Parallel Computing Using MPI & OpenMP

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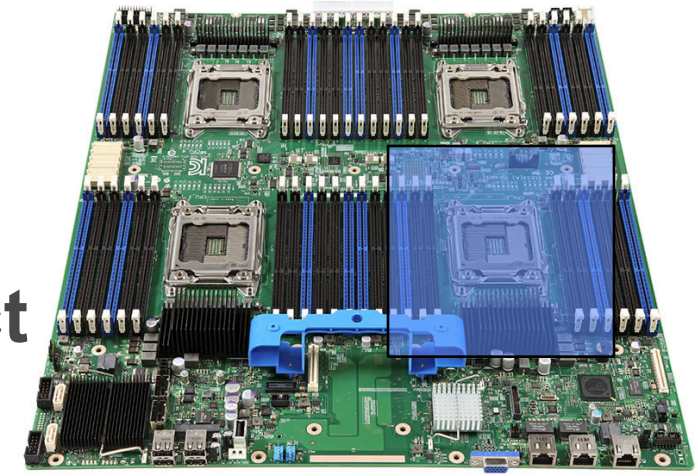
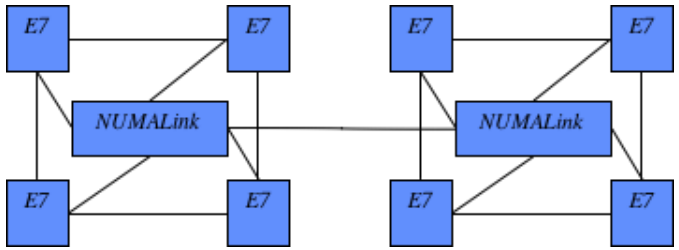
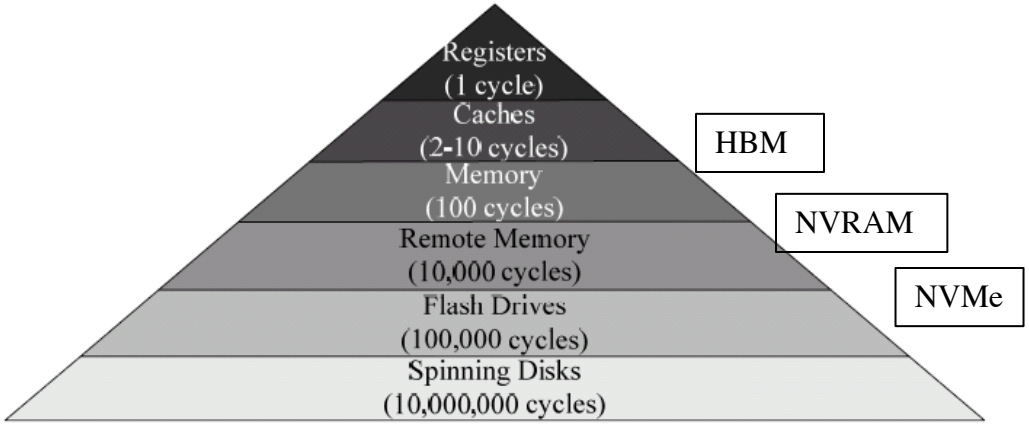
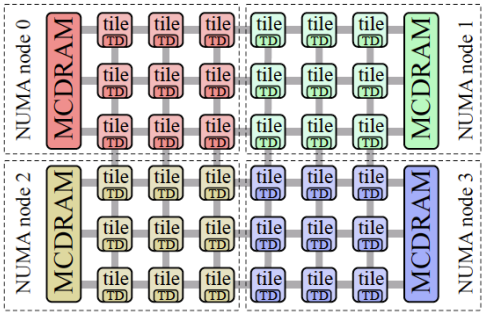
Current Supercomputer Architectures

- **Multi-socket server nodes**
  - NUMA
  - Accelerators
- **High performance interconnect**
  - e.g. Infiniband, OmniPath
- ***Scalable parallel approach needed to achieve performance***



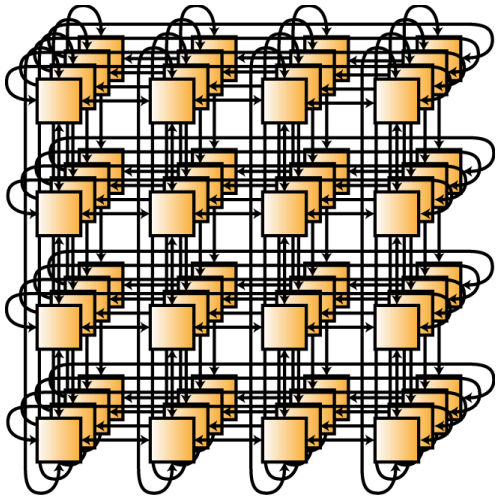


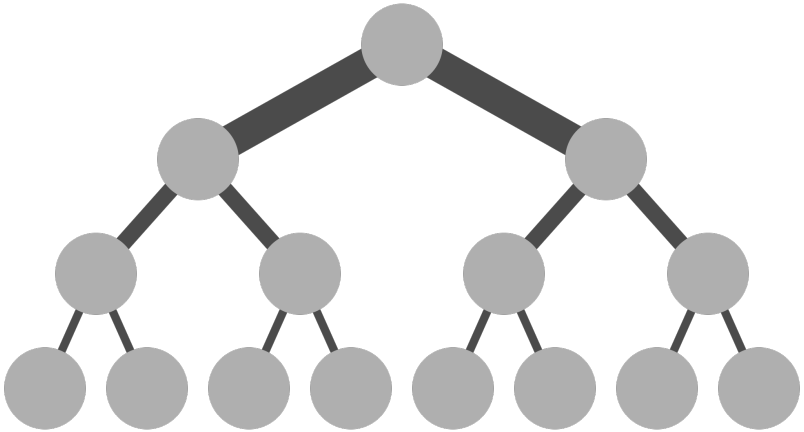




Network Topologies

- **Mesh, Torus, Hypercube**
- **Tree based**
  - Fat-tree
  - Clos
- **Dragonfly**
- **Metrics**
  - Bandwidth
  - Diameter, Connectivity
  - Bisection bandwidth





Parallel Computing

- **Executing instructions concurrently on physical resources (not time slicing)**
  - Multiple tightly coupled resources (e.g. cores) collaboratively solving a single problem
- **Benefits**
  - Capacity
    - Memory, storage
  - Performance
    - More instructions per unit of time (FLOPS)
    - Data streaming capability
- **Cost and Complexity**
  - Coordinate tasks and resources
  - Use resources efficiently

Classification - Flynn's Taxonomy

Single Instruction Single Data	Single Instruction Multiple Data
Multiple Instruction Single Data	Multiple Instruction Multiple Data

- **Single Program Multiple Data (SPMD)**
- **Multiple Program Multiple Data (MPMD)**

- **Single Instruction, Single Data [Serial codes]**
- **Single Instruction, Multiple Data**
  - Processors run the same instructions, each operates on different data
  - Technically, Hadoop MapReduce fits this mode
  - GPUs
- **Multiple Instruction, Single Data**
  - Multiple instructions acting on single data stream. E.g. Different analysis on same set of data.
- **Multiple Instruction, Multiple Data**
  - Every processor may execute different instructions
  - Every processor may work on different parts of data
  - Execution can be synchronous or asynchronous, deterministic or non-deterministic

Memory, Communication, and Execution Models

- **Shared**
  - Communication model: shared memory
- **Distributed**
  - Communication model: exchange messages
- **Execution Models**
  - Fork-Join (e.g. Thread Level Parallelism)
  - Single Program Multiple Data (SPMD)
- **Parallelism enabled by decomposing work**
  - Tasks can be executed concurrently
  - Some tasks can have dependencies

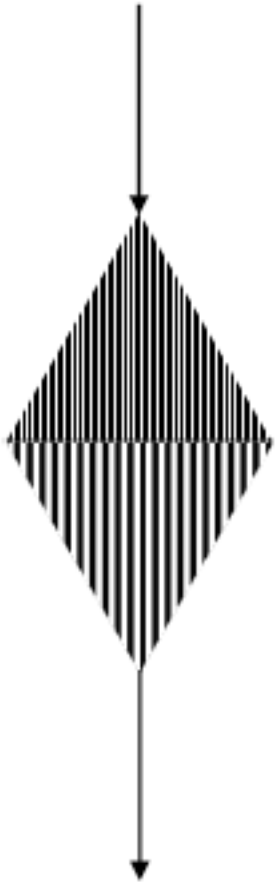
What is OpenMP?

- **High level parallelism abstraction based on thread**
  - Easy to use
  - Suitable to an incremental approach
- **A specification and evolving standard**
  - "a portable, scalable model … for developing portable parallel programs"
  - http://openmp.org
  - GNU, Intel, PGI, etc.
- **A set of**
  - Compiler directives
  - Library routines
  - Environment variables
  - Supports C/C++ and Fortran

```
#pragma omp parallel
{
  ....
}
```

OpenMP Models

- **Fork/Join Execution**
  - Process starts single threaded (master thread)
  - Forks child threads activated in parallel regions (team)
  - The team synchronizes and threads are disbanded
    - – barrier
  - Overhead is mitigated by reusing threads
  - Master thread continues execution of serial phases
- **Work decomposition**
  - Programming constructs
  - Scope and compound statements
  - Declarative in loops
  - Mapping to threads can be static or dynamic
  - Barriers and synchronization automatically inserted



Compiler Directives

- **Compiler directives is the main mechanism for introducing parallelism. Functionality enabled includes:**
  - Spawning a parallel region
  - Diving code among threads
  - Distributing loop iterations over threads
  - Serialization of parts of the code
  - Synchronization of work
- **Example:**

```
#pragma omp parallel default(shared) private(beta,pi)
```

Regions, Loops, Sections etc

#pragma omp parallel *[clause[[,]clause] ...] new-line*
structured-block
clause:
if(*scalar-expression*)
num_threads(*integer-expression*)
default(**shared** | **none**)
private(*list*)
firstprivate(*list*)
shared(*list*)
copyin(*list*)
reduction(*operator*: *list*)

- #pragma omp single/master
- simd
- tasks

#pragma omp for *[clause[[,] clause] ...] new-line for-loops*
clause:
private(*list*)
firstprivate(*list*)
lastprivate(*list*)
reduction(*operator*: *list*)
schedule(*kind[, chunk_size]*)
collapse(*n*)
ordered
nowait

#pragma omp sections *[clause[[,] clause] ...] new-line*
{
#pragma omp section
structured-block
…
}
clause:
private(*list*)
firstprivate(*list*)
lastprivate(*list*)
reduction(*operator*: *list*)
nowait

Scope of Variables

- **Clauses determine the scope of variables**
  - Default: shared (external)
  - Private
    - Also if declared inside region
  - firstprivate
  - shared
  - lastprivate
  - reductions
  - default
  - ….
- **Avoid race conditions!**

Parallel Region Construct

```
!$OMP PARALLEL [clause ...]
          IF (scalar_logical_expression)
          PRIVATE (list)
          SHARED (list)
          DEFAULT (PRIVATE | FIRSTPRIVATE | SHARED | NONE)
          FIRSTPRIVATE (list)
          REDUCTION (operator: list)
          COPYIN (list)
          NUM_THREADS (scalar-integer-expression)

  code block
!$OMP END PARALLEL
```

Number of Threads

- **Number of threads will be determined in the following order of precedence:**
  - Evaluation of the IF clause
  - Setting of NUM_THREADS clause
  - omp_set_num_threads() library function
  - OMP_NUM_THREADS environment variable
  - Default – usually ends up being the ***number of cores on the node*** (!)

- **The last factor can accidentally lead to oversubscription of nodes in hybrid MPI/OpenMP codes.**

Work – Sharing Constructs

Directive format (C version):

```
#pragma omp for [clause ...]  newline
            schedule (type [,chunk])
            ordered
            private (list)
            firstprivate (list)
            lastprivate (list)
            shared (list)
            reduction (operator: list)
            collapse (n)
            nowait

   for_loop
```

Work-Sharing

- **Schedule:**
  - Static – Loop iterations are statically divided (chunk or as close to even as possible)
  - Dynamic – Loop iterations are divided in size chunk, and dynamically scheduled among threads. When a thread finishes one chunk it is dynamically assigned another
  - Guided – Similar to dynamic but chunk size is proportionally reduced based on work remaining.
  - Runtime – set at runtime by environment variables
  - Auto – set by compiler or runtime system.

