COMS3008A: Parallel Computing
Introduction to MPI I

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Contents

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Expected Learning Outcome

- Understanding message passing programming model
- Apply the basic set of MPI functions to write simple MPI programs
- Compile and run MPI program on a cluster

Outline

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Message Passing Model

- The usual underlying hardware: a collection of processors, each with its own local memory (or address space).
- A process: a task
  - A process is (traditionally) a program counter and address space.
  - Processes may have multiple threads (program counters and associated stacks) sharing a single address space.
- Every process can communicate with every other processes.

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MPI

- MPI (Message Passing Interface) standard is the most popular message passing specification that supports parallel programming.
- MPI is a message passing library specification.
- MPI is for communication among processes, which have separate address spaces.
- Inter-process communication consists of
  - synchronization
  - movement of data from one process' address space to another's.

The Message Passing Model and MPI Contd.

- MPI is not
  - a language or compiler specification
  - a specific implementation or product
- MPI is for parallel computers, clusters, and heterogeneous networks.
- MPI versions:
  - MPI-1 supports the classical message-passing programming model: basic point-to-point communication, collectives, datatypes, etc. MPI-1 was defined (1994) by a broadly based group of parallel computer vendors, computer scientists, and applications developers.
  - MPI-2 was released in 1997
  - MPI-2.1 (2008) and MPI-2.2 (2009) with some corrections to the standard and small features
  - MPI-3 (2012) added several new features to MPI.
  - The Standard itself: at http://www.mpi-forum.org. All MPI official releases, in both postscript and HTML.

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The Minimal set of MPI Functions

`MPI_Init`	Initializes MPI.
`MPI_Finalize`	Terminates MPI.
`MPI_Comm_size`	Determines the number of processes.
`MPI_Comm_rank`	Determines the label of the calling process.
`MPI_Send`	Sends a message.
`MPI_Recv`	Receives a message.

Starting and Terminating MPI Programs

- `int MPI_Init(int *argc, char ***argv)`
  The parameters are from the parameters of the main C program.
  - Initialization: must call this prior to other MPI functions
- `int MPI_Finalize()`
  - Must call at the end of MPI program
- Return codes

  `MPI_SUCCESS`

  `MPI_ERROR`

Communicators

- `MPI_Comm`: communicator – communication domain
  - Group of processes that can communicate with one another
  - Supplied as an argument to all MPI message passing functions
  - Process can belong to multiple communication domain
- `MPI_COMM_WORLD`: root communicator – includes all the processes

Communicator Inquiry Functions

- `int MPI_Comm_size(MPI_Comm comm, int *size)`
  - Determine the number of processes
- `int MPI_Comm_rank(MPI_Comm comm, int *rank)`
  - index of the calling process
  - value: 0 — communicator size - 1

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Simple MPI Program — “Hello World”

```
1  #include <mpi.h>
2  #include <stdio.h>
3  int main(int argc, char *argv[])
4  {
5    int num_procs, myrank;
6
7    MPI_Init(&argc, &argv);
8
9    MPI_Comm_size(MPI_COMM_WORLD, &num_procs);
10   MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
11
12   printf("From process %d out of %d, Hello World!\n",
13     myrank, num_procs);
14
15   MPI_Finalize();
16   return 0;
17 }
```

Simple MPI Program Contd.

- Header file for MPI program — `#include <mpi.h>`
- Each active MPI process executes its own copy of the program.
- The first MPI function call made by every MPI process is the call to `MPI_Init`, which allows the system to do any setup needed to handle further calls to the MPI library.
- When MPI has been initialized, every active process becomes a member of a communicator called `MPI_COMM_WORLD`.

Simple MPI Program Contd.

- A communicator defines a *communication domain* – a set of processes that are allowed to communicate with each other – a communication context.
- A default communicator: `MPI_COMM_WORLD`, which includes all the processes started by the user.
- Communicators are used as arguments to all message transfer MPI routines.
- A process can belong to many different (possibly overlapping) communication domains.

Simple MPI Program Contd.

- A process calls function `MPI_Comm_rank` to determine its rank within a communicator.
- It calls `MPI_Comm_size` to determine the total number of processes in a communicator.

```
int id, p;
MPI_Comm_rank(MPI_COMM_WORLD, &id);
MPI_Comm_size(MPI_COMM_WORLD, &p);
```

- After a process has completed all of its MPI library calls, it calls function `MPI_Finalize`, allowing the system to free up resources (such as memory) that have been allocated to MPI, and shuts down MPI environment.

