CIS 631
Parallel Processing

Lecture 6: Message Passing
Programming and MPI

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Acknowledgements

☐ Portions of the lectures slides were adopted from:
  ☐ Argonne National Laboratory, MPI tutorials, 
  ☐ Lawrence Livermore National Laboratory, MPI tutorials.
Outline

☐ Background
  ☐ The message-passing model
  ☐ Origins of MPI and current status
  ☐ Sources of further MPI information

☐ Basics of MPI message passing
  ☐ Hello, World!
  ☐ Fundamental concepts
  ☐ Simple examples in Fortran and C

☐ Extended point-to-point operations
  ☐ non-blocking communication
  ☐ modes
The Message-Passing Model

- A process is a program counter and address space
- Processes may have multiple threads (program counters and associated stacks) sharing a single address space
- MPI is for communication among processes (not threads)
- Interprocess communication consists of
  - Synchronization
  - Data movement
Types of Parallel Computing Models

- Data parallel
  - Simultaneous execution on multiple data items
  - Single Instruction, Multiple Data (SIMD) is a type
- Task parallel
  - different instructions on different data (MIMD)
- SPMD (Single Program, Multiple Data)
  - Combination of data parallel and task parallel
  - Not synchronized at individual operation level
- Message passing is for MIMD/SPMD parallelism
  - Can be used for data parallel programming
Parallel Architecture Models and MPI

- Shared memory architectures
  - Parallel execution via shared memory
  - Bus-based or hierarchical memory systems
  - Distributed shared memory
  - Data coherency issues

- Distributed memory architectures
  - Communication-base parallel execution
  - Communication networks
  - Scalable

- MPI targeted for distributed memory architectures
  - Can also run on shared memory machines
Message Passing Programming

- Defined by communication requirements
  - Data communication
  - Control communication
- Program behavior determined by communication patterns
- Message passing infrastructure attempts to support the forms of communication most often used or desired
  - Basic forms provide functional access
    - Can be used most often
  - Complex form provide higher-level abstractions
    - Serve as basis for extension
  - Extensions for greater programming power
Cooperative Operations for Communication

- Data is cooperatively exchanged in message-passing
- Explicitly sent by one process and received by another
- Advantage of local control of memory
  - Any change in the receiving process’s memory is made with the receiver’s explicit participation
- Communication and synchronization are combined

![Diagram showing communication between processes](image-url)

- Process 0
  - Send(data)
- Process 1
  - Receive(data)

- time
One-Sided Operations for Communication

- One-sided operations between processes
  - Include remote memory reads and writes
- Only one process needs to explicitly participate
- Advantages?
  - Communication and synchronization are decoupled

Process 0

\[ \text{Put(data)} \]

\[ \text{(memory)} \]

Process 1

\[ \text{(memory)} \]

\[ \text{Get(data)} \]

\[ \text{time} \]
Pairwise vs. Collective Communication

- Communication between process pairs
  - Send/Receive or Put/Get
  - Synchronous or asynchronous (we’ll talk about this later)

- Collective communication between multiple processes
  - Process group (collective)
    - Several processes logically grouped together
  - Communication within group
  - Collective operations
    - Communication patterns
      - broadcast, multicast, subset, scatter/gather, …
    - Reduction operations
What is MPI (Message Passing Interface)?

- Message-passing library (interface) specification
  - Extended message-passing model
  - Not a language or compiler specification
  - Not a specific implementation or product
- Targeted for parallel computers, clusters, and NOWs
- Specified in C, C++, Fortran 77, F90
- Full-featured and robust
- Designed to access to advanced parallel hardware
  - End users
  - Library writers
  - Tool developers
Why Use MPI?

- Message passing is a mature parallel programming model
  - Well understood
  - Efficient to match to hardware
  - Many applications
- MPI provides a powerful, efficient, and portable way to express parallel programs
- MPI was explicitly designed to enable libraries…
- … which may eliminate the need for many users to learn (much of) MPI
- Need standard, rich, and robust implementation
Features of MPI

- General
  - Communicators combine context and group for security
  - Thread safety

- Point-to-point communication
  - Structured buffers and derived datatypes, heterogeneity
  - Modes: normal, synchronous, ready, buffered

- Collective
  - Both built-in and user-defined collective operations
  - Large number of data movement routines
  - Subgroups defined directly or by topology
Features of MPI (continued)

- Application-oriented process topologies
  - Built-in support for grids and graphs (based on groups)
- Profiling
  - Hooks allow users to intercept MPI calls
- Environmental
  - Inquiry
  - Error control
Features not in MPI-1

- Non-message-passing concepts not included:
  - Process management
  - Remote memory transfers
  - Active messages
  - Threads
  - Virtual shared memory
- MPI does not address these issues, but has tried to remain compatible with these ideas
  - E.g., thread safety as a goal
- Some of these features are in MPI-2
Is MPI Large or Small?