Simple OpenMP Program – Compute PI

- Find the number of tasks and taskids (omp_get_num_threads, omp_get_thread_num)
- PI is calculated using an integral. The number of intervals used for the integration is fixed at 128000.
- Use OpenMP loop parallelization to divide up the compute work.
- Introduce concept of private and shared variables.
- OpenMP reduction operation used to compute the sum for the final integral.
- Today's OpenMP examples are in: **/home/$USER/PARALLEL/OPENMP**
  (Run "make" in that directory to generate executables).

OpenMP Program to Compute PI

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
int main (int argc, char *argv[])
{
int nthreads, tid;
int i, INTERVALS;
double n_1, x, pi = 0.0;

INTERVALS=128000;
/* Fork a team of threads giving them their own
      copies of variables */
#pragma omp parallel private(nthreads, tid)
  {
  /* Obtain thread number */
  tid = omp_get_thread_num();
  printf("Hello from thread = %d\n", tid);
```

```
 /* Only master thread does this */
  if (tid == 0)
    {
    nthreads = omp_get_num_threads();
    printf("Number of threads = %d\n", nthreads);
    }

  }  /* All threads join master thread and disband */

  n_1 = 1.0 / (double)INTERVALS;

/* Parallel loop with reduction for calculating PI */
#pragma omp parallel for private(i,x)
shared(n_1,INTERVALS) reduction(+:pi)
  for (i = 0; i < INTERVALS; i++)
    {
    x = n_1 * ((double)i  - 0.5);
    pi += 4.0 / (1.0 + x * x);
    }
    pi *= n_1;
    printf ("Pi = %.12lf\n", pi);
}
```

OpenMP result: 1-D Heat Equation

$ sbatch --res=SI2019DAY4 pi_openmp.sb

```
[train129@comet-ln2 OPENMP]$ more pi.18444806.comet-06-08.out
Hello from thread = 8
Hello from thread = 0
Hello from thread = 3
Hello from thread = 2
Hello from thread = 15
Hello from thread = 1
Hello from thread = 11
Hello from thread = 5
Hello from thread = 12
Hello from thread = 4
Hello from thread = 9
Hello from thread = 6
Hello from thread = 7
Hello from thread = 10
Hello from thread = 13
Hello from thread = 14
Threre are 16 threads!
PI = 3.139384000000, Err = 2.208654e-03, Time = 0.045058
[train129@comet-ln2 OPENMP]$
```

More Work-Share Constructs

- **SECTIONS** directive – enclosed sections are divided among the threads.
- **WORKSHARE** directive – divides execution of block into units of work, each of which is executed once.
- **SINGLE** directive – Enclosed code is executed by only one thread.

Synchronization Constructs

- **MASTER** directive – Specifies region is executed only by the master thread.
- **CRITICAL** directive – Region of the code that is executed one thread at a time.
- **BARRIER** directive – synchronize all threads
- **TASKWAIT** directive – wait for all child tasks to complete
- **ATOMIC** directive – specific memory location updated atomically (not let all threads write at the same time)

Simple Application using OpenMP: 1-D Heat Equation

- $\partial T/\partial t = \alpha(\partial^2 T/\partial x^2)$; $T(0) = 0$; $T(1) = 0$; $(0 \leq x \leq 1)$
  $T(x,0)$ is know as an initial condition.

- Discretizing for numerical solution we get:
  $T^{(n+1)}_i - T^{(n)}_i = (\alpha \Delta t/\Delta x^2)(T^{(n)}_{i-1} - 2T^{(n)}_i + T^{(n)}_{i+1})$
  (*n* is the index in time and *i* is the index in space)

Fortran OpenMP Code: 1-D Heat Equation

```
 PROGRAM HEATEQN
      implicit none
      integer :: iglobal, itime, nthreads
      real*8 :: xalp,delx,delt,pi
      real*8 :: T(0:100,0:10)
      integer:: id
      integer:: OMP_GET_THREAD_NUM,
        OMP_GET_NUM_THREADS

!$OMP PARALLEL SHARED(nthreads)
!$OMP MASTER
      nthreads = omp_get_num_threads()
      write (*,*) 'There are', nthreads, 'threads'
!$OMP END MASTER
!$OMP END PARALLEL
      if (nthreads.ne.3) then
        write(*,*)"Use exactly 3 threads for this case"
        stop
      endif
      delx = 0.1d0
      delt = 1d-4
      xalp = 2.0d0
```

```
********** Initial Conditions
*********************************
      pi = 4d0*datan(1d0)
      do iglobal = 0, 10
        T(0,iglobal) = dsin(pi*delx*dfloat(iglobal))
      enddo
********** Iterations
*****************************************
      do itime = 1 , 3
       write(*,*)"Running Iteration Number ", itime
!$OMP PARALLEL DO PRIVATE(iglobal)
SHARED(T,xalp,delx,delt,itime)
       do iglobal = 1, 9
        T(itime,iglobal)=T(itime-1,iglobal)+
     +  xalp*delt/delx/delx*
     +  (T(itime-1,iglobal-1)-2*T(itime-1,iglobal)+T(itime-
1,iglobal+1))
       enddo
!$OMP BARRIER
      enddo
      do iglobal = 0, 10
        write(*,*)iglobal,T(3, iglobal)
      enddo
      END
```

OpenMP result: 1-D Heat Equation

$ sbatch --res=SI2019DAY4 heat_openmp.sb

Sample output file:

```
There are        3 threads
Running Iteration Number        1
Running Iteration Number        2
Running Iteration Number        3
         0  0.000000000000000E+000
         1  0.307205621017285
         2  0.584339815421976
         3  0.804274757358271
         4  0.945481682332598
         5  0.994138272681972
         6  0.945481682332598
         7  0.804274757358271
         8  0.584339815421977
         9  0.307205621017285
        10  7.797843424221369E-316
```

Data Scope Attribute Clauses

- PRIVATE – variables in the list are private to each thread.
- SHARED – variables in the list are shared between all threads.
- DEFAULT – default scope for all variables in a parallel region.
- FIRSTPRIVATE – variables are private and initialized according to value prior to entry into parallel or work sharing construct.
- LASTPRIVATE – variables are private, the value from the last iteration or section is copied to original variable object.
- Others – COPYIN, COPYPRIVATE
- REDUCTION – reduction on variables in the list

Run Time Library Routines

- Setting and querying number of threads
- Querying thread identifier, team size
- Setting and querying dynamic threads feature
- Querying if in parallel region and at what level
- Setting and querying nested parallelism
- Setting, initializing and terminating locks, nested locks.
- Querying wall clock time and resolution.

Environment Variables

- OMP_SCHEDULE – e.g set to “dynamic”
- OMP_NUM_THREADS
- OMP_DYNAMIC (TRUE or FALSE)
- OMP_PROC_BIND (TRUE or FALSE)
- OMP_NESTED (TRUE of FALSE)
- OMP_STACKSIZE – size of stack for created threads
- OMP_THREAD_LIMIT

General OpenMP Performance Considerations

- Avoid or minimize use of BARRIER, CRITICAL (complete serialization here!), ORDERED regions, and locks. Can use NOWAIT clause to avoid redundant barriers.

- Parallelize at a high level, i.e. maximize the work in the parallel regions to reduce parallelization overhead.

- Use appropriate loop scheduling – static has low synchronization overhead but can be unbalanced, dynamic (and guided) have higher synchronization overheads but can improve load balancing.

- Avoid false sharing (more about it in following slide)!

What is False Sharing?

- Most modern processors have a cache buffer between slow memory and high speed registers of the CPU.
- Accessing a memory location causes a “cache line” to be copied into the cache.
- In an OpenMP code two processors may be accessing two different elements in the same cache line. On writes this will lead to “cache line” being marked invalid (because cache coherency is being maintained).
- This will lead to an increase in memory traffic even though the write is to different elements (hence the term **false sharing**).
- This can have a drastic performance impact if such updates are occurring frequently in a loop.

False Sharing Example

Code snippet:

```
double global=0.0, local[NUM_THREADS];
#pragma omp parallel num_threads(NUM_THREADS)
{
 int tid = omp_get_thread_num();
 local[tid] = 0.0;
 #pragma omp for
 for (i = 0; i < N; i++)
 local[tid] += x[i];
 #pragma omp atomic
 global += local[me];
}
```

False Sharing - Solutions

- **Three options**
  - Compiler directives to align individual variables on cache line boundaries

```
__declspec (align(64)) int thread1_global_variable;
__declspec (align(64)) int thread2_global_variable;
```

  - Pad arrays/data structures to make sure array elements begin on cache line boundary.
  - Use thread local copies of data (assuming the copy overhead is small compared to overall run time).

Homework!

- **Download matrix multiply example from LLNL site:**
  - https://computing.llnl.gov/tutorials/openMP/samples/Fortran/omp_mm.f

  (wget https://computing.llnl.gov/tutorials/openMP/samples/Fortran/omp_mm.f on Comet)

- **Compile (ifort -fopenmp omp_mm.f) and run the example. See if you can vary the environmental variables, scheduling to get better performance!**

- **This is very quick intro. Lot of ongoing developments. Detailed specifications at:**
  - https://www.openmp.org/specifications/

Message Passing Interface (MPI)

- **Low level message passing abstraction**
  - SPMD execution model + messages
  - Designed for distributed memory. Implemented on hybrid distributed memory/shared memory systems.
- **MPI: API specification**
  - Portable: de-fact standard for parallel computing, portable, system specific optimizations without changing code interface
  - http://www.mpi-forum.org
  - Several implementations - e.g MVAPICH2 (default on Comet), Intel MPI, and OpenMPI
  - High performance implementations available virtually on any interconnect and system
  - Point-to-point communication, datatypes, collective operations
  - One-sided communication, Parallel file I/O, Tool support, …

Typical MPI Code Structure

MPI Include File

Variable declarations, etc

Begin Program

…

Serial code

….

MPI Initialization — Parallel Code begins

MPI Rank (process identification)

…

Parallel code based on rank

…

MPI Communications between processes

…

Parallel code based on rank

…

MPI Communications between processes

MPI Finalize (terminate) — Parallel Code ends

Serial Code

Simple MPI Program – Compute PI

- Initialize MPI (MPI_Init function)
- Find the number of tasks and taskids (MPI_Comm_size, MPI_Comm_rank)
- PI is calculated using an integral. The number of intervals used for the integration is fixed at 128000.
- Computes the sums for a different sections of the intervals in each MPI task.
- At the end of the code, the sums from all the tasks are added together to evaluate the final integral. This is accomplished through a reduction operation (MPI_Reduce function).
- Simple code illustrates decomposition of problem into parallel components.

MPI Program to Compute PI

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

int main(int argc, char *argv[])
 {
 int numprocs, rank;
 int i, iglob, INTERVALS, INTLOC;
 double n_1, x;
 double pi, piloc;

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

 INTERVALS=128000;
 printf("Hello from MPI task= %d\n", rank);
 MPI_Barrier(MPI_COMM_WORLD);
 if (rank == 0)
  {
 printf("Number of MPI tasks = %d\n", numprocs);
  }

 INTLOC=INTERVALS/numprocs;
 piloc=0.0;
 n_1=1.0/(double)INTERVALS;
 for (i = 0; i < INTLOC; i++)
  {
  iglob = INTLOC*rank+i;
  x = n_1 * ((double)iglob  - 0.5);
  piloc += 4.0 / (1.0 + x * x);
  }

MPI_Reduce(&piloc,&pi,1,MPI_DOUBLE,MPI_SUM,0,
MPI_COMM_WORLD);
 if (rank == 0)
  {
  pi *= n_1;
  printf ("Pi = %.12lf\n", pi);
  }

 MPI_Finalize();
}
```

PI Code : MPI Environment Functions

MPI_Init(&argc, &argv);

Initializes MPI, *must* be called (only once) in every MPI program before any MPI functions.

MPI_Comm_size(MPI_COMM_WORLD, &numprocs);

Returns the total number of tasks in the communicator. MPI uses communicators to define which collections of processes can communicate with each other. The default MPI_COMM_WORLD includes all the processes. User defined communicators are an option.

MPI_Comm_rank(MPI_COMM_WORLD, &rank);

Returns the rank (ID) of the calling MPI process within the communicator.

MPI_Finalize();

Ends the MPI execution environment. No MPI calls after this.!