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Compiling and Running MPI Programs

- MPI is a library. Applications can be written in C, C++ or Fortran and appropriate calls to MPI can be added where required
- Compilation
  - Regular applications: `gcc test.c -o test`
  - MPI applications: `mpicc hello_world.c -o test`
- Execution
  - Regular applications: `./test`
  - MPI applications (running with 16 processes):
    - `mpiexec -n 16 ./test` or
    - `mpirun -np 16 ./test`

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Installing MPI standard implementation

MPI standard implementation can be already provided as part of the OS, often as MPICH[1] or OpenMPI[2]. If it is not, it can usually be installed through the provided package management, e.g., `apt` in Ubuntu:

- for MPICH,

  ```
  sudo apt-get install libmpich-dev
  ```

- for OpenMPI,

  ```
  sudo apt-get install libopenmpi-dev
  ```

[1] MPICH. *High performance portable MPI*. https://www.mpich.org/.

[2] Open MPI. *Open source high performance computing*. https://www.open-mpi.org/.

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Data Communication

- Data communication in MPI: One process sends a copy of data to another process (or a group of processes), and the other process receives it.
- Communication requires the following information:
  - Sender: the receiver, data count, data type, a user defined tag for the message
  - Receiver: the sender, data count, data type, the tag for the message

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MPI Basic (Blocking) Send

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

- The message buffer is described by `buf`, `count`, `datatype`.
- The target process is specified by `dest` and `comm`.
  - `dest` is the rank of the target process in the communicator specified by `comm`.
- `tag` is a user-defined type for the message
- When this function returns, the data has been delivered to the communication system and the send buffer (described by `buf, count, datatype`) can be reused. The message may not have been received by the target process.

MPI Basic (Blocking) Receive

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

- Waits until a matching (on source, datatype, tag, comm) message is received from the communication system, and the buffer can be used.
- Source is the rank of sender in communicator `comm`, or `MPI_ANY_SOURCE`.
- `status` contains further information: The MPI type `MPI_Status` is a struct with at least three members `MPI_SOURCE`, `MPI_TAG`, and `MPI_ERROR` .
- `MPI_STATUS_IGNORE` can be used if we don't need any additional information

.

Simple Communication in MPI

```
1  #include <mpi.h>
2  #include <stdio.h>

4  int main(int argc, char ** argv){
5      int rank, data[100];

7      MPI_Init(&argc, &argv);
8      MPI_Comm_rank(MPI_COMM_WORLD, &rank);
9    //Array data needs to be initialized
10     if (rank == 0)
11         MPI_Send(data, 100, MPI_INT, 1, 0, MPI_COMM_WORLD
               );
12     else if (rank == 1)
13         MPI_Recv(data, 100, MPI_INT, 0, 0, MPI_COMM_WORLD
               , MPI_STATUS_IGNORE);

15     MPI_Finalize();
16     return 0;
17 }
```

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MPI Datatypes

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`

Sending and Receiving Messages

- MPI allows specification of wildcard arguments for both `source` and `tag`.
- If `source` is set to `MPI_ANY_SOURCE`, then any process of the communication domain can be the source of the message.
- If `tag` is set to `MPI_ANY_TAG`, then messages with any tag are accepted.
- Only a receiver can use wildcard arguments. Sender must use a process rank and nonnegative tag.
- On the receive side, the message must be of length equal to or less than the length field specified.

Sending and Receiving Messages

- On the receiving end, the `status` variable can be used to get information about the `MPI_Recv` operation.
- The corresponding data structure contains:

```
typedef struct MPI_Status {
  int MPI_SOURCE;
  int MPI_TAG;
  int MPI_ERROR;
};
```

- The `MPI_Get_count` function returns the source, tag and number of elements of datatype received

```
int MPI_Get_count(MPI_Status *status,  /* in  */
        MPI_Datatype datatype,         /* in  */
        int *count                     /* out */)
```

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Benchmarking the Performance

- Running time:
  - MPI provides a function called `MPI_Wtime` that returns a double-precision floating-point number of seconds that have elapsed since some point of time in the past.
  - Function `MPI_Wtick` returns a floating-point number that is the time in seconds between successive ticks of the clock, i.e., the precision of the result returned by `MPI_Wtime`.
- ```
  double MPI_Wtime()
  double MPI_Wtick()
  ```
  ```

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Example 1: Rotating a token around a ring

Example 1

Consider a set of n processes arranged in a ring. Process 0 sends a token message, say ”Hello!”, to process 1; process 1 passes it to process 2; process 2 to process 3, and so on. Process $n - 1$ sends back the message to process 0. Write an MPI program that performs this simple token ring.

Example 1 cont.