- MPI is large
  - MPI-1 is 128 functions, MPI-2 is 152 functions
  - Extensive functionality requires many functions
  - Not necessarily a measure of complexity

- MPI is small (6 functions)
  - Many parallel programs use just 6 basic functions

- “MPI is just right,” said Baby Bear
  - One can access flexibility when it is required
  - One need not master all parts of MPI to use it
Where to Use or Not Use MPI?

- **USE**
  - You need a portable parallel program
  - You are writing a parallel library
  - You have irregular or dynamic data relationships that do not fit a data parallel model
  - You care about performance

- **NOT USE**
  - You can use HPF or a parallel Fortran 90
  - You don’t need parallelism at all
  - You can use libraries (which may be written in MPI)
  - You need simple threading in a concurrent environment
Getting Started

- Writing MPI programs
- Compiling and linking
- Running MPI programs
A Simple MPI Program (C)

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

int main( int argc, char *argv[] )
{
    MPI_Init( &argc, &argv );
    printf( "Hello, world!\n" );
    MPI_Finalize();
    return 0;
}
```

What does this program do?
A Simple MPI Program (C++)

```cpp
#include <iostream.h>
#include "mpi++.h"

int main( int argc, char *argv[] )
{
    MPI::Init(argc,argv);
    cout << "Hello, world!" << endl;
    MPI::Finalize();
    return 0;
}
```
A Minimal MPI Program (Fortran)

program main
use MPI
integer ierr

call MPI_INIT( ierr )
print *, 'Hello, world!'
call MPI_FINALIZE( ierr )
end
**Notes on C and Fortran**

- C and Fortran library bindings correspond closely
- In C:
  - mpi.h must be #included
  - MPI functions return error codes or **MPI_SUCCESS**
- In Fortran:
  - mpif.h must be included, or use MPI module (MPI-2)
  - All MPI calls are to subroutines
    - place for the return code in the last argument
- C++ bindings, and Fortran-90 issues, are part of MPI-2
Error Handling

- By default, an error causes all processes to abort
- The user can cause routines to return (with an error code)
  - In C++, exceptions are thrown (MPI-2)
- A user can also write and install custom error handlers
- Libraries may handle errors differently from applications
Running MPI Programs

- MPI-1 does not specify how to run an MPI program
- Starting an MPI program is dependent on implementation
  - Scripts, program arguments, and/or environment variables

- `mpiexec <args>`
  - Recommended part of MPI-2, as a recommendation
  - `mpiexec` for MPICH (distribution from ANL)
  - `mpirun` for SGI’s MPI
Finding Out About the Environment

- Two important questions that arise in message passing
  - How many processes are being use in computation?
  - Which one am I?
- MPI provides functions to answer these questions
  - `MPI_Comm_size` reports the number of processes
  - `MPI_Comm_rank` reports the rank
    - number between 0 and size-1
    - identifies the calling process
Better “Hello World” (C)

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

int main( 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( "I am %d of %d\n", rank, size );
    MPI_Finalize();
    return 0;
}
```

square ¿ What does this program do and why is it better?
Better “Hello World” (Fortran)

program main
use MPI
integer ierr, rank, size

call MPI_INIT( ierr )
call MPI_COMM_RANK( MPI_COMM_WORLD, rank, ierr )
call MPI_COMM_SIZE( MPI_COMM_WORLD, size, ierr )
print *, 'I am ', rank, ' of ', size
call MPI_FINALIZE( ierr )
end
MPI Basic Send/Receive

☐ We need to fill in the details in

Process 0  Process 1

\(\text{Send(data)}\)  \(\text{Receive(data)}\)

time

☐ Things that need specifying:

- How will “data” be described?
- How will processes be identified?
- How will the receiver recognize/screen messages?
- What will it mean for these operations to complete?
What is message passing?

- Data transfer plus synchronization

  Process 0

  **Data**

  May I Send?

  Process 1

  Yes

  Data

  Time

- Requires cooperation of sender and receiver
- Cooperation not always apparent in code
Some Basic Concepts

- Processes can be collected into *groups*
- Each message is sent in a *context*
  - Must be received in the same context
- A group and context together form a *communicator*
- A process is identified by its *rank*
  - With respect to the group associated with a communicator
- There is a default communicator **MPI_COMM_WORLD**
  - Contains all initial processes
**MPI Datatypes**

- Message data (sent or received) is described by a triple
  - address, count, datatype
- An MPI *datatype* is recursively defined as:
  - Predefined data type from the language
  - A contiguous array of MPI datatypes
  - A strided block of datatypes
  - An indexed array of blocks of datatypes
  - An arbitrary structure of datatypes
- There are MPI functions to construct custom datatypes
  - Array of (int, float) pairs
  - Row of a matrix stored columnwise
**MPI Tags**