The other routines in the code are collectives and we will discuss them later in the talk.

Compiling and Running PI Example

cd /home/$USER/PARALLEL/SIMPLE

Compile: mpicc -o pi_mpi.exe pi_mpi.

Submit Job: sbatch --res=SI2019DAY4 pi_mpi.sb

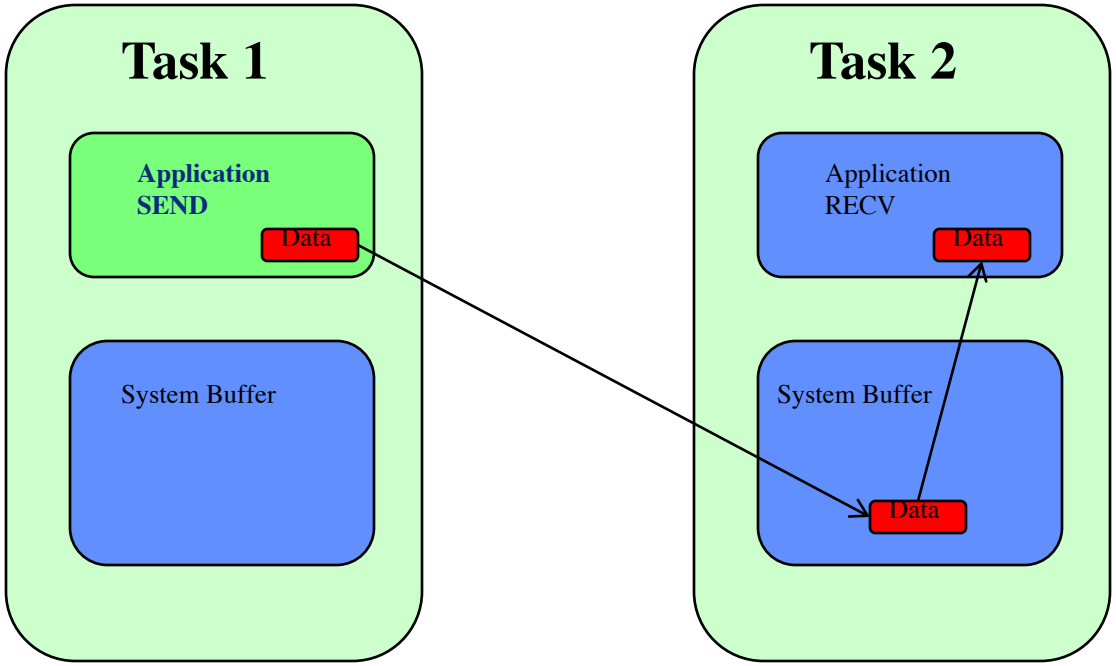
Sample Output:

```
Hello from MPI task= 12
Hello from MPI task= 14
Hello from MPI task= 8
Hello from MPI task= 3
Hello from MPI task= 2
Hello from MPI task= 4
Hello from MPI task= 13
Hello from MPI task= 9
Hello from MPI task= 5
Hello from MPI task= 1
Hello from MPI task= 11
Hello from MPI task= 10
Hello from MPI task= 15
Hello from MPI task= 7
Hello from MPI task= 6
Hello from MPI task= 0
Number of MPI tasks = 16
Pi = 3.141594606714
```

Point to Point Communication

- Passing data between two, and only two different MPI tasks.
- Typically one task performs a send operation and the other task performs a matching receive.
- MPI Send operations have choices with different synchronization (when does a send complete) and different buffering (where the data resides till it is received) modes.
- Any type of send routine can be paired with any type of receive routine.
- MPI also provides routines to probe status of messages, and “wait” routines.

Buffers



- Buffer space is used for data in transit – whether its waiting for a receive to be ready or if there are multiple sends arriving at the same receiving tasks.
- Typically a system buffer area managed by the MPI library (opaque to the user) is used. Can exist on both sending & receiving side.
- MPI also provides for user managed send buffer.

Blocking MPI Send, Receive Routines

- Blocking send call will return once it is safe for the application buffer (send data) to be reused.
- This can happen as soon as the data is copied into the system (MPI) buffer on receiving process.
- Synchronous if there is confirmation of safe send, and asynchronous otherwise.
- Blocking receive returns once the data is in the application buffer (receive data) and can by used by the application.

Blocking Send, Recv Example (Code Snippet)

```
if(myid == 0) {
      for(i = 0; i < 10; i++) {
        s_buf[i] = i*4.0;
      }
      MPI_Send(s_buf, size, MPI_FLOAT, 1, tag, MPI_COMM_WORLD);
   }
   else if(myid == 1) {
      MPI_Recv(r_buf, size, MPI_FLOAT, 0, tag, MPI_COMM_WORLD,
&reqstat);
      for (i = 0; i < 10; i++ ){
        printf("r_buf[%d] = %f\n", i, r_buf[i] );
      }
   }
```

Blocking Send, Recv Example

Location:$HOME/PARALLEL/PTOP

Compile: mpicc -o blocking.exe blocking.c

Submit Job: sbatch --res=SI2019DAY4 blocking.sb

Output:

```
r_buf[0] = 0.000000
r_buf[1] = 4.000000
r_buf[2] = 8.000000
r_buf[3] = 12.000000
r_buf[4] = 16.000000
r_buf[5] = 20.000000
r_buf[6] = 24.000000
r_buf[7] = 28.000000
r_buf[8] = 32.000000
r_buf[9] = 36.000000
```

Deadlocking MPI Tasks

- Take care to sequence blocking send/recvs. Easy to deadlock processes waiting on each other with circular dependencies.
- Can also occur with control errors and unexpected symantics
- For example, take the following code snippet:

```
if(myid == 0) {
    MPI_Ssend(s_buf, size, MPI_FLOAT, 1, tag1, MPI_COMM_WORLD);
    MPI_Recv(r_buf, size, MPI_FLOAT, 1, tag2, MPI_COMM_WORLD, &reqstat);
}
else if(myid == 1) {
    MPI_Ssend(s_buf, size, MPI_FLOAT, 0, tag2, MPI_COMM_WORLD);
    MPI_Recv(r_buf, size, MPI_FLOAT, 0, tag1, MPI_COMM_WORLD, &reqstat);
    for (i = 0; i < 10; i++ ){
      printf("r_buf[%d] = %f\n", i, r_buf[i] );
    }
```

- The MPI_Ssend on both tasks will not complete till the MPI_Recv is posted (which will never happen given the order).

Deadlock Example

- Location: $HOME/PARALLEL/PTOP
- Compile: mpicc -o deadlock.exe deadlock.c
- Submit Job: sbatch --res=SI2019DAY4 deadlock.sb
- It should technically finish in less than a second since the data transferred is a few bytes. However, the code deadlocks and hits the wallclock limit (2 minutes in the script).
- Error info:

slurmstepd: *** JOB 18444951 ON comet-01-05 CANCELLED AT 2018-08-09T09:00:15 DUE TO TIME LIMIT ***

[comet-01-05.sdsc.edu:mpirun_rsh][signal_processor] Caught signal 15, killing job

Connection to comet-01-05 closed by remote host.

Deadlock Example – Simple Fix

- Change the order on one of processes!
- For example, take the following code snippet:

```
if(myid == 0) {
    MPI_Ssend(s_buf, size, MPI_FLOAT, 1, tag1, MPI_COMM_WORLD);
    MPI_Recv(r_buf, size, MPI_FLOAT, 1, tag2, MPI_COMM_WORLD, &reqstat);
  }
  else if(myid == 1) {
    MPI_Recv(r_buf, size, MPI_FLOAT, 0, tag1, MPI_COMM_WORLD, &reqstat);
    MPI_Ssend(s_buf, size, MPI_FLOAT, 0, tag2, MPI_COMM_WORLD);
    for (i = 0; i < 10; i++ ){
      printf("r_buf[%d] = %f\n", i, r_buf[i] );
    }
```

- Now the MPI_Ssend on task 0 will complete since the corresponding MPI_Recv is posted first on task 1. (qsub deadlock-fix1.cmd)
- We will look at **Non-Blocking** options next.

Deadlock Example (Fix 1)

- Location: $HOME/PARALLEL/PTOP
- Compile: mpicc -o deadlock-fix1.exe deadlock-fix1.c
- Submit Job: sbatch --res=SI2019DAY4 deadlock-fix1.sb
- Fix works!

```
$ more deadlock-fix1.out
r_buf[0] = 0.000000
r_buf[1] = 4.000000
r_buf[2] = 8.000000
r_buf[3] = 12.000000
r_buf[4] = 16.000000
r_buf[5] = 20.000000
r_buf[6] = 24.000000
r_buf[7] = 28.000000
r_buf[8] = 32.000000
r_buf[9] = 36.000000
```

Non-Blocking MPI Send, Receive Routines

- Non-Blocking MPI Send, Receive routines return before there is any confirmation of receives or completion of the actual message copying operation.
- The routines simply put in the request to perform the operation.
- MPI wait routines can be used to check status and block till the operation is complete and it is safe to modify/use the information in the application buffer.
- This non-blocking approaches allows computations (that don't depend on this data in transit) to continue while the communication operations are in progress. This allows for hiding the communication time with useful work and hence improves parallel efficiency.

Non-Blocking Send, Recv Example

- **Example uses MPI_Isend, MPI_Irecv, MPI_Wait**
- **Code snippet:**

```
if(myid == source){
        s_buf=1024;
        MPI_Isend(&s_buf,count,MPI_INT,destination,tag,MPI_COMM_WORLD,&request);
    }
    if(myid == destination {
        MPI_Irecv(&r_buf,count,MPI_INT,source,tag,MPI_COMM_WORLD,&request);
    }
    MPI_Wait(&request,&status);
```

- **Compile & Run:**

mpicc -o nonblocking.exe nonblocking.c

qsub nonblocking.cmd

Sample output:

processor 0 sent 1024

processor 1 got 1024

Deadlock Example – Non-Blocking Option

- Change the order on one of processes!
- For example, take the following code snippet:

```
if(myid == 0) {
    MPI_Isend(s_buf, size, MPI_FLOAT, 1, tag1, MPI_COMM_WORLD, &request);
    MPI_Recv(r_buf, size, MPI_FLOAT, 1, tag2, MPI_COMM_WORLD, &reqstat);
  }
  else if(myid == 1) {
    MPI_Ssend(s_buf, size, MPI_FLOAT, 0, tag2, MPI_COMM_WORLD);
    MPI_Recv(r_buf, size, MPI_FLOAT, 0, tag1, MPI_COMM_WORLD, &reqstat);
    for (i = 0; i < 10; i++ ){
      printf("r_buf[%d] = %f\n", i, r_buf[i] );
    }
```

- Now the MPI_Ssend on task 0 will complete since the corresponding MPI_Recv is posted first on task 1. (qsub deadlock-fix1.cmd)
- We will look at **Non-Blocking** options next.

Deadlock Example (Fix 2)

- Location: $HOME/PARALLEL/PTOP
- Compile: mpicc -o deadlock-fix2-nb.exe deadlock-fix2-nb.c
- Submit Job: sbatch --res=SI2019DAY4 deadlock-fix2-nb.sb
- Fix works!

```
$ more deadlock-fix2-nb.out
r_buf[0] = 0.000000
r_buf[1] = 4.000000
r_buf[2] = 8.000000
r_buf[3] = 12.000000
r_buf[4] = 16.000000
r_buf[5] = 20.000000
r_buf[6] = 24.000000
r_buf[7] = 28.000000
r_buf[8] = 32.000000
r_buf[9] = 36.000000
```

Collective MPI Routines

- Synchronization Routines: All processes in group/communicator wait till they get synchronized.
- Data Movement: Send/Receive data from all processes. E.g. Broadcast, Scatter, Gather, AlltoAll.
- Collective Computation (reductions): Perform reduction operations (min, max, add, multiply, etc.) on data obtained from all processes.
- Collective Computation and Data Movement combined (Hybrid).

