (hint: use flush if you must). Of course most "serious" IO is file-based and will depend upon a distributed file system (you hope).

Do all nodes really run the *same* code?

Yes, they do run the same code independently. You might think this is a serious constraint on getting each PE to do unique work. Not at all. They can use their PE numbers to diverge in behavior as much as they like.

The extreme case of this is to have different PEs execute entirely different sections of code based upon their PE number.

```
if (my_PE_num = 0)
    Routine_SpaceInvaders
else if (my_PE_num = 1)
    Routine_CrackPasswords
else if (my_PE_num =2)
    Routine_WeatherForecast
    .
    .
    .
```

So, we can see that even though we have a logical limitation of having each PE execute the same program, for all practical purposes we can really have each PE running an entirely unrelated program by bundling them all into one executable and then calling them as separate routines based upon PE number.

Master and Slaves PEs

The much more common case is to have a single PE that is used for some sort of coordination purpose, and the other PEs run code that is the same, although the data will be different. This is how one would implement a master/slave or host/node paradigm.

```
if (my_PE_num = 0)
    MasterCodeRoutine
else
    SlaveCodeRoutine
```

Of course, the above Hello World code is the trivial case of

```
EverybodyRunThisRoutine
```

and consequently the only difference will be in the output, as it at least uses the PE number.

Communicators

Our last little detail in Hello World is the first parameter in

```
MPI_Comm_rank (MPI_COMM_WORLD, &my_PE_num)
```

This parameter is known as the "communicator" and can be found in many of the MPI routines. In general, it is used so that one can divide up the PEs into subsets for various algorithmic purposes. For example, if we had an array - distributed across the PEs – for which we wished to find the determinant, we could define some subset of the PEs that holds a certain column of the array so that we could address only that column conveniently. Or, we might wish to define a communicator for just the odd PEs. Or just the “ocean” PEs in a weather model. You get the idea.

However, this is a convenience that can be dispensed with in simpler algorithms. As such, one will often see the value `MPI_COMM_WORLD` when a communicator is required. This is simply the global set and states we don't really care to deal with any particular subset here. We will use it in all of our examples. We will delve into its considerable usefulness in the Advanced talk.

Fundamental Concept of MPI

Do you get it?

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

main(int argc, char** argv){
    int my_PE_num;

    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);
    printf("Hello from %d.\n", my_PE_num);
    MPI_Finalize();
}
```

```
program hello
include 'mpif.h'

integer my_pe_num, errcode

call MPI_INIT(errcode)
call MPI_COMM_RANK(MPI_COMM_WORLD, my_pe_num, errcode)
print *, 'Hello from ', my_pe_num, '.'
call MPI_FINALIZE(errcode)
end
```



```
Hello from 5.
Hello from 3.
Hello from 1.
Hello from 2.
Hello from 7.
Hello from 0.
Hello from 6.
Hello from 4.
```

Recap

- Write standard C or Fortran with some MPI routines added in.
- Compile.
- Run simultaneously, but independently, on multiple nodes.

Second Example: Sending and Receiving Messages

Hello World might be illustrative, but we haven't really done any message passing yet.

Let's write about the simplest possible message passing program:

It will run on 2 PEs and will send a simple message (the number 42) from PE 1 to PE 0. PE 0 will then print this out.

Sending a Message

Sending a message is a simple procedure. In our case the routine will look like this in C (the common pages are in C, so you should get used to seeing this format):

```
MPI_Send( &numbertosend, 1, MPI_INT, 0, 10, MPI_COMM_WORLD)
```

<code>&numbertosend</code>	a pointer to whatever we wish to send. In this case it is simply an integer. It could be anything from a character string to a column of an array or a structure. It is even possible to pack several different data types in one message.
<code>1</code>	the number of items we wish to send. If we were sending a vector of 10 int's, we would point to the first one in the above parameter and set this to the size of the array.
<code>MPI_INT</code>	the type of object we are sending. Possible values are: <code>MPI_CHAR</code> , <code>MPI_SHORT</code> , <code>MPI_INT</code> , <code>MPI_LONG</code> , <code>MPI_UNSIGNED_CHAR</code> , <code>MPI_UNSIGNED_SHORT</code> , <code>MPI_UNSIGNED</code> , <code>MPI_UNSIGNED_LING</code> , <code>MPI_FLOAT</code> , <code>MPI_DOUBLE</code> , <code>MPI_LONG_DOUBLE</code> , <code>MPI_BYTE</code> , <code>MPI_PACKED</code> Most of these are obvious in use. <code>MPI_BYTE</code> will send raw bytes (on a heterogeneous workstation cluster this will suppress any data conversion). <code>MPI_PACKED</code> can be used to pack multiple data types in one message, and we can also define our own types. We will save that for the advanced talk.
<code>0</code>	Destination of the message. In this case PE 0.
<code>10</code>	Message tag. All messages have a tag attached to them that can be very useful for sorting messages. For example, one could give high priority control messages a different tag than data messages. When receiving, the program would check for messages that use the control tag first. We just picked 10 at random.
<code>MPI_COMM_WORLD</code>	We don't really care about any subsets of PEs here. So, we just chose this "default".

Receiving a Message

Receiving a message is equally simple and very symmetric with MPI_Send (hint: *cut and paste is your friend here*). In our case it will look like:

```
MPI_Recv( &numbertoreceive, 1, MPI_INT, MPI_ANY_SOURCE, MPI_ANY_TAG, MPI_COMM_WORLD, &status)
```

&numbertoreceive	A pointer to the variable that will receive the item. In our case it is simply an integer that has some undefined value until now.
1	Number of items to receive. Just 1 here.
MPI_INT	Datatype. Better be an int, since that's what we sent.
MPI_ANY_SOURCE	The node to receive from. We could use 1 here since the message is coming from there, but we'll illustrate the "wild card" method of receiving a message from anywhere.
MPI_ANY_TAG	We could use a value of 10 here to filter out any other messages (there aren't any) but, again, this was a convenient place to show how to receive any tag.
MPI_COMM_WORLD	Just using default set of all PEs.
&status	A structure that receives the status data which includes the source and tag of the message.

Send and Receive C Code

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

int my_PE_num, numbertoreceive, numbertosend=42;
MPI_Status status;

MPI_Init(&argc, &argv);
MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);

if (my_PE_num==0){
    MPI_Recv( &numbortoreceive, 1, MPI_INT, MPI_ANY_SOURCE, MPI_ANY_TAG, MPI_COMM_WORLD, &status);
    printf("Number received is: %d\n", numbortoreceive);
}
else MPI_Send( &numbortosend, 1, MPI_INT, 0, 10, MPI_COMM_WORLD);

MPI_Finalize(); }
```