- Messages are sent with an accompanying user-defined integer *tag*
  - Assist the receiving process in identifying the message
- Messages can be screened at the receiving end by specifying a specific tag
  - `MPI_ANY_TAG` matches any tag in a receive
- Tags are sometimes called “message types”
  - MPI calls them “tags” to avoid confusion with datatypes
MPI Basic (Blocking) Send

MPI_SEND (start, count, datatype, dest, tag, comm)

- The message buffer is described by
  - start, count, datatype
- The target process is specified by dest
  - rank of the target process in the communicator specified by comm
- When this function returns
  - data has been delivered to the system
  - buffer can be reused
- Message may not have been received by target process
MPI Basic (Blocking) Receive

MPI_RECV(start, count, datatype, source, tag, comm, status)

- Waits until a matching message is received from system
  - Matches on source and tag
  - Buffer must be available
- source is rank in communicator specified by comm
  - Or MPI_ANY_SOURCE
- Status contains further information
- Receiving fewer than count is OK, more is not
Retrieving Further Information

- Status is a data structure allocated in the user’s program.
- In C:

```c
int recvd_tag, recvd_from, recvd_count;
MPI_Status status;
MPI_Recv(..., MPI_ANY_SOURCE, MPI_ANY_TAG, ..., &status)
recvd_tag = status.MPI_TAG;
recvd_from = status.MPI_SOURCE;
MPI_Get_count(&status, datatype, &recvd_count);
```
Simple Fortran Example - 1

```fortran
program main
use MPI

integer rank, size, to, from, tag, count, i, ierr
integer src, dest
integer st_source, st_tag, st_count
integer status(MPI_STATUS_SIZE)
double precision data(10)

call MPI_INIT( ierr )
call MPI_COMM_RANK( MPI_COMM_WORLD, rank, ierr )
call MPI_COMM_SIZE( MPI_COMM_WORLD, size, ierr )
print *, 'Process ', rank, ' of ', size, ' is alive'
dest = size - 1
src = 0
```
Simple Fortran Example - 2

if (rank .eq. 0) then
    do 10, i=1, 10
        data(i) = i
    10 continue
    call MPI_SEND( data, 10, MPI_DOUBLE_PRECISION, 
                   dest, 2001, MPI_COMM_WORLD, ierr)
else if (rank .eq. dest) then
    tag = MPI_ANY_TAG
    source = MPI_ANY_SOURCE
    call MPI_RECV( data, 10, MPI_DOUBLE_PRECISION, 
                   source, tag, MPI_COMM_WORLD, 
                   status, ierr)
Simple Fortran Example - 3

call MPI_GET_COUNT( status, MPI_DOUBLE_PRECISION,
                    st_count, ierr )

st_source = status( MPI_SOURCE )
st_tag = status( MPI_TAG )
print *, 'status info: source = ', st_source,
        ' tag = ', st_tag, 'count = ', st_count

endif

call MPI_FINALIZE( ierr )
end
Why Datatypes?

- All data is labeled by type in MPI
- Enables heterogeneous communication
  - Support communication between processes on machines with different memory representations and lengths of elementary datatypes
- Allows application-oriented layout of data in memory
  - Reduces memory-to-memory copies in implementation
  - Allows use of special hardware (scatter/gather)
Tags and Contexts

- Separation of messages by use of tags
  - Requires libraries to be aware of tags of other libraries
  - This can be defeated by use of “wild card” tags

- Contexts are different from tags
  - No wild cards allowed
  - Allocated dynamically by the system
  - When a library sets up a communicator for its own use

- User-defined tags still provided in MPI
  - For user convenience in organizing application

- Use `MPI_Comm_split` to create new communicators
Many parallel programs can be written using:

- `MPI_INIT()`
- `MPI_FINALIZE()`
- `MPI_COMM_SIZE()`
- `MPI_COMM_RANK()`
- `MPI_SEND()`
- `MPI_RECV()`

Point-to-point (send/recv) isn’t the only way...

- Add more support for communication
Introduction to Collective Operations in MPI

- Called by all processes in a communicator

- **MPI_BCAST**
  - Distributes data from one process (the root) to all others

- **MPI_REDUCE**
  - Combines data from all processes in communicator
  - Returns it to one process

- In many numerical algorithms, **SEND/RECEIVE** can be replaced by **BCAST/REDUCE**, improving both simplicity and efficiency.
Example: *PI in Fortran - 1*

```fortran
program main
use MPI
double precision  PI25DT
parameter (PI25DT = 3.141592653589793238462643d0)
double precision  mypi, pi, h, sum, x, f, a
integer n, myid, numprocs, i, ierr

! function to integrate
f(a) = 4.d0 / (1.d0 + a*a)
call MPI_INIT( ierr )
call MPI_COMM_RANK( MPI_COMM_WORLD, myid, ierr )
call MPI_COMM_SIZE( MPI_COMM_WORLD, numprocs, ierr )

10 if ( myid .eq. 0 ) then
   write(6,98)
98     format('Enter the number of intervals: (0 quits)')
   read(5,99) n
99     format(i10)
endif
```