Synchronization Example

- **Our simple PI program had a synchronization example.**
- **Code Snippet:**

```
printf("Hello from MPI task= %d\n", rank);
MPI_Barrier(MPI_COMM_WORLD);
if (rank == 0)
  {
  printf("Number of MPI tasks = %d\n", numprocs);
  }
```

- **All tasks will wait till they are synchronized at this point.**

Broadcast Example

- **Code Snippet** (**All collectives examples in $HOME/PARALLEL/COLLECTIVES**):
  - if(myid .eq. source)then
  - do i=1,count
  - buffer(i)=i
  - enddo
  - endif
  - **Call MPI_Bcast(buffer, count, MPI_INTEGER,source,&**
  - **MPI_COMM_WORLD,ierr)**
- **Compile:**
  - **mpif90 -o bcast.exe bcast.f90**
- **Run:**
  - **sbatch --res=SI2019DAY4 bcast.sb**
- **Output:**

```
processor       1  got       1       2       3       4
processor       0  got       1       2       3       4
processor       2  got       1       2       3       4
processor       3  got       1       2       3       4
```

Reduction Example

- **Code Snippet:**

```
myidp1 = myid+1
call MPI_Reduce(myidp1,ifactorial,1,MPI_INTEGER,MPI_PROD,root,MPI_COMM_WORLD,ierr)
if (myid.eq.root) then
    write(*,*)numprocs,"! = ",ifactorial
endif
```

- **Compile:**

```
mpif90 -o factorial.exe factorial.f90
```

- **Run:**

```
sbatch --res=SI2019DAY4 factorial.sb
```

- **Output:**

```
8 ! =       40320
```

MPI_Allreduce example

- **Code Snippet:**

```
imaxloc=IRAND(myid)
call MPI_ALLREDUCE(imaxloc,imax,1,MPI_INTEGER,MPI_MAX,MPI_COMM_WORLD,
mpi_err)
if (imax.eq.imaxloc) then
    write(*,*)"Max=",imax,"on task",myid
endif
```

- **Compile:**

```
mpif90 -o allreduce.exe allreduce.f90
```

- **Run:**

```
sbatch --res=SI2019DAY4 allreduce.sb
```

- **Output:**

```
Max=     337897 on task         7
```

Data Types

C Data Types		FORTRAN Data Types
MPI_CHAR	MPI_C_DOUBLE_COMPLEX	MPI_CHARACTER
MPI_WCHAR	MPI_C_LONG_DOUBLE_COMPLEX	MPI_INTEGER
MPI_SHORT	MPI_C_BOOL	MPI_INTEGER1
MPI_INT	MPI_LOGICAL	MPI_INTEGER2
MPI_LONG	MPI_C_LONG_DOUBLE_COMPLEX	MPI_INTEGER4
MPI_LONG_LONG_INT	MPI_INT8_T	MPI_REAL
MPI_LONG_LONG	MPI_INT16_T	MPI_REAL2
MPI_SIGNED_CHAR	MPI_INT32_T	MPI_REAL4
MPI_UNSIGNED_CHAR	MPI_INT64_T	MPI_REAL8
MPI_UNSIGNED_SHORT	MPI_UINT8_T	MPI_DOUBLE_PRECISION
MPI_UNSIGNED_LONG	MPI_UINT16_T	MPI_COMPLEX
MPI_UNSIGNED	MPI_UINT32_T	MPI_DOUBLE_COMPLEX
MPI_FLOAT	MPI_UINT64_T	MPI_LOGICAL
MPI_DOUBLE	MPI_BYTE	MPI_BYTE
MPI_LONG_DOUBLE	MPI_PACKED	MPI_PACKED
MPI_C_COMPLEX		
MPI_C_FLOAT_COMPLEX		

MPI Reduction Operations

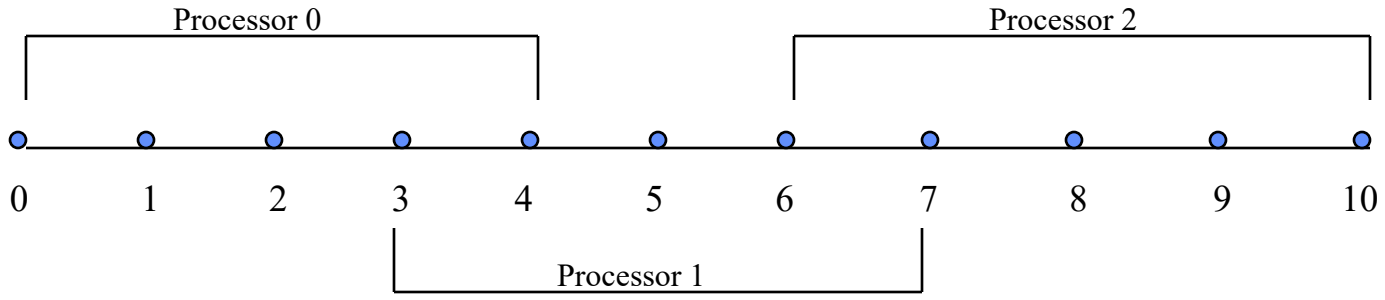
NAME	OPERATION
MPI_MAX	Maximum
MPI_MIN	Minimum
MPI_SUM	Sum
MPI_PROD	Product
MPI_LAND	Logical AND
MPI_BAND	Bit-wise AND
MPI_LOR	Logical OR
MPI_BOR	Bit-wise OR
MPI_LXOR	Logical XOR
MPI_BXOR	Bit-wise XOR
MPI_MAXLOC	Maximum value and location
MPI_MINLOC	Minimum value and location

Decomposition and Mapping

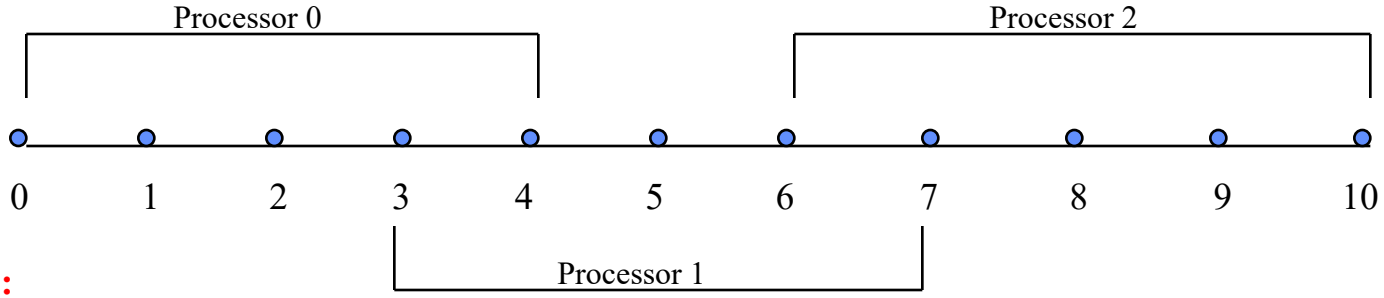
- **Data and work decomposition**
  - Map partitioned domain to processes
- **Mapping**
  - Processes/ranks topology
  - System/Domain/Data
- **How to share data?**
  - Exchange messages and replicate data
- **Load imbalance**
  - What if the system is not regular?
  - Is work proportional to size of partitions?

Simple Application using MPI: 1-D Heat Equation

- $\partial T/\partial t = \alpha(\partial^2 T/\partial x^2)$; T(0) = 0; T(1) = 0; (0 ≤x≤1)
  T(x,0) is know as an initial condition.
- Discretizing for numerical solution we get:
  $T^{(n+1)}_i - T^{(n)}_i = (\alpha\Delta t/\Delta x^2)(T^{(n)}_{i-1} - 2T^{(n)}_i + T^{(n)}_{i+1})$
  (*n* is the index in time and *i* is the index in space)
- In this example we solve the problem using 11 points and we distribute this problem over exactly 3 processors (for easy demo) shown graphically below:



Simple Application using MPI: 1-D Heat Equation



Processor 0:

Local Data Index : ilocal = 0 , 1, 2, 3, 4

Global Data Index: iglobal = 0, 1, 2, 3, 4

Solve the equation at (1,2,3)

Data Exchange: **Get 4 from processor 1; Send 3 to processor 1**

Processor 1:

Local Data Index : ilocal = 0, 1, 2, 3, 4

Global Data Index : iglobal = 3, 4, 5, 6, 7

Solve the equation at (4,5,6)

Data Exchange: **Get 3 from processor 0; Get 7 from processor 2; Send 4 to processor 0; Send 6 to processor 2**

Processor 2:

Local Data Index : ilocal = 0, 1, 2, 3, 4

Global Data Index : iglobal = 6, 7, 8, 9, 10

Solve the equation at (7,8,9)

Data Exchange: **Get 6 from processor 1; Send 7 to processor 1**

FORTRAN MPI CODE: 1-D Heat Equation

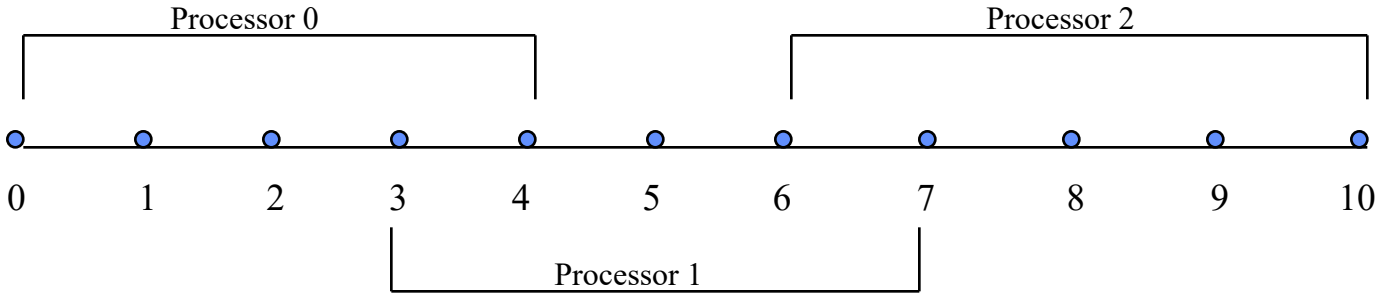
```
  PROGRAM HEATEQN
    implicit none
    include "mpif.h"
    integer :: iglobal, ilocal, itime
    integer :: ierr, nnodes, my_id
    integer :: dest, from, status(MPI_STATUS_SIZE),tag
    integer :: msg_size
    real*8 :: xalp,delx,delt,pi
    real*8 :: T(0:100,0:5), TG(0:10)
    CHARACTER(20) :: FILEN

    delx = 0.1d0
    delt = 1d-4
    xalp = 2.0d0

    call MPI_INIT(ierr)
    call MPI_COMM_SIZE(MPI_COMM_WORLD,
nnodes, ierr)
    call MPI_COMM_RANK(MPI_COMM_WORLD,
my_id, ierr)

    if (nnodes.ne.3) then
      if (my_id.eq.0) then
       print *, "This test needs exactly 3 tasks"
      endif
```

```
     print *, "Process ", my_id, "of", nnodes ,"has started"
!************* Initial Conditions
*************************************
      pi = 4d0*datan(1d0)
      do ilocal = 0, 4
        iglobal = 3*my_id+ilocal
        T(0,ilocal) = dsin(pi*delx*dfloat(iglobal))
      enddo
      write(*,*)"Processor", my_id, "has finished setting
     + initial conditions"
!************* Iterations
*****************************************
      do itime = 1 , 3
       if (my_id.eq.0) then
         write(*,*)"Running Iteration Number ", itime
       endif
       do ilocal = 1, 3
         T(itime,ilocal)=T(itime-1,ilocal)+
     +   xalp*delt/delx/delx*
     +   (T(itime-1,ilocal-1)-2*T(itime-1,ilocal)+T(itime-
1,ilocal+1))
       enddo
       if (my_id.eq.0) then
         write(*,*)"Sending and receiving overlap points"
         dest = 1
```