```
1  MPI_Init(&argc,&argv);
2  MPI_Comm_size(MPI_COMM_WORLD, &nproces);
3  MPI_Comm_rank(MPI_COMM_WORLD, &myrank);

5  if (myrank == 0)
6    prev = nproces - 1;
7  else
8    prev = myrank - 1;
9  if (myrank == (nproces - 1))
10   next = 0;
11 else
12   next = myrank + 1;
13 if (myrank == 0)
14   strcpy(token, "Hello!");
15 MPI_Send(token, MSG_SZ, MPI_CHAR, next, tag,
       MPI_COMM_WORLD);
16 MPI_Recv(token, MSG_SZ, MPI_CHAR, prev, tag,
       MPI_COMM_WORLD, MPI_STATUS_IGNORE);
17 printf("Process %d received token %s from process %d.\n",
       myrank, token, prev);
```

Example 1 cont.

```
DATE: Wed Sep 29 16:26:19 SAST 2021
Job is running on nodes  mscluster[30,47,50,55]
------------------------------------------------------
SLURM: sbatch is running on mscluster0.ms.wits.ac.za
SLURM: job ID is 141789
SLURM: submit directory is /home-mscluster/hwang/PC/
   mpi_lab1
SLURM: number of nodes allocated is 4
SLURM: number of tasks is 8
SLURM: job name is PC_mpi_com
------------------------------------------------------
Process 1 received token Hello! from process 0.
Process 7 received token hR???- from process 6.
Process 0 received token h?p??- from process 7.
Process 2 received token hRU7?- from process 1.
Process 3 received token h?^??- from process 2.
Process 4 received token h?? from process 3.
Process 6 received token h?^P?- from process 5.
Process 5 received token h?6??- from process 4.
```

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Example 1 cont.

```
1  if (myrank == 0) {
2  strcpy(token, "Hello World!");
3    MPI_Send(token, MSG_SZ, MPI_CHAR, next, tag,
         MPI_COMM_WORLD);
4    MPI_Recv(token, MSG_SZ, MPI_CHAR, prev, tag,
         MPI_COMM_WORLD, MPI_STATUS_IGNORE);
5    printf("Process %d received token %s from process %d.\n
         ", myrank, token, prev);
6  }
7  else {
8    MPI_Recv(token, MSG_SZ, MPI_CHAR, prev, tag,
         MPI_COMM_WORLD, MPI_STATUS_IGNORE);
9    MPI_Send(token, MSG_SZ, MPI_CHAR, next, tag,
         MPI_COMM_WORLD);
10   printf("Process %d received token %s from process %d.\n
         ", myrank, token, prev);
11 }
```

Example 1 cont.

```
DATE: Wed Sep 29 16:26:19 SAST 2021
Job is running on nodes  mscluster[30,47,50,55]
------------------------------------------------------
SLURM: sbatch is running on mscluster0.ms.wits.ac.za
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   mpi_lab1
SLURM: number of nodes allocated is 4
SLURM: number of tasks is 8
SLURM: job name is PC_mpi_com
------------------------------------------------------
Process 1 received token Hello World! from process 0.
Process 2 received token Hello World! from process 1.
Process 3 received token Hello World! from process 2.
Process 4 received token Hello World! from process 3.
Process 5 received token Hello World! from process 4.
Process 6 received token Hello World! from process 5.
Process 7 received token Hello World! from process 6.
Process 0 received token Hello World! from process 7.
```

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Example 2: The Sieve of Eratosthens – finds primes between 2 and n

Example 2

1. Create a list of integers $2, 3, 4, \ldots, n$, none of which is marked.
2. Set k to 2, the first unmarked number on the list.
3. Repeat until $k^2 > n$
   (a) Mark all multiples of k between k^2 and n
   (b) Find the smallest number greater than k that is unmarked. Set k to this new value.
4. The unmarked numbers are primes

Example 2 Contd.

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60

Table: Integers from 2 to 60

	2	3		5		7		9		11		13		15		17		19	
21		23		25		27		29		31		33		35		37		39	
41		43		45		47		49		51		53		55		57		59	

Table: Sieve = 2

	2	3		5		7				11		13				17		19	
		23		25				29		31				35		37			
41		43				47		49				53		55				59	

Table: Sieve = 3

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Example 2 Contd.

	2	3		5		7				11		13				17		19	
		23						29		31						37			
41		43				47		49				53						59	

Table: Sieve = 5

	2	3		5		7				11		13				17		19	
		23						29		31						37			
41		43				47						53						59	

Table: Sieve = 7

The Sieve of Eratosthens – parallelization

- The key parallel computation is step 3.(a)
- Communications among the sub problems; Two communications are needed to perform step 3.(b): a reduction and a broadcast.
- To simplify the problem, let's eliminate the reduction by assuming $n/p > \sqrt{n}$, then the first process is responsible for finding the next value of k.
- Decomposing the problem: data decomposition –
  - Block decomposition: the range of array elements for each process i is $\lfloor in/p \rfloor \sim \lfloor (i+1)n/p \rfloor - 1$.
  - Block-cyclic decomposition

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Collective Communication and Computation Operations

- MPI provides an extensive set of functions for performing common collective communication operations.
- Each of these operations is defined over a group corresponding to the communicator.
- All processors in a communicator must call these operations.

Collective Communication Operations

- The barrier synchronization operation is performed in MPI using:

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

  The one-to-all broadcast operation is:

```
int MPI_Bcast(void *buf, int count,MPI_Datatype datatype
int source, MPI_Comm comm)
```

- The all-to-one reduction operation is:

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

Predefined Reduction Operations

Operation	Meaning	Datatypes
MPI_MAX	Maximum	C integers and floating point
MPI_MIN	Minimum	C integers and floating point
MPI_SUM	Sum	C integers and floating point
MPI_PROD	Product	C integers and floating point
MPI_LAND	Logical AND	C integers
MPI_BAND	Bit-wise AND	C integers and byte
MPI_LOR	Logical OR	C integers
MPI_BOR	Bit-wise OR	C integers and byte
MPI_LXOR	Logical XOR	C integers
MPI_BXOR	Bit-wise XOR	C integers and byte
MPI_MAXLOC	max-max value-location	Data-pairs
MPI_MINLOC	min-min value-location	Data-pairs

A Simple Reduction Program

```
1  #include "mpi.h"
2  #include <stdio.h>
3  #include <math.h>
4  int main(int argc, char **argv){
5    int n, numprocs, myrank, myval, sum;
6    MPI_Init(&argc, &argv);
7    MPI_Comm_size(MPI_COMM_WORLD, &numprocs);
8    MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
9    if(myrank == 0){
10     printf("Enter the number to be broadcasted: (0 quits
           .)");
11     scanf("%d", &n);
12   }
13   MPI_Bcast(&n, 1, MPI_INT, 0, MPI_COMM_WORLD);
14   //printf("Rank %d received %d\n", myrank + 1, n);
15   myval = n * 2;
16   MPI_Reduce(&myval, &sum, 1, MPI_INT, MPI_SUM, 0,
       MPI_COMM_WORLD);
17   if(myrank==0)
18     printf("Sum = %d \n", sum);
19   MPI_Finalize();
20   return 0;
21 }
```

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Function Prototypes

```
1  int MPI_Init(int *argc, char ***argv)
2  int MPI_Finalize()
3  int MPI_Comm_size(MPI_Comm comm, int *size)
4  int MPI_Comm_rank(MPI_Comm comm, int *rank)
5  int MPI_Reduce(void *sendbuf,void *recvbuf,int count,
6    MPI_Datatype datatype,MPI_Op op,int root,MPI_Comm
       comm)
7  int MPI_Bcast(void *buf,int count,MPI_Datatype datatype
     ,
8    int root,MPI_Comm comm)
9  double MPI_Wtime()
10 double MPI_Wtick()
```

Outline

What is MPICH

- MPICH is a high-performance and widely portable open-source implementation of MPI
- It provides all features of MPI that have been defined so far (including MPI-1, MPI-2.0, MPI-2.1, MPI-2.2, and MPI-3.0)
- http://www.mpich.org
- Compiling MPI program using MPICH
  - For C programs: `mpicc test.c -o test`
  - For C++ programs: `mpicxx test.cpp -o test`
  - To link to a math library: `mpicc test.c -o test -lm`

Running MPI programs with MPICH

- Launch 16 processes on the local node:
  `mpiexec -n 16 ./test`
- Launch 16 processes on 4 nodes (each has 4 cores)
  `mpiexec -hosts h1:4,h2:4,h3:4,h4:4 -n 16 ./test`
  Runs the first four processes on h1, the next four on h2, etc.
  (`h1, h2, h3, h4` are host names separated by comma.)
  `mpiexec -hosts h1,h2,h3,h4 -n 16 ./test` Runs the first process on h1, the second on h2, etc., and wraps around. So, h1 will have the 1st, 5th, 9th and 13th processes.

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Summary

We learnt

- Basic set of MPI functions to write simple MPI programs
  - Initialize and finalize MPI
  - Inquire the basic MPI execution environment
  - Basic point to point communication: send and receive
  - Basic collective communication: broadcast and reduction
- Developing MPI programs through examples
- Compiling and running MPI programs
- Useful resources: *Introduction to Parallel Computing: From Algorithms to Programming on State-of-the-Art Platforms* and *Parallel Programming in C with MPI and OpenMP*.