Lecture 6
Example: PI in Fortran - 2

call MPI_BCAST( n, 1, MPI_INTEGER, 0,
+               MPI_COMM_WORLD, ierr)

c check for quit signal
if ( n .le. 0 ) goto 30

c calculate the interval size
h = 1.0d0/n
sum  = 0.0d0
do 20 i = myid+1, n, numprocs
   x   = h * (dble(i) - 0.5d0)
   sum = sum + f(x)
20   continue
mypi = h * sum

c collect all the partial sums
   call MPI_REDUCE( mypi, pi, 1, MPI_DOUBLE_PRECISION,
+                 MPI_SUM, 0, MPI_COMM_WORLD,ierr)
Example: PI in Fortran - 3

c

node 0 prints the answer

if (myid .eq. 0) then
    write(6, 97) pi, abs(pi - PI25DT)
97    format(' pi is approximately: ', F18.16, +       ' Error is: ', F18.16)
    endif
  goto 10
  goto 10
30  call MPI_FINALIZE(ierr)
end
Example: PI in C -1

```c
#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;
    }
    MPI_Finalize();
}
```

Lecture 6


Example: \textit{PI in C - 2}

\begin{verbatim}

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
", pi, fabs(pi - PI25DT));

 MPI_Finalize();
return 0;
\end{verbatim}

\end{document}
Alternative set of 6 Functions for Simplified MPI

- Replace send and receive functions
  - `MPI_INIT`
  - `MPI_FINALIZE`
  - `MPI_COMM_SIZE`
  - `MPI_COMM_RANK`
  - `MPI_BCAST`
  - `MPI_REDUCE`

- What else is needed (and why)?
Need to be Careful with Communication

- Send a large message from process 0 to process 1
  - If there is insufficient storage at the destination, the send must wait for the user to provide the memory space (through a receive)

<table>
<thead>
<tr>
<th>Process 0</th>
<th>Process 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Send (1)</td>
<td>Send (0)</td>
</tr>
<tr>
<td>Recv (1)</td>
<td>Recv (0)</td>
</tr>
</tbody>
</table>

- This is unsafe because it depends on availability of system buffers
Some Solutions to the “unsafe” Problem

☐ Order the operations more carefully:

<table>
<thead>
<tr>
<th>Process 0</th>
<th>Process 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Send(1)</td>
<td>Recv(0)</td>
</tr>
<tr>
<td>Recv(1)</td>
<td>Send(0)</td>
</tr>
</tbody>
</table>

☐ Use non-blocking operations

<table>
<thead>
<tr>
<th>Process 0</th>
<th>Process 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isend(1)</td>
<td>Isend(0)</td>
</tr>
<tr>
<td>Irecv(1)</td>
<td>Irecv(0)</td>
</tr>
<tr>
<td>Waitall</td>
<td>Waitall</td>
</tr>
</tbody>
</table>
Toward a Portable MPI Environment (MPICH)

- MPICH is a high-performance portable implementation
- It runs on MPP's, clusters, and heterogeneous NOWs
- In a wide variety of environments, one can do:
  - configure
  - make
  - mpicc -mpitrace myprog.c
  - mpirun -np 10 myprog
  - upshot myprog.log
  - to build, compile, run, and analyze performance.
Extending the Message-Passing Interface

- Dynamic Process Management
  - Dynamic process startup
  - Dynamic establishment of connections
- One-sided communication
  - Put/get
  - Other operations
- Parallel I/O
- Other MPI-2 features
  - Generalized requests
  - Bindings for C++/ Fortran-90; interlanguage issues
Summary

- The parallel computing community has cooperated on the development of a standard for message-passing libraries
- There are many implementations, on nearly all platforms
- MPI subsets are easy to learn and use
- Lots of MPI material is available
Next Class

☐ More MPI
Exercise 2 – Communication Patterns

- Create code skeletons for four communication patterns:
  - Master - slave
  - Ring
  - Binary tree
  - 2D nearest-neighbor

- Implement for general number of processes
- Develop testcases to demonstrate on NIC cluster
Project 1 – Conway’s Game of Life in 3D

- Develop 3D version of Conway’s Game of Life
  - Simulates life evolution
  - “Cells” live or die with each simulation timestep
  - Rules govern healthiness

- Strategy
  - Domain decomposition on 3D regular volume
  - Nearest neighbor communication (rules govern nearness)

- Visualization of simulation execution
  - Requires global communication at periodic timesteps