Fortran MPI Code: 1-D Heat Equation (Contd.)

```
 msg_size = 1
      call
MPI_SEND(T(itime,3),msg_size,MPI_DOUBLE_PRECISION,dest,
     +               tag,MPI_COMM_WORLD,ierr)
      endif
      if (my_id.eq.1) then
        from = 0
        dest = 2
        msg_size = 1
        call
MPI_SEND(T(itime,3),msg_size,MPI_DOUBLE_PRECISION,dest,
     +               tag,MPI_COMM_WORLD,ierr)
        call
MPI_RECV(T(itime,0),msg_size,MPI_DOUBLE_PRECISION,from
,
     +               tag,MPI_COMM_WORLD,status,ierr)
      endif
      if (my_id.eq.2) then
        from = 1
        dest = 1
        msg_size = 1
        call
MPI_SEND(T(itime,1),msg_size,MPI_DOUBLE_PRECISION,dest,
     +               tag,MPI_COMM_WORLD,ierr)
        call
MPI_RECV(T(itime,0),msg_size,MPI_DOUBLE_PRECISION,from
,
     +               tag,MPI_COMM_WORLD,status,ierr)
      endif
      if (my_id.eq.1) then
        from = 2
        dest = 0
        msg_size = 1
        call MPI_RECV(T(itime,4),msg_size,MPI_DOUBLE_PRECISION,from,
     +               tag,MPI_COMM_WORLD,status,ierr)
        call MPI_SEND(T(itime,1),msg_size,MPI_DOUBLE_PRECISION,dest,
     +               tag,MPI_COMM_WORLD,ierr)
      endif
      if (my_id.eq.0) then
        from = 1
        msg_size = 1
        call MPI_RECV(T(itime,4),msg_size,MPI_DOUBLE_PRECISION,from,
     +               tag,MPI_COMM_WORLD,status,ierr)
      endif
      enddo

      if (my_id.eq.0) then
        write(*,*)"SOLUTION SENT TO FILE AFTER 3 TIMESTEPS:"
      endif
      FILEN = 'data'//char(my_id+48)//'.dat'
      open (5, file=FILEN)
      write(5,*)"Processor ",my_id
      do ilocal = 0 , 4
       iglobal = 3*my_id + ilocal
       write(5,*)"ilocal=",ilocal,";iglobal=",iglobal,";T=",T(3,ilocal)
      enddo
      close(5)
      call MPI_FINALIZE(ierr)

      END
```

Simple Application using MPI: 1-D Heat Equation



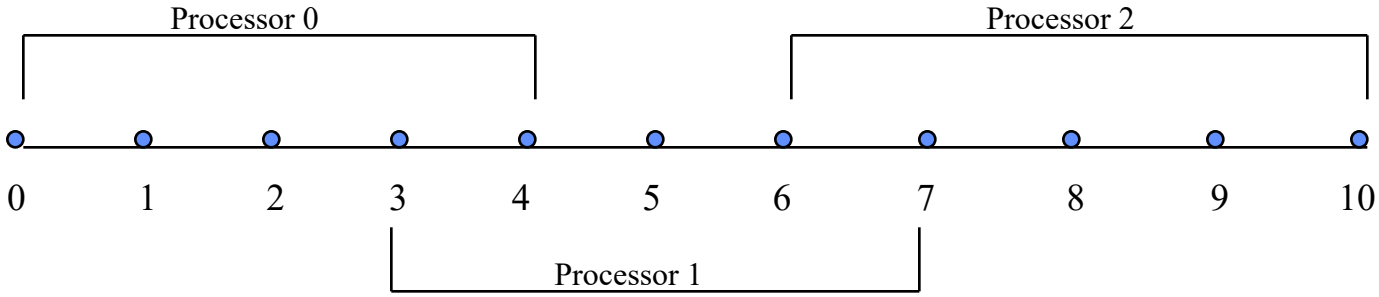
- Compilation

  Fortran: mpif90 -nofree -o heat_mpi.exe heat_mpi.f90

- Run Job:

  sbatch --res=SI2019DAY4 heat_mpi.sb

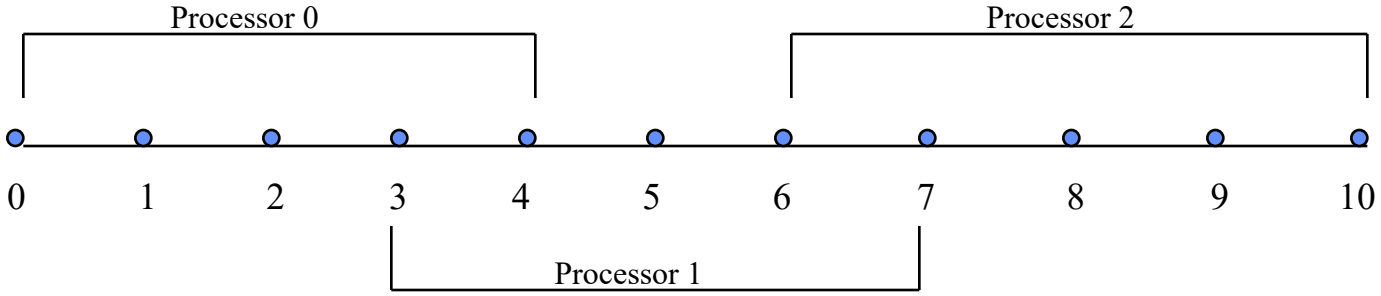
Simple Application using MPI: 1-D Heat Equation



OUTPUT FROM SAMPLE PROGRAM

```
Process  0 of 3 has started
 Processor 0 has finished                setting initial conditions
 Process  1 of 3 has started
 Processor 1 has finished                setting initial conditions
 Process  2 of 3 has started
 Processor 2 has finished                setting initial conditions
 Running Iteration Number  1
 Sending and receiving overlap points
 Running Iteration Number  2
 Sending and receiving overlap points
 Running Iteration Number  3
 Sending and receiving overlap points
 SOLUTION SENT TO FILE AFTER 3 TIMESTEPS:
```

Simple Application using MPI: 1-D Heat Equation




```
% more data0.dat
 Processor  0
 ilocal= 0 ;iglobal= 0 ;T= 0.00000000000000000E+00
 ilocal= 1 ;iglobal= 1 ;T= 0.307205621017284991
 ilocal= 2 ;iglobal= 2 ;T= 0.584339815421976549
 ilocal= 3 ;iglobal= 3 ;T= 0.804274757358271253
 ilocal= 4 ;iglobal= 4 ;T= 0.945481682332597884
```

```
% more data2.dat
 Processor  2
 ilocal= 0 ;iglobal= 6 ;T= 0.945481682332597995
 ilocal= 1 ;iglobal= 7 ;T= 0.804274757358271253
 ilocal= 2 ;iglobal= 8 ;T= 0.584339815421976660
 ilocal= 3 ;iglobal= 9 ;T= 0.307205621017285102
 ilocal= 4 ;iglobal= 10 ;T= 0.00000000000000000E+00
```

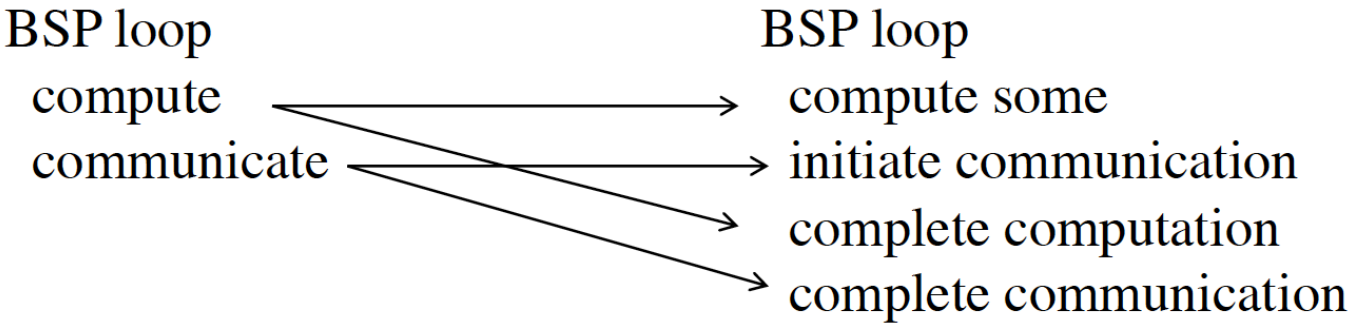
```
% more data1.dat
 Processor  1
 ilocal= 0 ;iglobal= 3 ;T= 0.804274757358271253
 ilocal= 1 ;iglobal= 4 ;T= 0.945481682332597884
 ilocal= 2 ;iglobal= 5 ;T= 0.994138272681972301
 ilocal= 3 ;iglobal= 6 ;T= 0.945481682332597995
 ilocal= 4 ;iglobal= 7 ;T= 0.804274757358271253
```

Performance Considerations

- **Overlap communication with computation**
  - Use non-blocking primitives
  - Hide communication cost
  - Split-phase programming
- **Minimize surface-to-volume ratio**
  - Ghost cell exchange
- **Avoid communication**
  - Even at the cost of some more computation
  - Example: double size of ghost cell and communicate every other time step
  - Communication avoiding algorithms

Asynchronous Communication

- **Overlap communication w/ computation**
  - High performance interconnects can offload communication tasks from CPU to adapter
- **Condition**
  - No data dependencies on transfer
- **Split-phase programming**



MPI – Profiling, Tracing Tools

- Several options available. On Comet we have mpiP, TAU, and Allinea MAP installed.
- Useful when you are trying to isolate performance issues.
- Tools can give you info on how much time is being spent in communication. The levels of detail vary with each tool.
- In general identify scaling bottlenecks and try to overlap communication with computation where possible.

mpiP example

- **Location: $HOME/PARALLEL/MISC**
- **Compile:**

  mpif90 -nofree -g -o heat_mpi_profile.exe heat_mpi.f90 -L/share/apps/compute/mpiP/v3.4.1/mv2/lib -lmpiP -L/share/apps/compute/libiberty -liberty -L/share/apps/compute/libunwind/v1.1/mv2/lib -lunwind

- **Executable already exists. Just submit heat_mpi_profile.sb.**
- **Once the job runs you get a .mpiP file.**

mpiP output

```
@ Command : ./heat_mpi_profile.exe
@ Version                  : 3.4.1
@ MPIP Build date          : Aug  9 2018, 12:07:41
@ Start time               : 2018 08 09 12:12:23
@ Stop time                : 2018 08 09 12:12:23
@ Timer Used               : PMPI_Wtime
@ MPIP env var             : [null]
@ Collector Rank           : 0
@ Collector PID            : 31588
@ Final Output Dir         : .
@ Report generation        : Single collector task
@ MPI Task Assignment      : 0 comet-06-13.sdsc.edu
@ MPI Task Assignment      : 1 comet-06-13.sdsc.edu
@ MPI Task Assignment      : 2 comet-06-13.sdsc.edu

---------------------------------------------------------------------------
@--- MPI Time (seconds) ------------------------------------------------------
---------------------------------------------------------------------------
Task    AppTime    MPITime     MPI%
   0      0.024    0.00989    41.22
   1     0.0243     0.0099    40.81
   2     0.0243   0.000126     0.52
```

mpiP Output

```
   *       0.0726      0.0199     27.44
---------------------------------------------------------------------------
@--- Callsites: 1 -----------------------------------------------------------
---------------------------------------------------------------------------
 ID Lev File/Address        Line Parent_Funct             MPI_Call
  1   0 0x40ca45                  [unknown]               Recv
---------------------------------------------------------------------------
@--- Aggregate Time (top twenty, descending, milliseconds) ------------------
---------------------------------------------------------------------------
Call                 Site       Time    App%    MPI%     COV
Recv                    1       19.5   26.87   97.93    0.86
Send                    1      0.412    0.57    2.07    0.21
---------------------------------------------------------------------------
@--- Aggregate Sent Message Size (top twenty, descending, bytes) ------------
---------------------------------------------------------------------------
Call                 Site      Count      Total       Avrg  Sent%
Send                    1         12         96          8 100.00
---------------------------------------------------------------------------
@--- Callsite Time statistics (all, milliseconds): 6 ------------------------
---------------------------------------------------------------------------
Name                 Site Rank  Count      Max      Mean       Min   App%   MPI%
Recv                    1    0      3     9.73      3.25   0.00504  40.63  98.55
Recv                    1    1      6     9.69      1.62   0.00194  40.14  98.36
```

mpiP output

```
---------------------------------------------------------------------------
@--- Callsite Time statistics (all, milliseconds): 6 ----------------------
---------------------------------------------------------------------------
Name                 Site Rank  Count      Max       Mean        Min   App%   MPI%
Recv                    1    0      3     9.73       3.25    0.00504  40.63  98.55
Recv                    1    1      6     9.69       1.62    0.00194  40.14  98.36
Recv                    1    2      3    0.015    0.00664    0.00188   0.08  15.83
Send                    1    0      3    0.136     0.0477    0.00303   0.60   1.45
Send                    1    1      6    0.146     0.0272    0.00203   0.67   1.64
Send                    1    2      3   0.0999     0.0353    0.00298   0.44  84.17
Send                    1    *     24     9.73       0.83    0.00188  27.44 100.00
---------------------------------------------------------------------------
@--- Callsite Message Sent statistics (all, sent bytes) -------------------
---------------------------------------------------------------------------
Name                 Site Rank   Count       Max      Mean       Min       Sum
Send                    1    0      3         8         8         8        24
Send                    1    1      6         8         8         8        48
Send                    1    2      3         8         8         8        24
Send                    1    *     12         8         8         8        96
---------------------------------------------------------------------------
@--- End of Report --------------------------------------------------------
---------------------------------------------------------------------------
```

More Complex routines

- Derived Data Types
- User defined reduction functions
- Groups/communicator management
- Parallel I/O
- One Sided Communication Routines (RDMA)
- MPI-3 Standard has over 400 routines(!).