Send and Receive Fortran Code

```
program sender
implicit none
include 'mpif.h'

integer my_pe_num, errcode, numbertoreceive, numbertosend, status(MPI_STATUS_SIZE)

call MPI_INIT(errcode)
call MPI_COMM_RANK(MPI_COMM_WORLD, my_pe_num, errcode)

numbertosend = 42

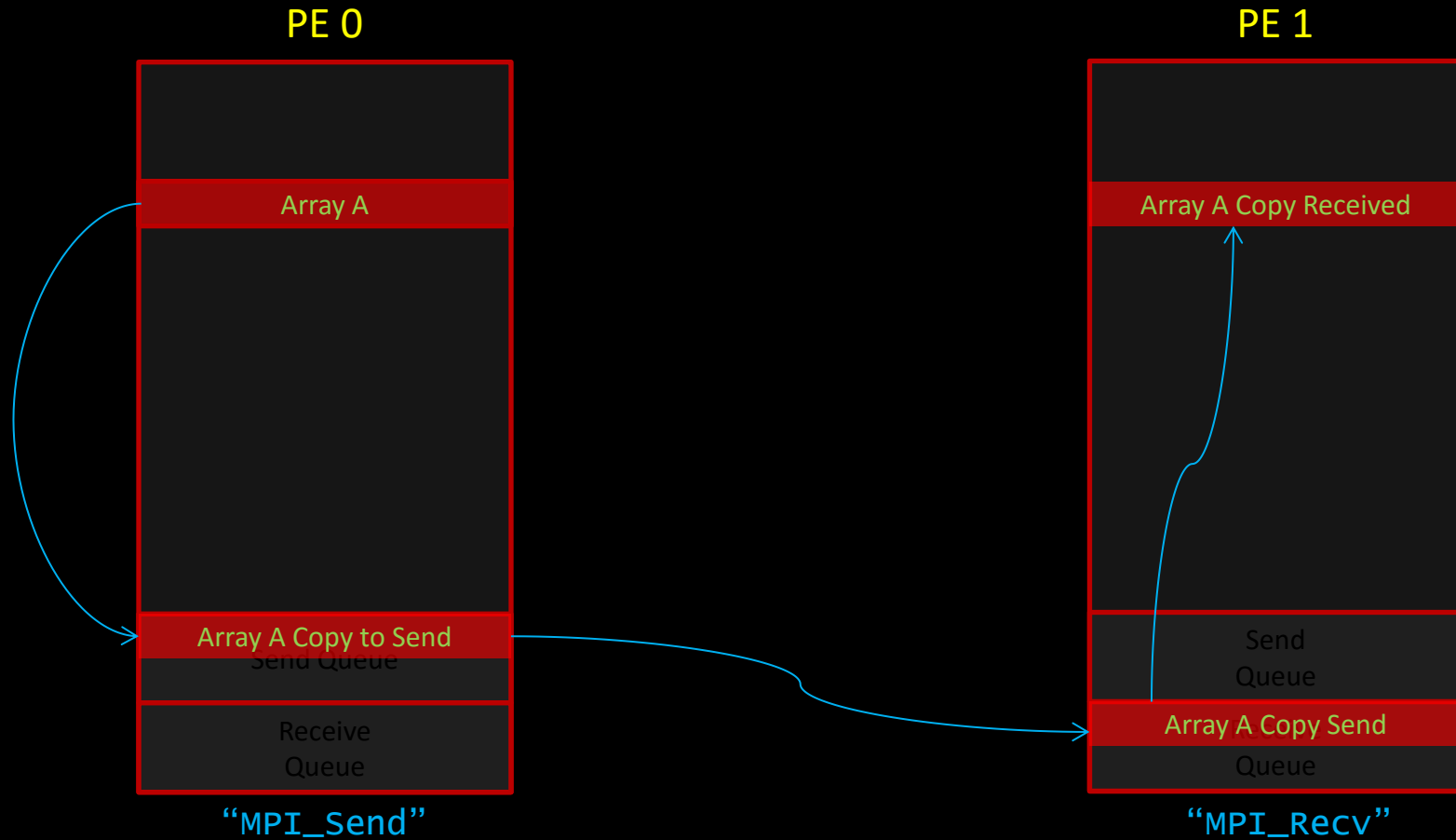
if (my_pe_num.EQ.0) then
  call MPI_Recv( numbertoreceive, 1, MPI_INTEGER, MPI_ANY_SOURCE, MPI_ANY_TAG, MPI_COMM_WORLD, status, errcode)
  print *, 'Number received is:' , numbertoreceive
endif

if (my_pe_num.EQ.1) then
  call MPI_Send( numbertosend, 1, MPI_INTEGER, 0, 10, MPI_COMM_WORLD, errcode)
endif

call MPI_FINALIZE(errcode)

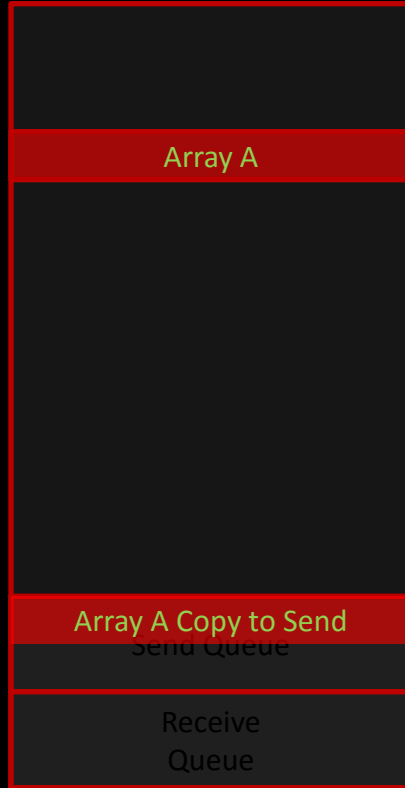
end
```

Default MPI Messaging

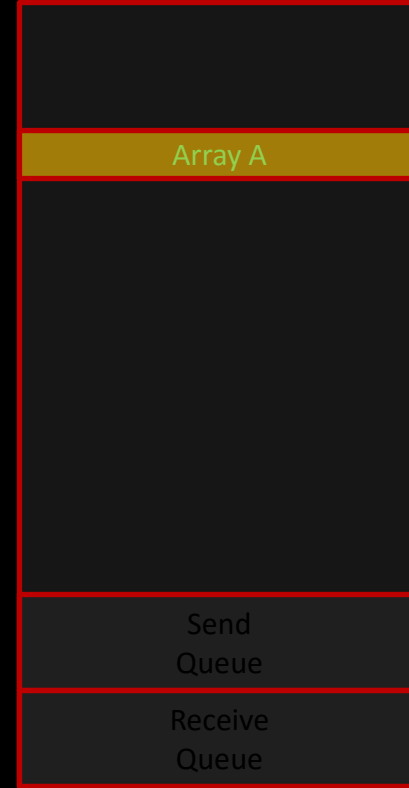


Send makes a copy

PE 0



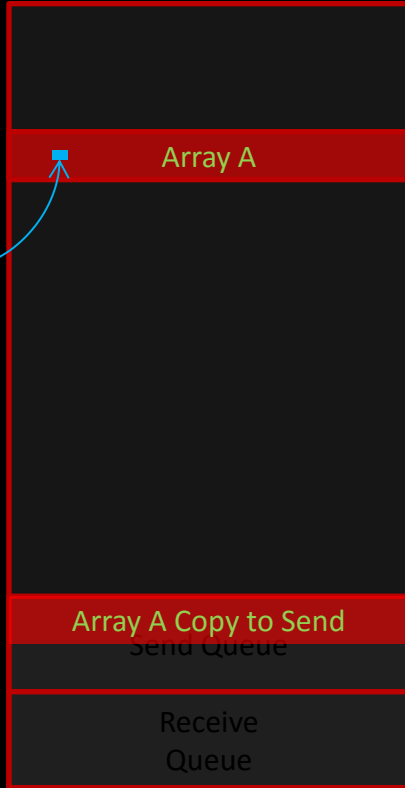
PE 1



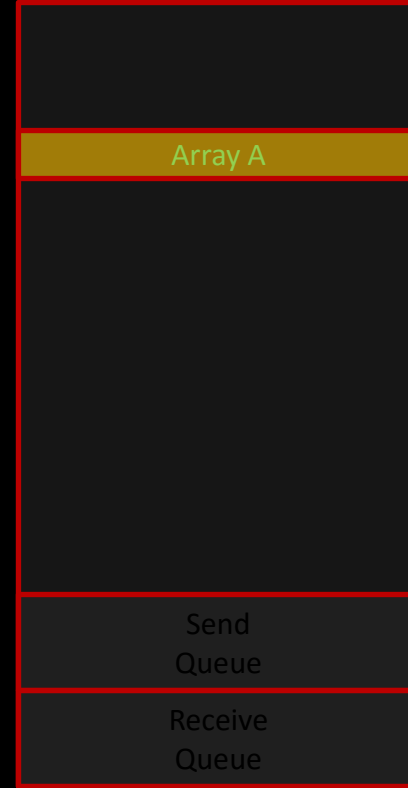
“MPI_Send(A, PE 1)”

Why make a copy?