Homework!

- **Change directory to $HOME/PARALLEL/MISC**
- **Code “sample.f” has two bugs.**
- **Compile:**

  mpif90 -o sample.exe sample.f

  Run: sbatch sample.sb

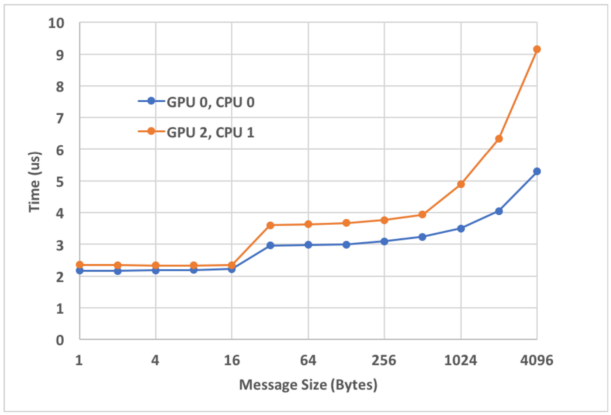
  See if you can identify the two bugs!

MVAPICH2-GDR on Comet

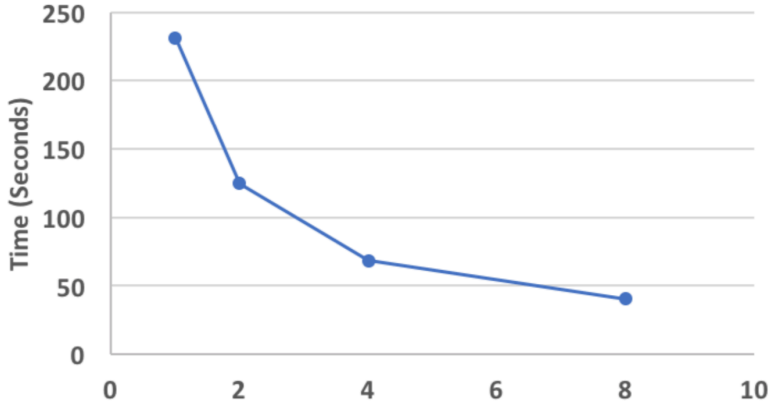
- Dr. DK Panda's team (Ohio State), have been enhancing MVAPICH2 to utilize GPUDirect capabilities and achieve low MPI latencies and high bandwidth.

- MVAPICH2-GDR is available on the SDSC Comet GPU nodes featuring NVIDIA K80s and P100s.

- Applications that use MVAPICH2-GDR include HOOMD-Blue, OSU-Caffe, and TensorFlow (Horovod).



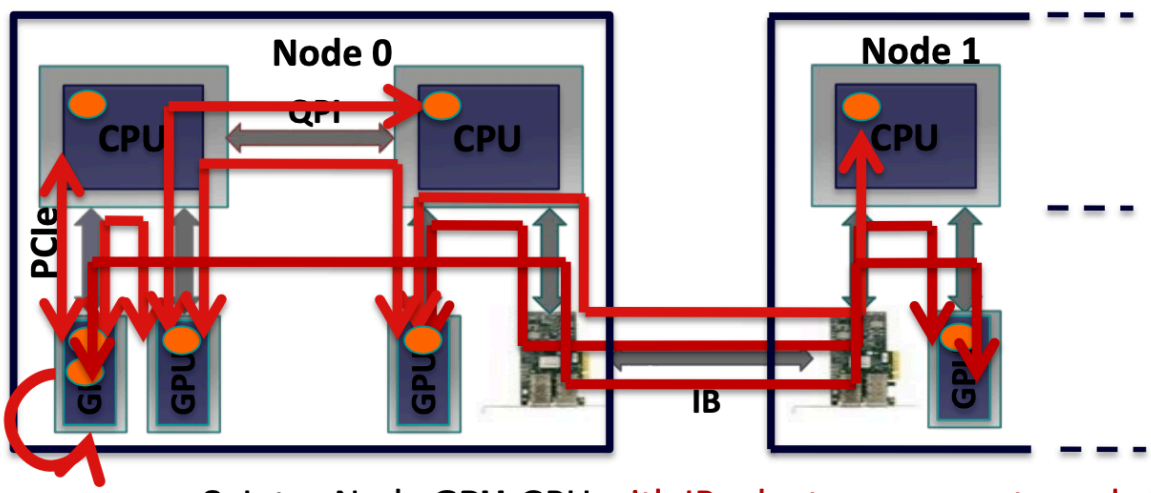
- Latency between GPU 0 , process bound to CPU 0 on both nodes: 2.17 μs
- Latency between GPU 2 , process bound to CPU 1 on both nodes: 2.35 μs



Scaling of OSU-Caffe performance w.r.t number of GPUS; Runs using MVAPICH2-GDR

Optimizing MPI Data Movement on GPU Clusters

- Connected as PCIe devices – Flexibility but Complexity



Memory buffers

1. Intra-**GPU**
2. Intra-Socket **GPU**-GPU
3. Inter-Socket **GPU**-GPU
4. Inter-Node **GPU**-GPU
5. Intra-Socket **GPU**-Host
6. Inter-Socket **GPU**-Host
7. Inter-Node **GPU**-Host

8. Inter-Node **GPU**-GPU with IB adapter on remote socket

and more . . .

- For each path different schemes: Shared_mem, IPC, GPUDirect RDMA, pipeline …
- Critical for runtimes to optimize data movement while hiding the complexity

Reference: Dhabaleswar K. (DK) Panda, Hari Subramoni *"MVAPICH2-GDR: Pushing the Frontier of HPC and Deep Learning"*, **GTC 2017**

GPU-Aware (CUDA-Aware) MPI Library: MVAPICH2-GPU

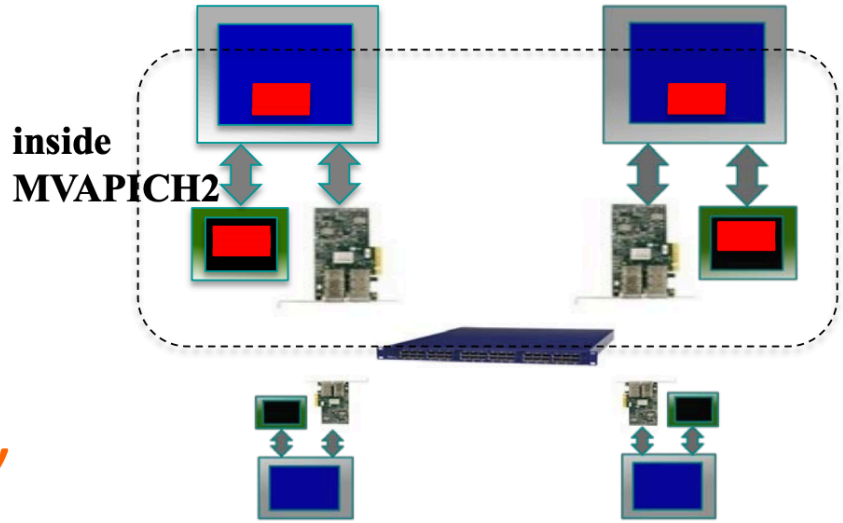
- Standard MPI interfaces used for unified data movement
- Takes advantage of Unified Virtual Addressing (>= CUDA 4.0)
- Overlaps data movement from GPU with RDMA transfers

At Sender:

```
MPI_Send(s_devbuf, size, …);
```

At Receiver:

```
MPI_Recv(r_devbuf, size, …);
```

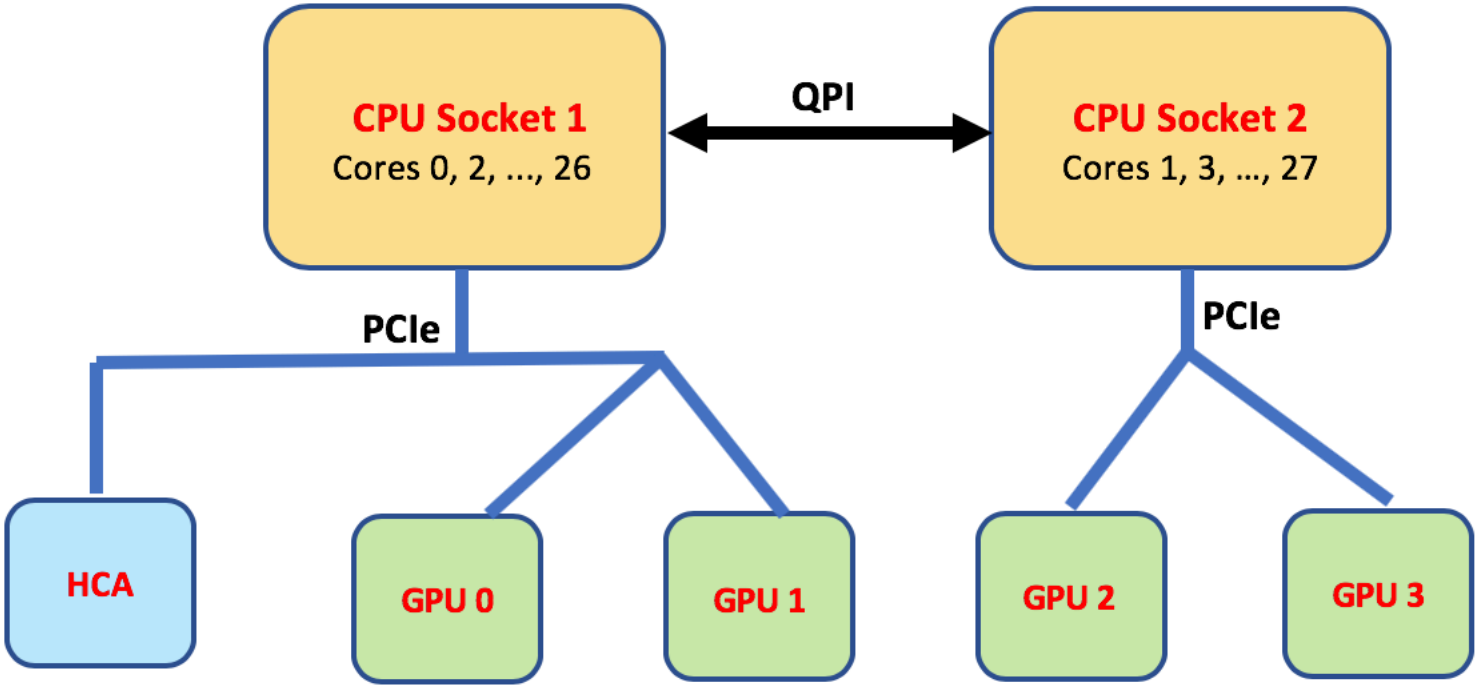


High Performance and High Productivity

Reference: Dhabaleswar K. (DK) Panda, Hari Subramoni *"MVAPICH2-GDR: Pushing the Frontier of HPC and Deep Learning"*, **GTC 2017**