PE 0



PE 1



"A[12][32] = 18"

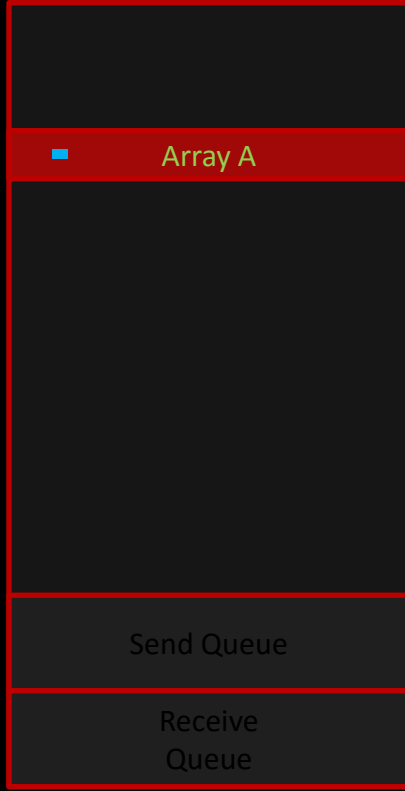
Message in flight



“X = Y + Z * 4”

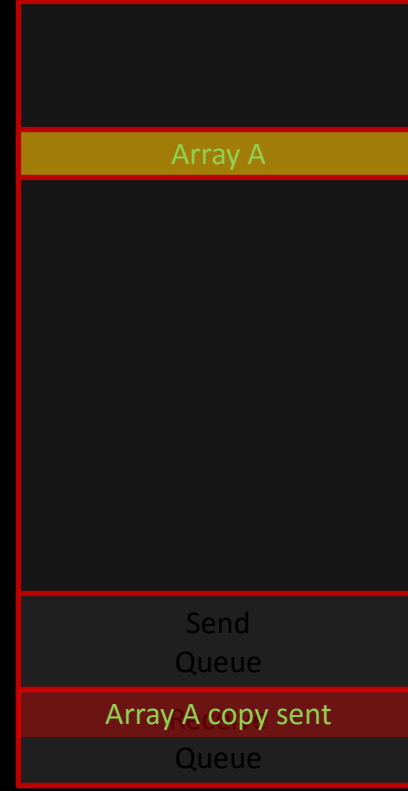
Sitting in receive queue

PE 0



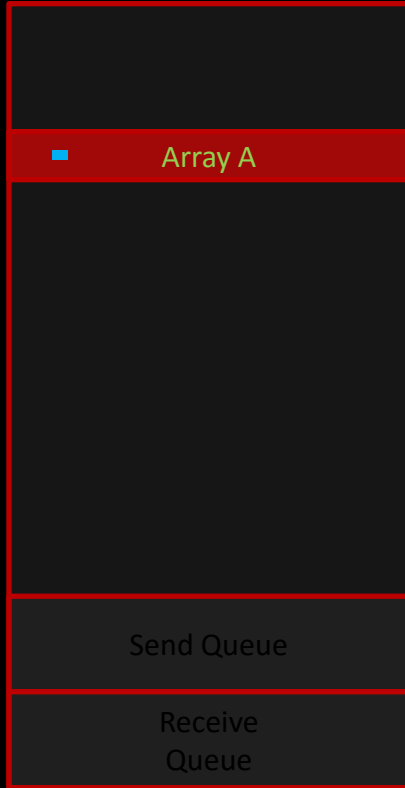
"w = 3.14159 * 2"

PE 1



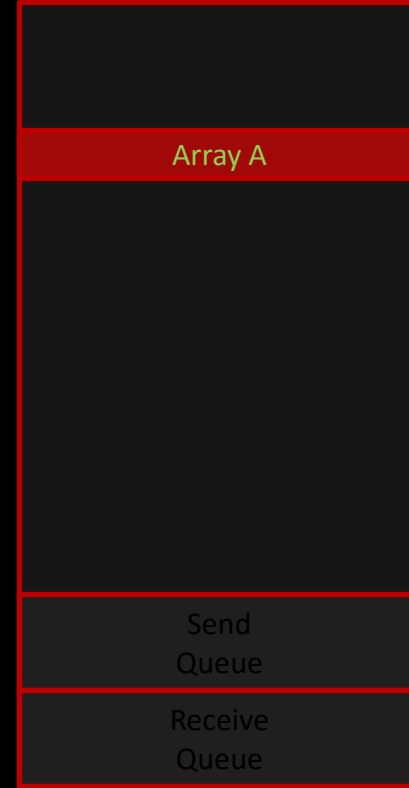
Received

PE 0



“goto some_where”

PE 1



“MPI_Recv(A, PE 0)”

Receive Queue

The message queue contains all of the message that have already arrived. You can just grab the next one in the queue with MPI_ANY_SOURCE and MPI_ANY_TAG, or you can be selective.

Source	Tag	Results in Data
1	2	4444
3	2	1008*
2	1	43*
2	2	56
ANY_SOURCE	2	1008 or 4444 or 56*
1	ANY_TAG	4444*

* MPI's only ordering guarantee is that messages from the same source will stay in order. So, you will receive and retrieve the first sent message from any source first.

Note that communicators can also function as filters, but data types and data counts **do not**. Mismatched data types are an error, and may not even be detected at runtime!

Message Queue on PE 0

Data	Source	Tag
43	2	1
1008	3	2
4444	1	2
80999	2	1
5345	3	1
9044	1	1
5666	3	1
339	2	1
346	3	2
789879	2	1
78942	2	1
56	2	2
44509	1	1

Non-Blocking Sends and Receives

All of the receives that we are using here are blocking. This means that they will wait until a message matching their requirements for source and tag has been received into the queue.

The default Sends try not to block, but don't guarantee it. As your data structures grow large, this blocking behavior may well emerge.

Blocking MPI_Send

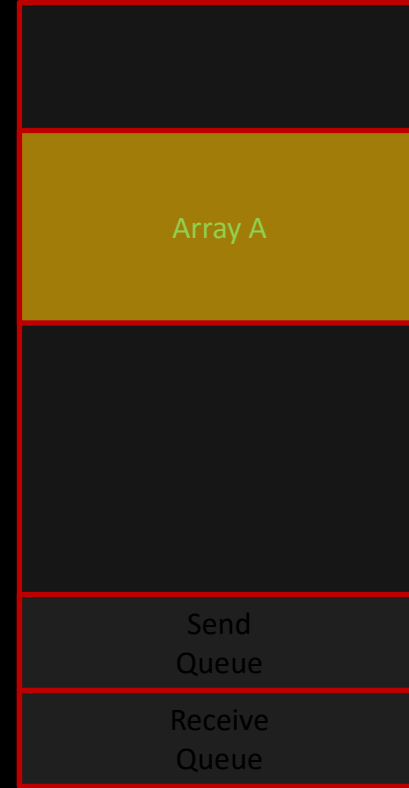
PE 0



“MPI_Send(A, PE 1)”

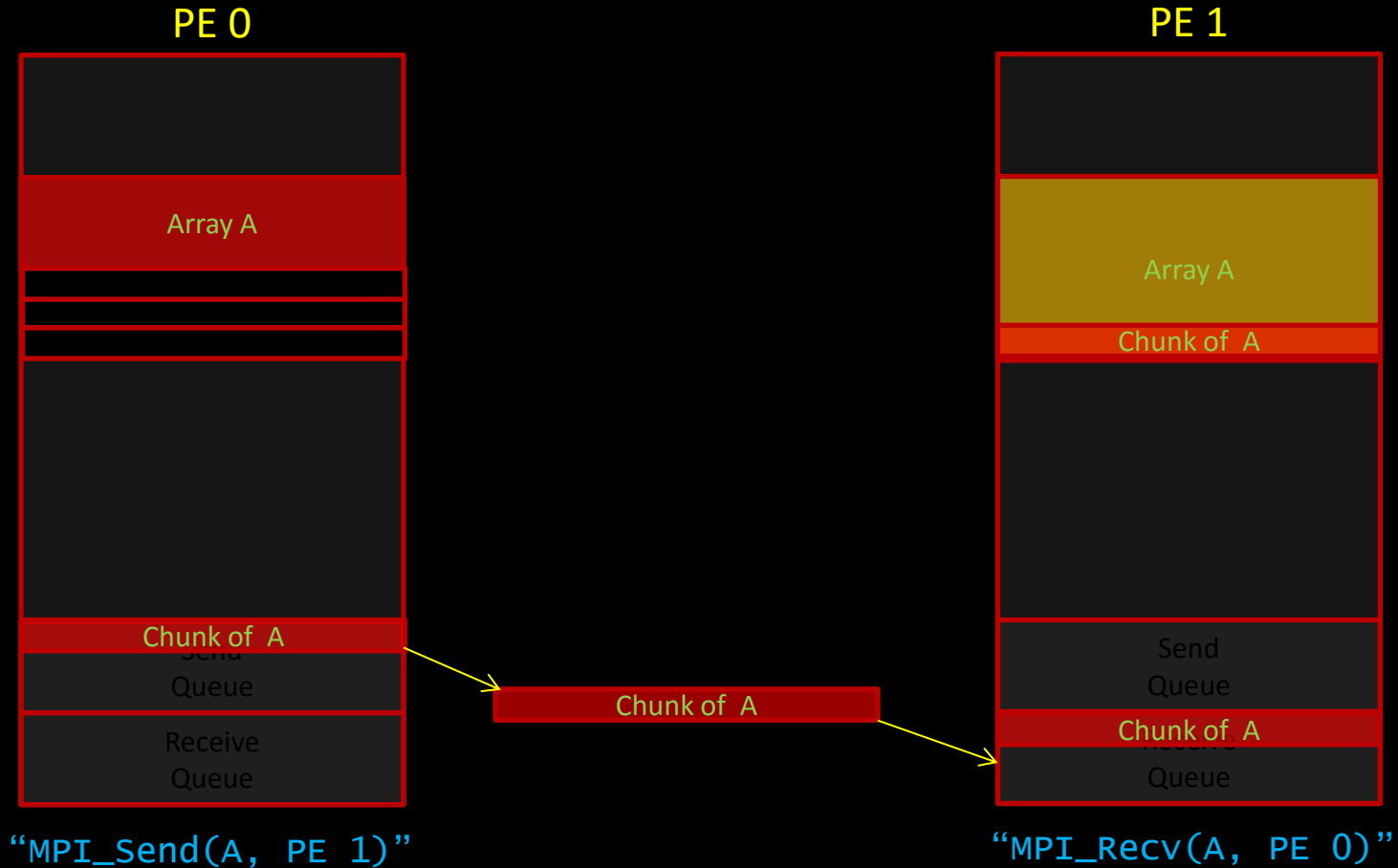
“A[12][32] = 18”

PE 1



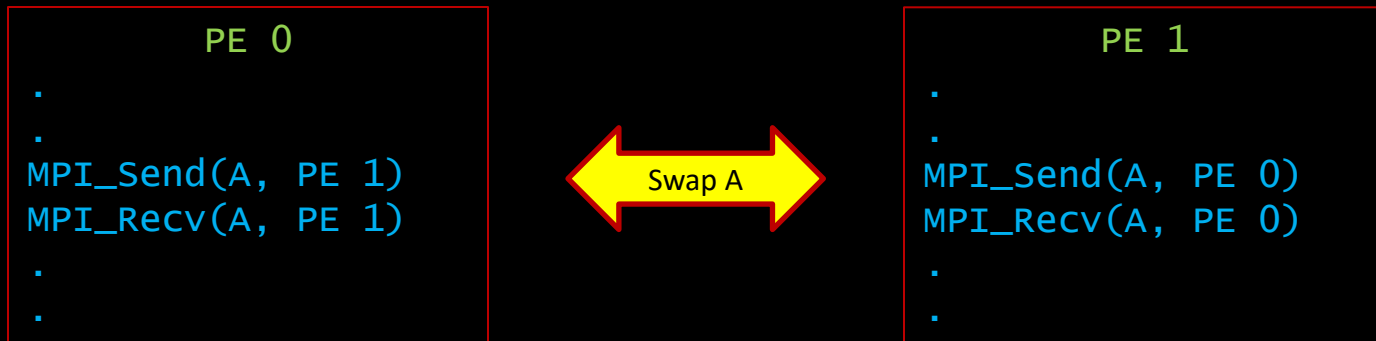
“X = Y + 4”

Receive Issued



Non-Blocking Sends and Receives

This may seem like a strictly performance issue, but it is not. What about the very common case of:



If both PEs block on Send, we have a **deadlock**. The code will hang forever.

Non-Blocking Sends and Receives

This is a very useful subject, but we can comfortably defer it until the Advanced MPI talk because:

- It is straightforward to convert blocking sends and receives to non-blocking when needed.
- It is often (but not always) easier to implement and debug a code with blocking and then optimize to non-blocking.
- It would clutter up our examples with additional complexity and would not gain us anything here.

Communication Modes

There are also variations on the normal blocking send and receive that alter the standard buffering behavior and may buy some optimization with little effort. If your algorithm is set up correctly, it may be just a matter of changing one letter in the routine and you have a speedier code. There are four possible modes (with differently named MPI_XSEND routines) for buffering and sending messages in MPI. We use the standard mode for all of our work.

Standard mode	Send will usually not block even if a receive for that message has not occurred. Exception is if there are resource limitations (buffer space).
Buffered Mode MPI_Bsend	Similar to above, but will never block (just return error).
Synchronous Mode MPI_Ssend	Will only return when matching receive has started. No extra buffer copy needed, but also can't do any additional computation. <i>Good for checking code safety.</i>
Ready Mode MPI_Rsend	Will only work if matching receive is already waiting. Must be well synchronized or behavior is undefined.