MVAPICH2-GDR

Comet P100 node layout

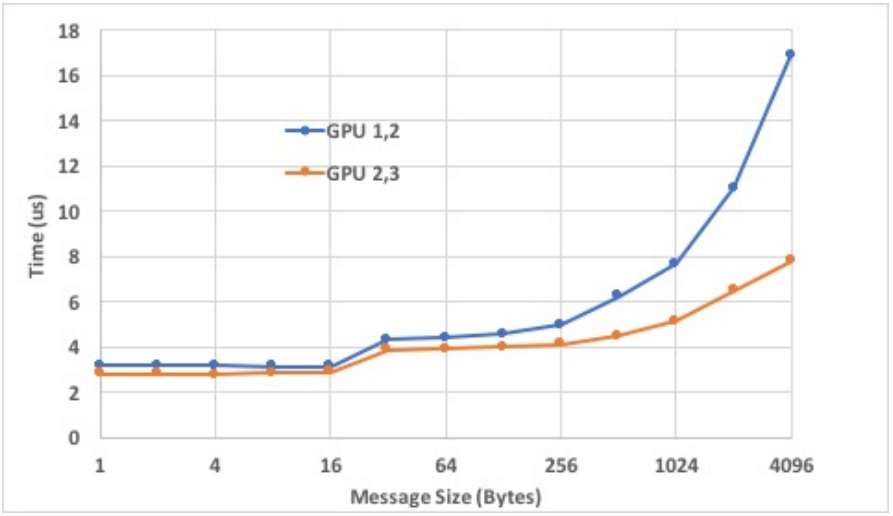


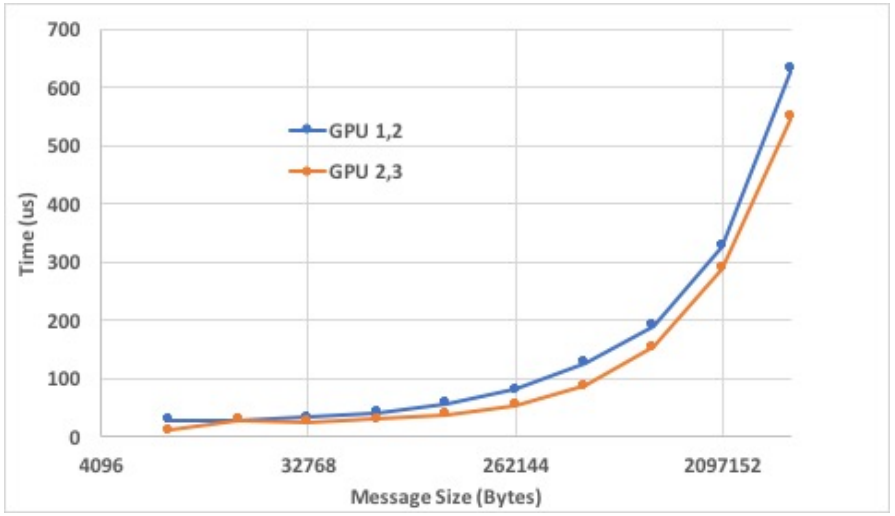
Comet K80 node architecture

```
        GPU0    GPU1    GPU2    GPU3    mlx4_0  CPU Affinity
GPU0     X      PIX     SOC     SOC     SOC     0-0,2-2,4-4,6-6,8-8,10-10,12-12,14-14,16-16,18-18,20-20,22-22
GPU1    PIX      X      SOC     SOC     SOC     0-0,2-2,4-4,6-6,8-8,10-10,12-12,14-14,16-16,18-18,20-20,22-22
GPU2    SOC     SOC      X      PIX     PHB     1-1,3-3,5-5,7-7,9-9,11-11,13-13,15-15,17-17,19-19,21-21,23-23
GPU3    SOC     SOC     PIX      X      PHB     1-1,3-3,5-5,7-7,9-9,11-11,13-13,15-15,17-17,19-19,21-21,23-23
mlx4_0  SOC     SOC     PHB     PHB      X

Legend:

  X   = Self
  SOC  = Connection traversing PCIe as well as the SMP link between CPU sockets(e.g. QPI)
  PHB  = Connection traversing PCIe as well as a PCIe Host Bridge (typically the CPU)
  PXB  = Connection traversing multiple PCIe switches (without traversing the PCIe Host Bridge)
  PIX  = Connection traversing a single PCIe switch
  NV#  = Connection traversing a bonded set of # NVLinks
```

- 4 GPUs per node
- GPUs (0,1) and (2,3) can do P2P communication
- Mellanox InfiniBand adapter associated with second socket (GPUs 2, 3)

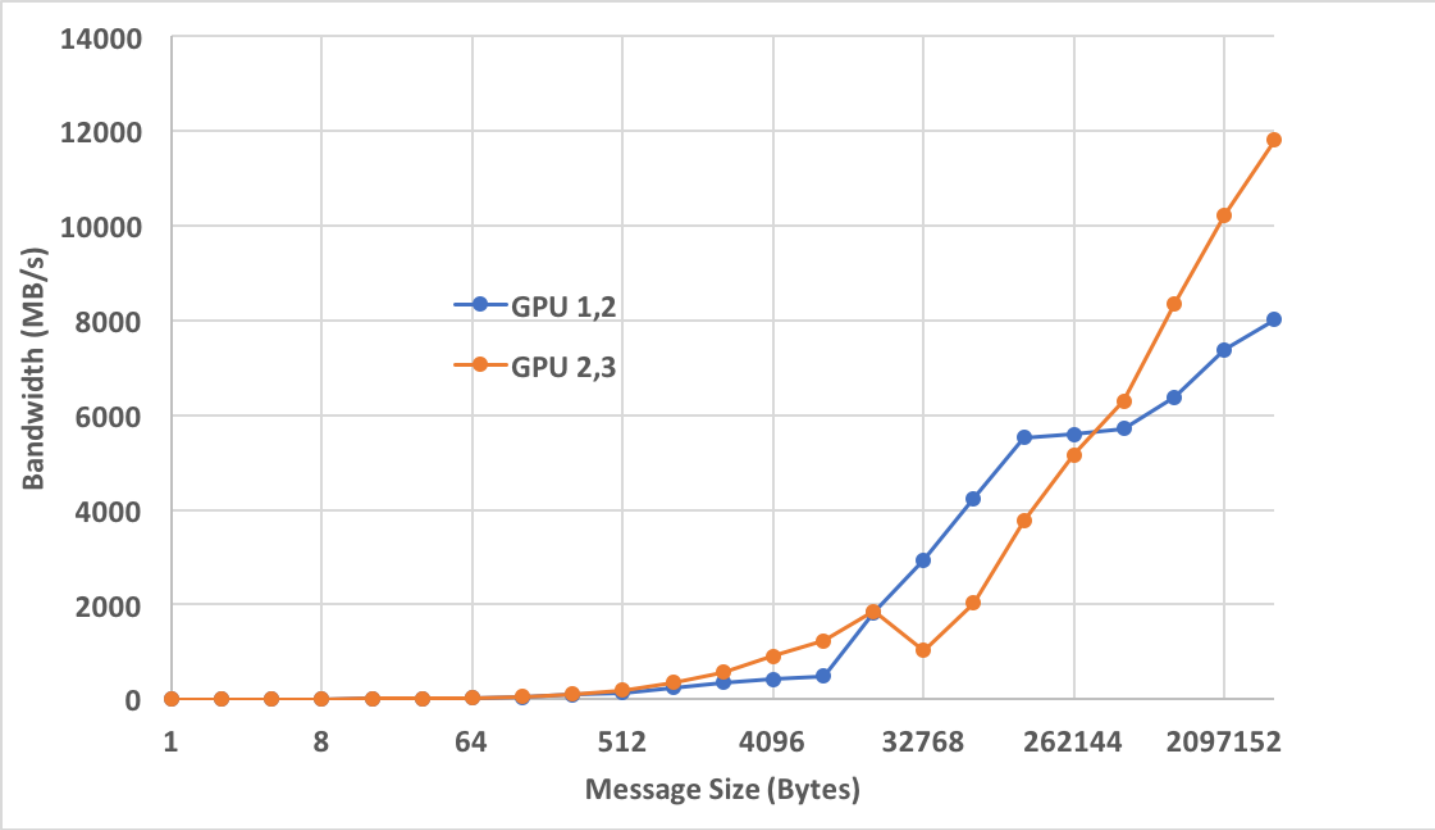
OSU Latency (osu_latency) Benchmark Intra-node, K80 nodes



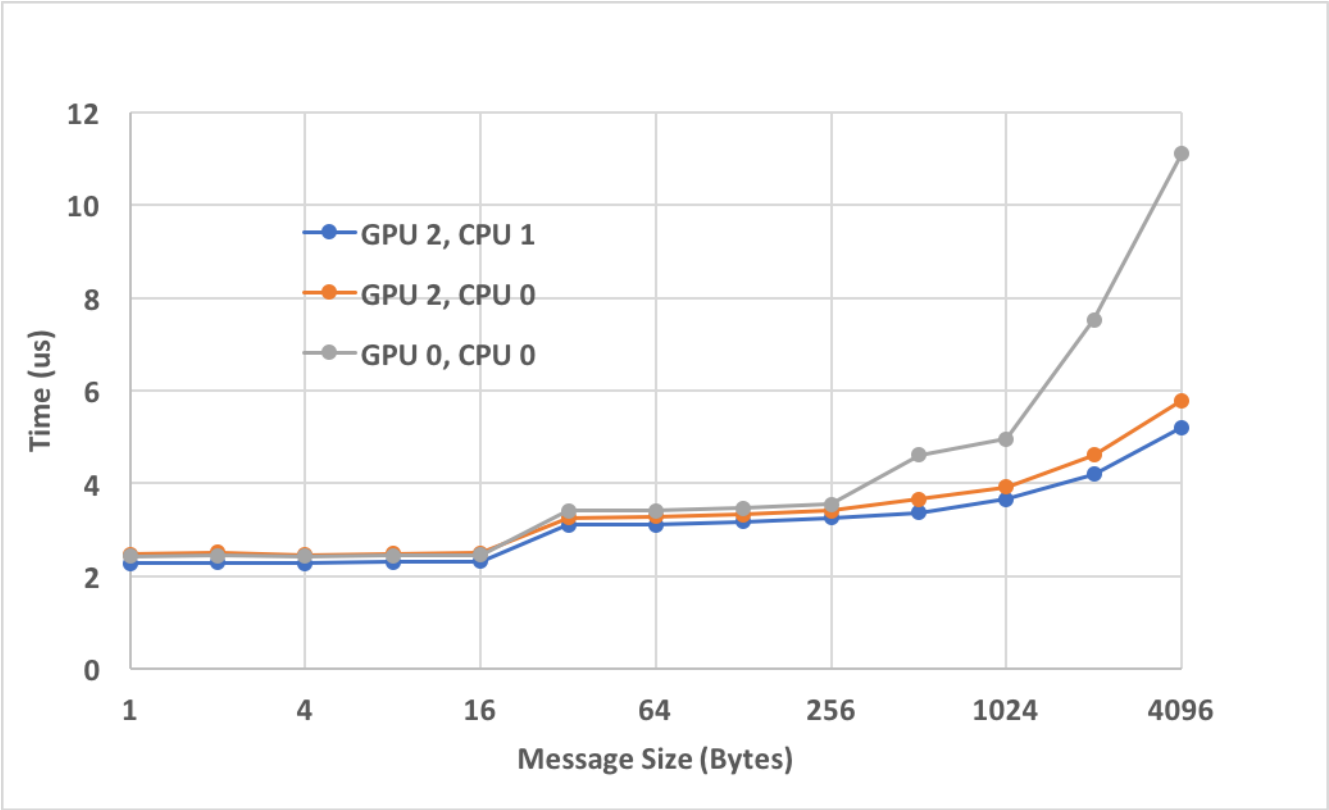


- Latency between GPU 2 , GPU 3: 2.82 μs
- Latency between GPU 1 , GPU 2: 3.18 μs