But it really is quite simple

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

int my_PE_num, numbertoreceive, numbertosend=42;
MPI_Status status;

MPI_Init(&argc, &argv);
MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);

if (my_PE_num==0){
    MPI_Recv( &numbortoreceive, 1, MPI_INT, MPI_ANY_SOURCE, MPI_ANY_TAG, MPI_COMM_WORLD, &status);
    printf("Number received is: %d\n", numbortoreceive);
}
else MPI_Send( &numbortosend, 1, MPI_INT, 0, 10, MPI_COMM_WORLD);

MPI_Finalize(); }
```

But it really is quite simple

```
program sender
implicit none
include 'mpif.h'

integer my_pe_num, errcode, numbertoreceive, numbertosend, status(MPI_STATUS_SIZE)

call MPI_INIT(errcode)
call MPI_COMM_RANK(MPI_COMM_WORLD, my_pe_num, errcode)

numbertosend = 42

if (my_pe_num.EQ.0) then
  call MPI_Recv( numbertoreceive, 1, MPI_INTEGER, MPI_ANY_SOURCE, MPI_ANY_TAG, MPI_COMM_WORLD, status, errcode)
  print *, 'Number received is:' , numbertoreceive
endif

if (my_pe_num.EQ.1) then
  call MPI_Send( numbertosend, 1, MPI_INTEGER, 0, 10, MPI_COMM_WORLD, errcode)
endif

call MPI_FINALIZE(errcode)

end
```

Third Example: Synchronization

We are going to write another code which will employ the remaining tool that we need for general parallel programming: synchronization. Many algorithms require that you be able to get all of the nodes into some controlled state before proceeding to the next stage. This is usually done with a synchronization point that requires all of the nodes (or some specified subset at the least) to reach a certain point before proceeding. Sometimes the manner in which messages block will achieve this same result implicitly, but it is often necessary to explicitly do this and debugging is often greatly aided by the insertion of synchronization points which are later removed for the sake of efficiency.

Third Example: Synchronization

Our code will perform the rather pointless operations of:

- 1) Have PE 0 send a number to the other 3 PEs
Foreshadowing:
Broadcast
MPI_Bcast()
- 2) have them multiply that number by their own PE number
- 3) they will then print the results out, in order (remember the hello world program?)
Synchronize
MPI_Barrier()
- 4) and send them back to PE 0
Reduction
MPI_Reduce()
- 5) which will print out the sum.

Synchronization: C Code

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

main(int argc, char** argv){

    int my_PE_num, numbertoreceive, numbertosend=4,index, result=0;
    MPI_Status status;

    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);

    if (my_PE_num==0)
        for (index=1; index<4; index++)
            MPI_Send( &numbertosend, 1,MPI_INT, index, 10,MPI_COMM_WORLD);
    else{
        MPI_Recv( &numbortoreceive, 1, MPI_INT, 0, 10, MPI_COMM_WORLD, &status);
        result = numbortoreceive * my_PE_num;
    }

    for (index=1; index<4; index++){
        MPI_Barrier(MPI_COMM_WORLD);
        if (index==my_PE_num) printf("PE %d's result is %d.\n", my_PE_num, result);
    }

    if (my_PE_num==0){
        for (index=1; index<4; index++){
            MPI_Recv( &numbortoreceive, 1,MPI_INT,index,10, MPI_COMM_WORLD, &status);
            result += numbortoreceive;
        }
        printf("Total is %d.\n", result);
    }
    else
        MPI_Send( &result, 1, MPI_INT, 0, 10, MPI_COMM_WORLD);

    MPI_Finalize();
}
```

Synchronization: Fortran Code

```
program synch
implicit none

include 'mpif.h'

integer my_pe_num, errcode, numbertoreceive, numbertosend
integer index, result
integer status(MPI_STATUS_SIZE)

call MPI_INIT(errcode)
call MPI_COMM_RANK(MPI_COMM_WORLD, my_pe_num, errcode)

numbertosend = 4
result = 0

if (my_pe_num.EQ.0) then
  do index=1,3
    call MPI_Send( numbertosend, 1, MPI_INTEGER, index, 10, MPI_COMM_WORLD, errcode)
  enddo
else
  call MPI_Recv( numbertoreceive, 1, MPI_INTEGER, 0, 10, MPI_COMM_WORLD, status, errcode)
  result = numbertoreceive * my_pe_num
endif

do index=1,3
  call MPI_Barrier(MPI_COMM_WORLD, errcode)
  if (my_pe_num.EQ.index) then
    print *, 'PE ',my_pe_num,'s result is ',result,','
  endif
enddo

if (my_pe_num.EQ.0) then
  do index=1,3
    call MPI_Recv( numbertoreceive, 1, MPI_INTEGER, index,10, MPI_COMM_WORLD, status, errcode)
    result = result + numbertoreceive
  enddo
  print *,'Total is ',result,','
else
  call MPI_Send( result, 1, MPI_INTEGER, 0, 10, MPI_COMM_WORLD, errcode)
endif

call MPI_FINALIZE(errcode)
end
```

Step 1 – Master, Slave

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

main(int argc, char** argv){

    int my_PE_num, numbertoreceive, numbertosend=4,index, result=0;
    MPI_Status status;

    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);

    if (my_PE_num==0)
        for (index=1; index<4; index++)
            MPI_Send( &numbertosend, 1,MPI_INT, index, 10,MPI_COMM_WORLD);
    else{
        MPI_Recv( &numbortoreceive, 1, MPI_INT, 0, 10, MPI_COMM_WORLD, &status);
        result = numbortoreceive * my_PE_num;
    }

    for (index=1; index<4; index++){
        MPI_Barrier(MPI_COMM_WORLD);
        if (index==my_PE_num) printf("PE %d's result is %d.\n", my_PE_num, result);
    }

    if (my_PE_num==0){
        for (index=1; index<4; index++){
            MPI_Recv( &numbortoreceive, 1,MPI_INT,index,10, MPI_COMM_WORLD, &status);
            result += numbortoreceive;
        }
        printf("Total is %d.\n", result);
    }
    else
        MPI_Send( &result, 1, MPI_INT, 0, 10, MPI_COMM_WORLD);

    MPI_Finalize();
}
```

Step 2 – Master, Slave

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

main(int argc, char** argv){

    int my_PE_num, numbertoreceive, numbertosend=4,index, result=0;
    MPI_Status status;

    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);

    if (my_PE_num==0)
        for (index=1; index<4; index++)
            MPI_Send( &numbertosend, 1,MPI_INT, index, 10,MPI_COMM_WORLD);
    else{
        MPI_Recv( &numbortoreceive, 1, MPI_INT, 0, 10, MPI_COMM_WORLD, &status);
        result = numbortoreceive * my_PE_num;
    }

    for (index=1; index<4; index++){
        MPI_Barrier(MPI_COMM_WORLD);
        if (index==my_PE_num) printf("PE %d's result is %d.\n", my_PE_num, result);
    }

    if (my_PE_num==0){
        for (index=1; index<4; index++){
            MPI_Recv( &numbortoreceive, 1,MPI_INT,index,10, MPI_COMM_WORLD, &status);
            result += numbortoreceive;
        }
        printf("Total is %d.\n", result);
    }
    else
        MPI_Send( &result, 1, MPI_INT, 0, 10, MPI_COMM_WORLD);

    MPI_Finalize();
}
```

Step 3: Print in order...

Remember Hello World's random order? What if we did:

```
IF myPE=0 PRINT "Hello from 0."  
IF myPE=1 PRINT "Hello from 1."  
IF myPE=2 PRINT "Hello from 2."  
IF myPE=3 PRINT "Hello from 3."  
IF myPE=4 PRINT "Hello from 4."  
IF myPE=5 PRINT "Hello from 5."  
IF myPE=6 PRINT "Hello from 6."  
IF myPE=7 PRINT "Hello from 7."
```

Would this print in order?

What if one PE was 1,000,000 times faster than another?

Step 3: Print in order...

No. How about?

```
IF myPE=0 PRINT "Hello from 0."  
BARRIER  
IF myPE=1 PRINT "Hello from 1."  
BARRIER  
IF myPE=2 PRINT "Hello from 2."  
BARRIER  
IF myPE=3 PRINT "Hello from 3."  
BARRIER  
IF myPE=4 PRINT "Hello from 4."  
BARRIER  
IF myPE=5 PRINT "Hello from 5."  
BARRIER  
IF myPE=6 PRINT "Hello from 6."  
BARRIER  
IF myPE=7 PRINT "Hello from 7."
```

Would this print in order?

What if one PE was 1,000,000 times faster than another?

Step 3: Print in order...

Now let's be lazy:

```
FOR X = 0 to 7
  IF MyPE = X
    PRINT "Hello from MyPE."
  BARRIER
```

Step 3 – Master, Slave

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

main(int argc, char** argv){

    int my_PE_num, numbertoreceive, numbertosend=4,index, result=0;
    MPI_Status status;

    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);

    if (my_PE_num==0)
        for (index=1; index<4; index++){
            MPI_Send( &numbertosend, 1,MPI_INT, index, 10,MPI_COMM_WORLD);
        }
    else{
        MPI_Recv( &numbortoreceive, 1, MPI_INT, 0, 10, MPI_COMM_WORLD, &status);
        result = numbortoreceive * my_PE_num;
    }

    for (index=1; index<4; index++){
        MPI_Barrier(MPI_COMM_WORLD);
        if (index==my_PE_num) printf("PE %d's result is %d.\n", my_PE_num, result);
    }

    if (my_PE_num==0){
        for (index=1; index<4; index++){
            MPI_Recv( &numbortoreceive, 1,MPI_INT,index,10, MPI_COMM_WORLD, &status);
            result += numbortoreceive;
        }
        printf("Total is %d.\n", result);
    }
    else
        MPI_Send( &result, 1, MPI_INT, 0, 10, MPI_COMM_WORLD);

    MPI_Finalize();
}
```


Step 4 – Master, Slave

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

main(int argc, char** argv){

    int my_PE_num, numbertoreceive, numbertosend=4,index, result=0;
    MPI_Status status;

    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);

    if (my_PE_num==0)
        for (index=1; index<4; index++){
            MPI_Send( &numbertosend, 1,MPI_INT, index, 10,MPI_COMM_WORLD);
        }
    else{
        MPI_Recv( &numbortoreceive, 1, MPI_INT, 0, 10, MPI_COMM_WORLD, &status);
        result = numbortoreceive * my_PE_num;
    }

    for (index=1; index<4; index++){
        MPI_Barrier(MPI_COMM_WORLD);
        if (index==my_PE_num) printf("PE %d's result is %d.\n", my_PE_num, result);
    }

    if (my_PE_num==0){
        for (index=1; index<4; index++){
            MPI_Recv( &numbortoreceive, 1,MPI_INT,index,10, MPI_COMM_WORLD, &status);
            result += numbortoreceive;
        }
        printf("Total is %d.\n", result);
    }
    else
        MPI_Send( &result, 1, MPI_INT, 0, 10, MPI_COMM_WORLD);

    MPI_Finalize();
}
```

Step 5 – Master, Slave

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

main(int argc, char** argv){

    int my_PE_num, numbertoreceive, numbertosend=4,index, result=0;
    MPI_Status status;

    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_PE_num);

    if (my_PE_num==0)
        for (index=1; index<4; index++){
            MPI_Send( &numbertosend, 1,MPI_INT, index, 10,MPI_COMM_WORLD);
        }
    else{
        MPI_Recv( &numbortoreceive, 1, MPI_INT, 0, 10, MPI_COMM_WORLD, &status);
        result = numbortoreceive * my_PE_num;
    }

    for (index=1; index<4; index++){
        MPI_Barrier(MPI_COMM_WORLD);
        if (index==my_PE_num) printf("PE %d's result is %d.\n", my_PE_num, result);
    }

    if (my_PE_num==0){
        for (index=1; index<4; index++){
            MPI_Recv( &numbortoreceive, 1,MPI_INT,index,10, MPI_COMM_WORLD, &status);
            result += numbortoreceive;
        }
        printf("Total is %d.\n", result);
    }
    else
        MPI_Send( &result, 1, MPI_INT, 0, 10, MPI_COMM_WORLD);

    MPI_Finalize();
}
```

Step 1 – Master, Slave

```
program synch
implicit none

include 'mpif.h'

integer my_pe_num, errcode, numbertoreceive, numbertosend
integer index, result
integer status(MPI_STATUS_SIZE)

call MPI_INIT(errcode)
call MPI_COMM_RANK(MPI_COMM_WORLD, my_pe_num, errcode)

numbertosend = 4
result = 0

if (my_pe_num.EQ.0) then
  do index=1,3
    call MPI_Send( numbertosend, 1, MPI_INTEGER, index, 10, MPI_COMM_WORLD, errcode)
  enddo
else
  call MPI_Recv( numbertoreceive, 1, MPI_INTEGER, 0, 10, MPI_COMM_WORLD, status, errcode)
  result = numbertoreceive * my_pe_num
endif

do index=1,3
  call MPI_Barrier(MPI_COMM_WORLD, errcode)
  if (my_pe_num.EQ.index) then
    print *, 'PE ',my_pe_num,'s result is ',result,','
  endif
enddo

if (my_pe_num.EQ.0) then
  do index=1,3
    call MPI_Recv( numbertoreceive, 1, MPI_INTEGER, index,10, MPI_COMM_WORLD, status, errcode)
    result = result + numbertoreceive
  enddo
  print *, 'Total is ',result,','
else
  call MPI_Send( result, 1, MPI_INTEGER, 0, 10, MPI_COMM_WORLD, errcode)
endif

call MPI_FINALIZE(errcode)
end
```

Step 2 – Master, Slave

```
program synch
implicit none

include 'mpif.h'

integer my_pe_num, errcode, numbertoreceive, numbertosend
integer index, result
integer status(MPI_STATUS_SIZE)

call MPI_INIT(errcode)
call MPI_COMM_RANK(MPI_COMM_WORLD, my_pe_num, errcode)

numbertosend = 4
result = 0

if (my_pe_num.EQ.0) then
  do index=1,3
    call MPI_Send( numbertosend, 1, MPI_INTEGER, index, 10, MPI_COMM_WORLD, errcode)
  enddo
else
  call MPI_Recv( numbertoreceive, 1, MPI_INTEGER, 0, 10, MPI_COMM_WORLD, status, errcode)
  result = numbertoreceive * my_pe_num
endif

do index=1,3
  call MPI_Barrier(MPI_COMM_WORLD, errcode)
  if (my_pe_num.EQ.index) then
    print *, 'PE ',my_pe_num,'s result is ',result,','
  endif
enddo

if (my_pe_num.EQ.0) then
  do index=1,3
    call MPI_Recv( numbertoreceive, 1, MPI_INTEGER, index,10, MPI_COMM_WORLD, status, errcode)
    result = result + numbertoreceive
  enddo
  print *,'Total is ',result,','
else
  call MPI_Send( result, 1, MPI_INTEGER, 0, 10, MPI_COMM_WORLD, errcode)
endif

call MPI_FINALIZE(errcode)
end
```

Step 3 – Master, Slave

```
program synch
implicit none

include 'mpif.h'

integer my_pe_num, errcode, numbertoreceive, numbertosend
integer index, result
integer status(MPI_STATUS_SIZE)

call MPI_INIT(errcode)
call MPI_COMM_RANK(MPI_COMM_WORLD, my_pe_num, errcode)

numbertosend = 4
result = 0

if (my_pe_num.EQ.0) then
  do index=1,3
    call MPI_Send( numbertosend, 1, MPI_INTEGER, index, 10, MPI_COMM_WORLD, errcode)
  enddo
else
  call MPI_Recv( numbertoreceive, 1, MPI_INTEGER, 0, 10, MPI_COMM_WORLD, status, errcode)
  result = numbertoreceive * my_pe_num
endif

do index=1,3
  call MPI_Barrier(MPI_COMM_WORLD, errcode)
  if (my_pe_num.EQ.index) then
    print *, 'PE ',my_pe_num,'s result is ',result,','
  endif
enddo

if (my_pe_num.EQ.0) then
  do index=1,3
    call MPI_Recv( numbertoreceive, 1, MPI_INTEGER, index,10, MPI_COMM_WORLD, status, errcode)
    result = result + numbertoreceive
  enddo
  print *,'Total is ',result,','
else
  call MPI_Send( result, 1, MPI_INTEGER, 0, 10, MPI_COMM_WORLD, errcode)
endif

call MPI_FINALIZE(errcode)
end
```

Step 4 – Master, Slave

```
program synch
implicit none

include 'mpif.h'

integer my_pe_num, errcode, numbertoreceive, numbertosend
integer index, result
integer status(MPI_STATUS_SIZE)

call MPI_INIT(errcode)
call MPI_COMM_RANK(MPI_COMM_WORLD, my_pe_num, errcode)

numbertosend = 4
result = 0

if (my_PE_num.EQ.0) then
  do index=1,3
    call MPI_Send( numbertosend, 1, MPI_INTEGER, index, 10, MPI_COMM_WORLD, errcode)
  enddo
else
  call MPI_Recv( numbertoreceive, 1, MPI_INTEGER, 0, 10, MPI_COMM_WORLD, status, errcode)
  result = numbertoreceive * my_PE_num
endif

do index=1,3
  call MPI_Barrier(MPI_COMM_WORLD, errcode)
  if (my_PE_num.EQ.index) then
    print *, 'PE ',my_PE_num,'s result is ',result,','
  endif
enddo

if (my_PE_num.EQ.0) then
  do index=1,3
    call MPI_Recv( numbertoreceive, 1, MPI_INTEGER, index,10, MPI_COMM_WORLD, status, errcode)
    result = result + numbertoreceive
  enddo
  print *,'Total is ',result,','
else
  call MPI_Send( result, 1, MPI_INTEGER, 0, 10, MPI_COMM_WORLD, errcode)
endif

call MPI_FINALIZE(errcode)
end
```

Step 5 – Master, Slave

```
program synch
implicit none

include 'mpif.h'

integer my_pe_num, errcode, numbertoreceive, numbertosend
integer index, result
integer status(MPI_STATUS_SIZE)

call MPI_INIT(errcode)
call MPI_COMM_RANK(MPI_COMM_WORLD, my_pe_num, errcode)

numbertosend = 4
result = 0

if (my_pe_num.EQ.0) then
  do index=1,3
    call MPI_Send( numbertosend, 1, MPI_INTEGER, index, 10, MPI_COMM_WORLD, errcode)
  enddo
else
  call MPI_Recv( numbertoreceive, 1, MPI_INTEGER, 0, 10, MPI_COMM_WORLD, status, errcode)
  result = numbertoreceive * my_pe_num
endif

do index=1,3
  call MPI_Barrier(MPI_COMM_WORLD, errcode)
  if (my_pe_num.EQ.index) then
    print *, 'PE ',my_pe_num,'s result is ',result,','
  endif
enddo

if (my_pe_num.EQ.0) then
  do index=1,3
    call MPI_Recv( numbertoreceive, 1, MPI_INTEGER, index,10, MPI_COMM_WORLD, status, errcode)
    result = result + numbertoreceive
  enddo
  print *,'Total is ',result,','
else
  call MPI_Send( result, 1, MPI_INTEGER, 0, 10, MPI_COMM_WORLD, errcode)
endif

call MPI_FINALIZE(errcode)
end
```

Results of “Synchronization”

The output you get when running this codes with 4 PEs is:

```
PE 1's result is 4.  
PE 2's result is 8.  
PE 3's result is 12.  
Total is 24
```


Analysis of “Synchronization”

The best way to make sure that you understand what is happening in the code above is to look at things from the perspective of each PE in turn. THIS IS THE WAY TO DEBUG ANY MESSAGE-PASSING CODE.

Follow from the top to the bottom of the code as PE 0, and do likewise for PE 1. See exactly where one PE is dependent on another to proceed. Look at each PE's progress as though it is 100 times faster or slower than the other nodes. Would this affect the final program flow? It shouldn't unless you made assumptions that are not always valid.

Final Example: Beyond the Basics

You now have the 4 primitives that you need to write any algorithm. However, there are much more efficient ways to accomplish certain tasks, both in terms of typing and computing.

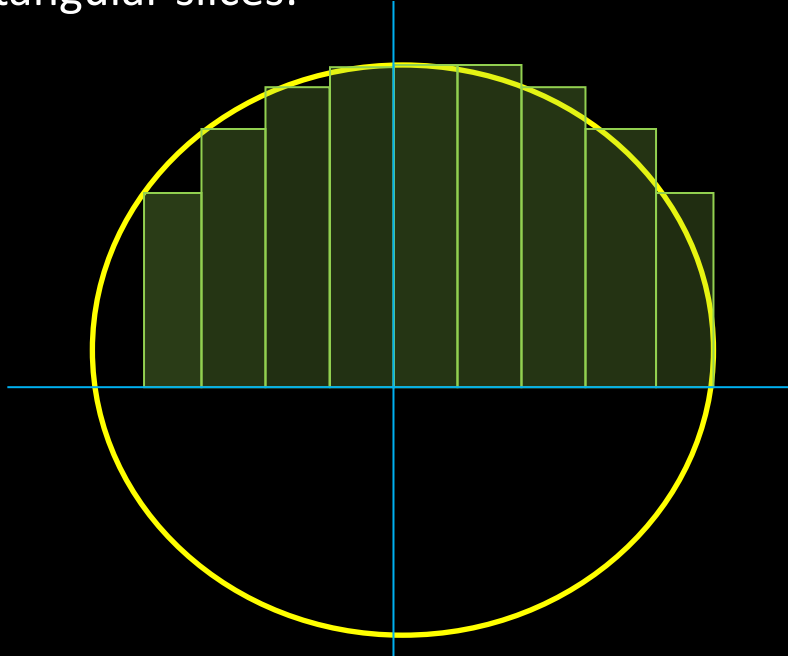
We will look at a few very useful and common routines (reduction, broadcasts, and `Comm_Size`) as we do a final example.

You will then be a full-fledged (or maybe fledgling) MPI programmer.

Final Example: Finding Pi

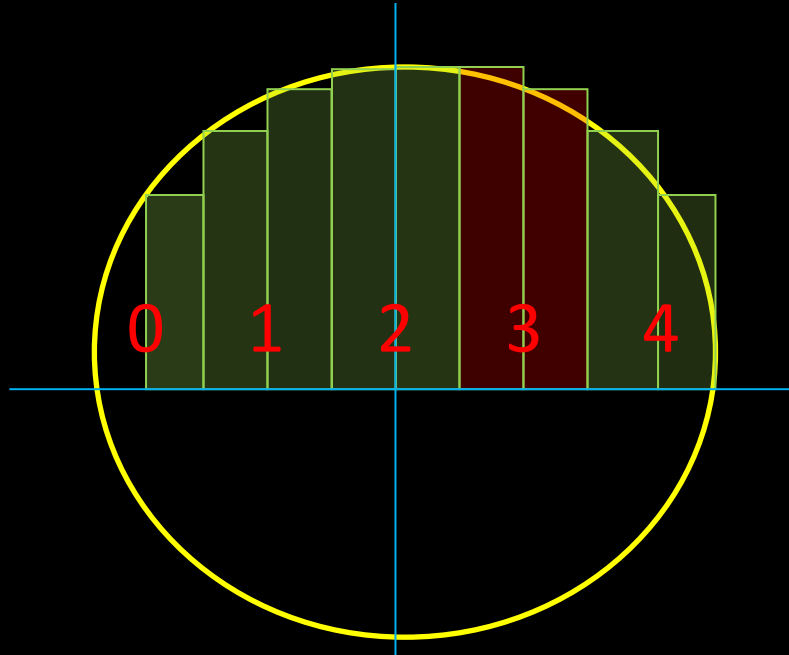
Our last example will find the value of pi by integrating over the area of a circle of radius 1. We just use the fact that the Area = πR^2 and that the equation for such a circle is $x^2 + y^2 = 1$.

We will use the standard (and classic serial) method of finding the area under a curve by adding up a bunch of rectangular slices:



Final Example: Finding Pi

We can parallelize this very effectively by just having a number of PE's work on subsections and add up their final results. With 5 PE's, we should expect it to take roughly 1/5 as long to reach an answer.



Final Example: Finding Pi

We could easily do this with the commands we have in hand. However, this is a good time to introduce a few of the more common and powerful additional MPI commands: broadcast and reduce.

`MPI_Bcast()` is very useful when we want to communicate some common data to every PE. We know we can do this with a loop, as in the previous example, but with Bcast we not only save some typing and make the code more readable, but we enable the hardware to use a much more efficient broadcast mode. Picture the difference between me giving you each this lecture point-to-point, or “broadcasting” to you all as I am.

We use `MPI_Bcast()` here to let all of the nodes know how many intervals the user would like to employ for the approximation. You will find yourself using it frequently.

Final Example: Finding Pi

We also need to add together each PE's partial sum. We just did something like this in the previous example, but once again we find that MPI provides us with a command that saves typing and is makes more efficient use of the hardware.

`MPI_Reduce()` allows us to do this loop with one command. However, it can be used for more than just adding numbers. Other common operations are mins and maxes, but there are plenty more.

Note that both Bcast and Reduce require all of the PE's to participate, and require you to designate one particular PE as the sender or collector. This will often be 0 if it is the master PE.

Finding Pi

```
#include <mpi.h>
#include <math.h>

int main( int argc, char **argv ){
    int    n, my_pe_num, numprocs, index;
    float  mypi, pi, h, x, start, end;

    MPI_Init(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &numprocs );
    MPI_Comm_rank(MPI_COMM_WORLD, &my_pe_num );

    if( my_pe_num == 0 ){
        printf("How many intervals? ");
        scanf("%d", &n);
    }

    MPI_Bcast(&n, 1, MPI_INT, 0, MPI_COMM_WORLD);

    mypi = 0;
    h= (float) 2/n; /*Size of each slice*/
    start = (my_pe_num*2/numprocs)-1; /*Slices for this PE*/
    end   = ((my_pe_num+1)*2/numprocs)-1;

    for (x = start; x < end; x = x+h)
        mypi = mypi + h * 2* sqrt(1-x*x);

    MPI_Reduce(&mypi, &pi, 1, MPI_FLOAT, MPI_SUM, 0, MPI_COMM_WORLD);

    if( my_pe_num == 0 ){
        printf("Pi is approximately %f\n", pi);
        printf("Error is %f\n", pi-3.14159265358979323846);
    }

    MPI_Finalize();
}
```

Just what you would guess.



Do Not Make Any Assumptions

Do not make any assumptions about the mechanics of the actual message-passing. Remember that MPI is designed to operate not only on fast MPP networks, but also on Internet size meta-computers. As such, the order and timing of messages may be considerably skewed.

MPI makes only one guarantee: two messages sent from one process to another process will arrive in that relative order. However, a message sent later from another process may arrive before, or between, those two messages.

Remember that buffer sizes, as well as the data chunks you want to communicate, can change greatly from one platform or run to the next. You may have to use the non-blocking calls to accommodate these limits and avoid deadlocks.

References

There are a wide variety of materials available on the Web, some of which are intended to be used as hardcopy manuals and tutorials. A good starting point for documents is the MPI Forum Docs page:

<http://www.mpi-forum.org/docs/docs.html>

A good index of MPI man pages can be found at:

<http://www.mpich.org/static/docs/latest/www3/>

Two very useful books:

- *Using MPI: portable parallel programming with the message-passing interface (third edition)*. William Gropp, Ewing Lusk, Anthony Skjellum. MIT Press
- *Using Advanced MPI*. Gropp, Hoefler, Thakur and Lusk. MIT Press

Why Not Use MPI?

While I hope you are all excited about trying out the exercises because this stuff isn't really all that intimidating, it wouldn't be fair if I didn't explain why this might not always be the answer to all of life's problems:

- **You will likely have to rewrite portions in all areas of your code.**
 - Old, dusty subroutines written by a long-departed grad student.
- **You will have to understand almost all of your code.**
 - Old, dusty subroutines written by a long-departed grad student.
- **You can't do it incrementally.**
 - Major data structures have to be decomposed up front.
- **Debugging will be “different”.**
 - You aren't just finding the bad line of code. You sometimes need to find the bad PE.

So, full disclosure aside, let's start writing some massively parallel code...

Exercises

Exercise 1: Write a code that runs on 8 PEs and does a “circular shift.” This means that every PE sends some data to its nearest neighbor either “up” (one PE higher) or “down.” To make it circular, PE 7 and PE 0 are treated as neighbors. Make sure that whatever data you send is received.

Exercise 2: Write, using only the routines that we have covered in the first three examples, (MPI_Init, MPI_Comm_Rank, MPI_Send, MPI_Recv, MPI_Barrier, MPI_Finalize) a program that determines how many PEs it is running on. It should perform as the following:

```
mpirun -n 4 exercise  
I am running on 4 PEs.
```

```
mpirun -n 16 exercise  
I am running on 16 PEs.
```

You would normally obtain this information with the simple *MPI_Comm_size()* routine. The solution may not be as simple as it first seems. Remember, make no assumptions about when any given message may be received.

Exercises Summary

A concise index of all MPI calls, with each parameter described is:

<http://www.mpich.org/static/docs/latest/www3/>

Exercise 1: Write a code that runs on 8 PEs and does a “circular shift.”

Exercise 2: Write (using only `MPI_Init`, `MPI_Comm_Rank`, `MPI_Send`, `MPI_Recv`, `MPI_Barrier`, and `MPI_Finalize`) a program that determines how many PEs it is running on.

Example session for Exercise 2 (after you’ve edited *your_program.c* into existence):

```
% interact                if you aren't already on a compute node (and interact -n28 normally)
% mpicc your_program.c    or  mpif90 your_program.f90
% mpirun -n 4 a.out
I am running on 4 PEs.
%
```