OSU Bandwidth (osu_bw) Benchmark
Intra-node, K80 nodes

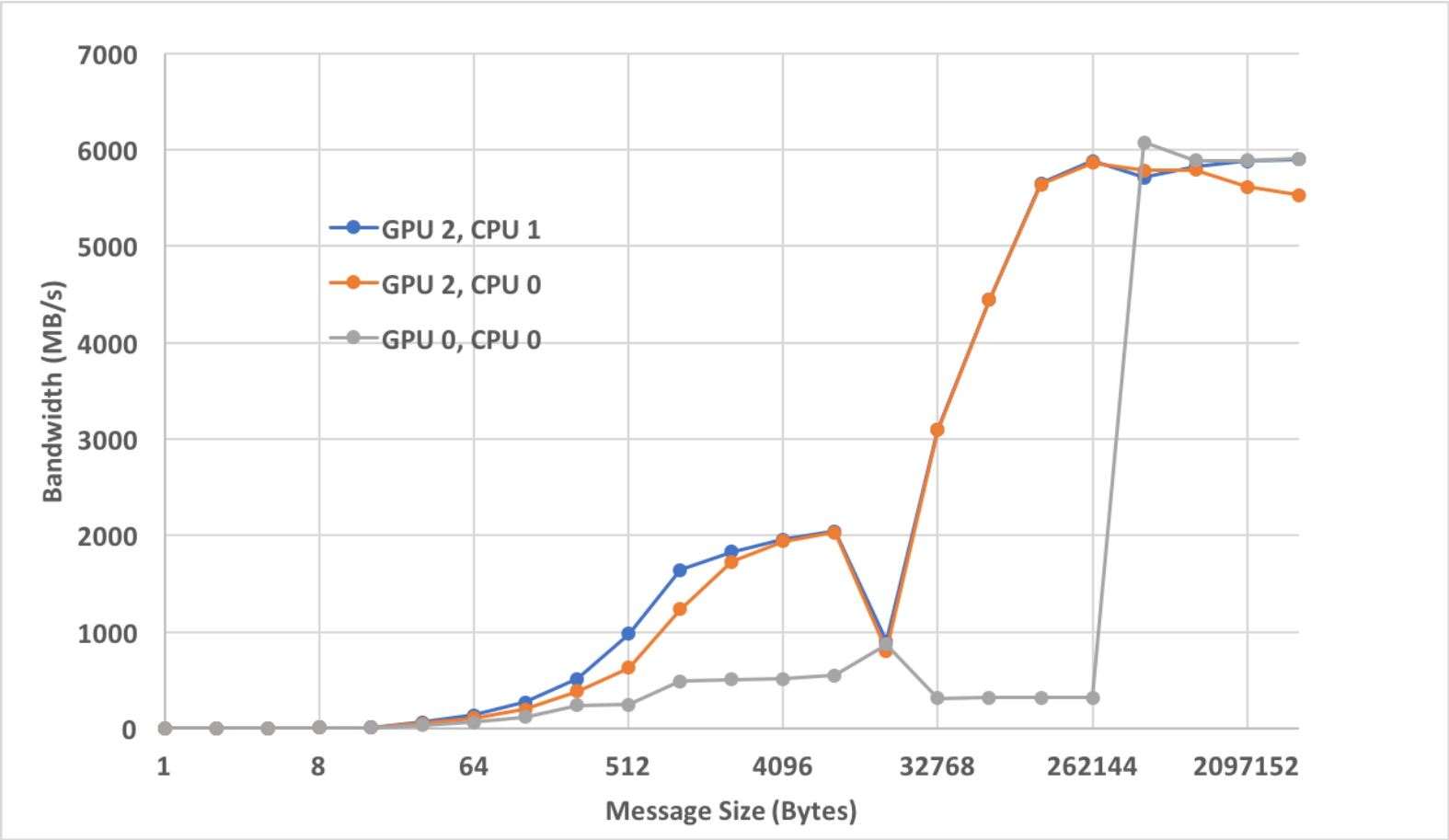


OSU Latency (osu_latency) Benchmark
Inter-node, K80 nodes



- Latency between GPU 2 , process bound to CPU 1 on both nodes: 2.27 μs
- Latency between GPU 2 , process bound to CPU 0 on both nodes: 2.47 μs
- Latency between GPU 0 , process bound to CPU 0 on both nodes: 2.43 μs

OSU Bandwidth (osu_bw) Benchmark
Inter-node, K80 nodes

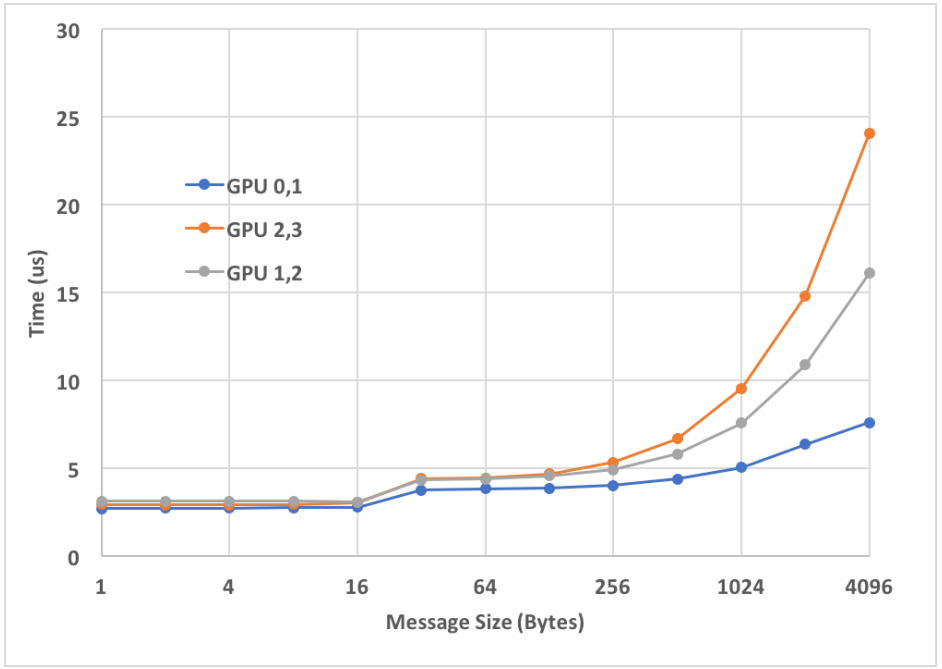


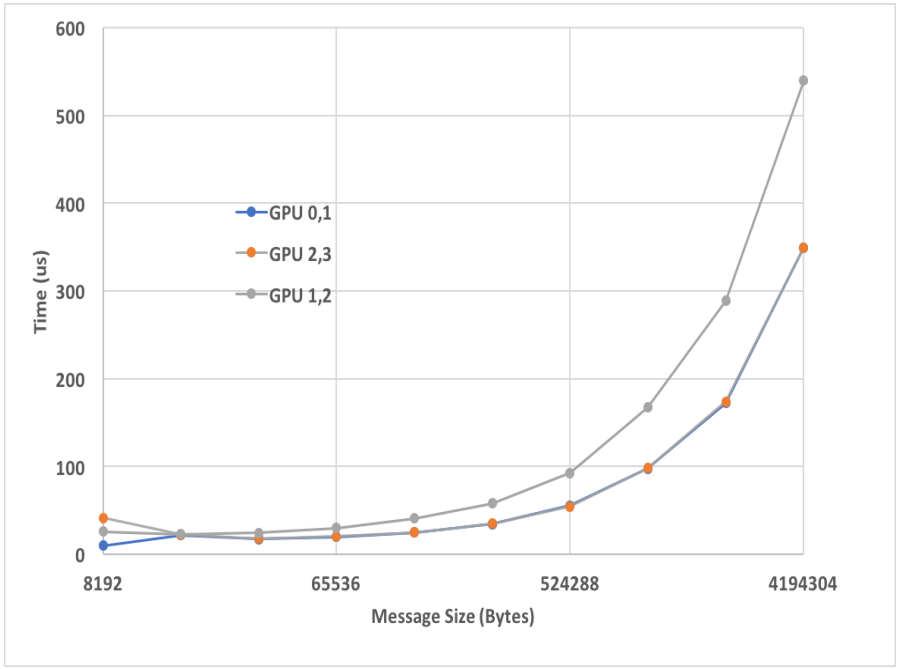
Comet P100 node architecture

```
        GPU0    GPU1    GPU2    GPU3    mlx4_0  CPU Affinity
GPU0     X      PIX     SOC     SOC     PHB     0-0,2-2,4-4,6-6,8-8,10-10,12-12,14-14,16-16,18-18,20-20,22-22,24-24,26-26
GPU1    PIX      X      SOC     SOC     PHB     0-0,2-2,4-4,6-6,8-8,10-10,12-12,14-14,16-16,18-18,20-20,22-22,24-24,26-26
GPU2    SOC     SOC      X      PIX     SOC     1-1,3-3,5-5,7-7,9-9,11-11,13-13,15-15,17-17,19-19,21-21,23-23,25-25,27-27
GPU3    SOC     SOC     PIX      X      SOC     1-1,3-3,5-5,7-7,9-9,11-11,13-13,15-15,17-17,19-19,21-21,23-23,25-25,27-27
mlx4_0  PHB     PHB     SOC     SOC      X

Legend:

  X    = Self
  SOC  = Connection traversing PCIe as well as the SMP link between CPU sockets(e.g. QPI)
  PHB  = Connection traversing PCIe as well as a PCIe Host Bridge (typically the CPU)
  PXB  = Connection traversing multiple PCIe switches (without traversing the PCIe Host Bridge)
  PIX  = Connection traversing a single PCIe switch
  NV#  = Connection traversing a bonded set of # NVLinks
```

- 4 GPUs per node
- GPUs (0,1) and (2,3) can do P2P communication
- Mellanox InfiniBand adapter associated with first socket (GPUs 0, 1)

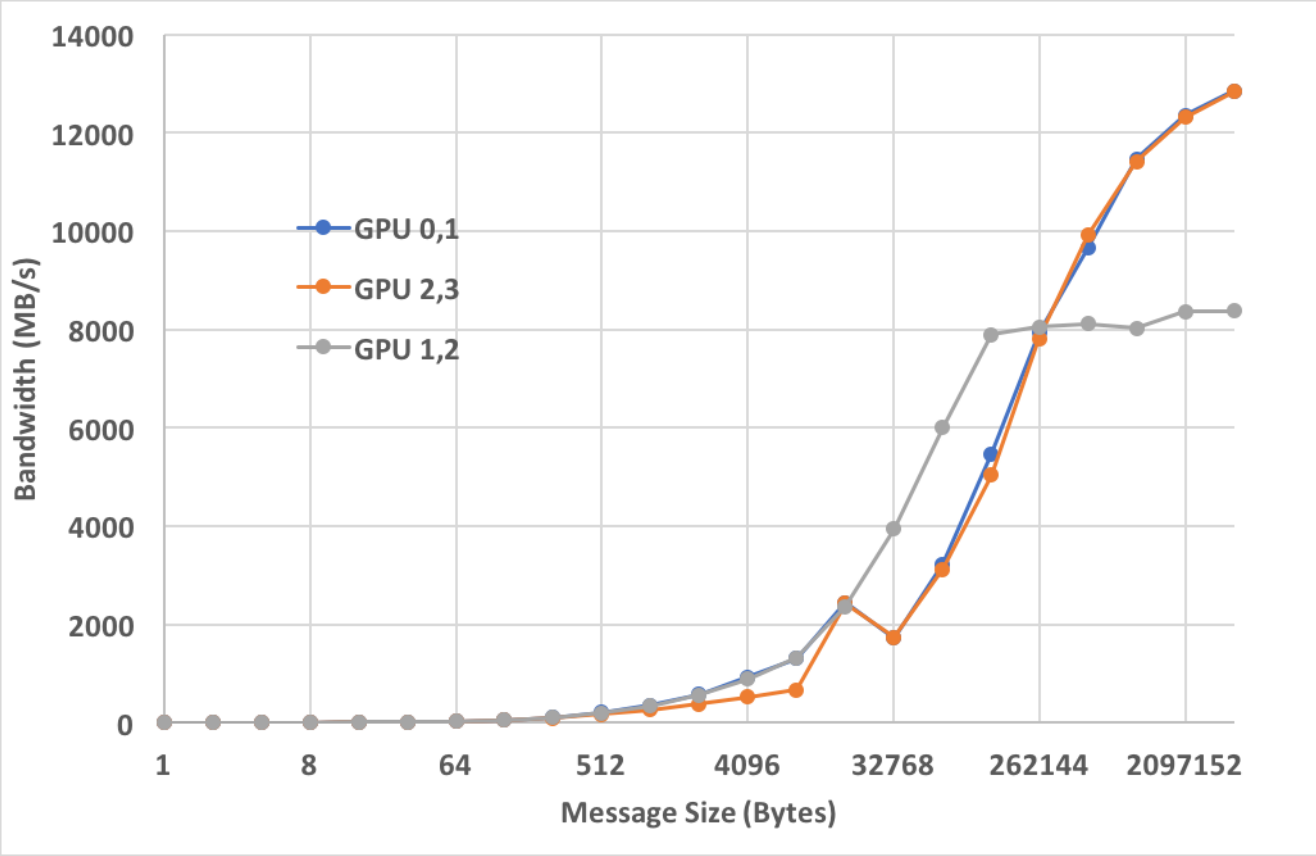
OSU Latency (osu_latency) Benchmark Intra-node, P100 nodes



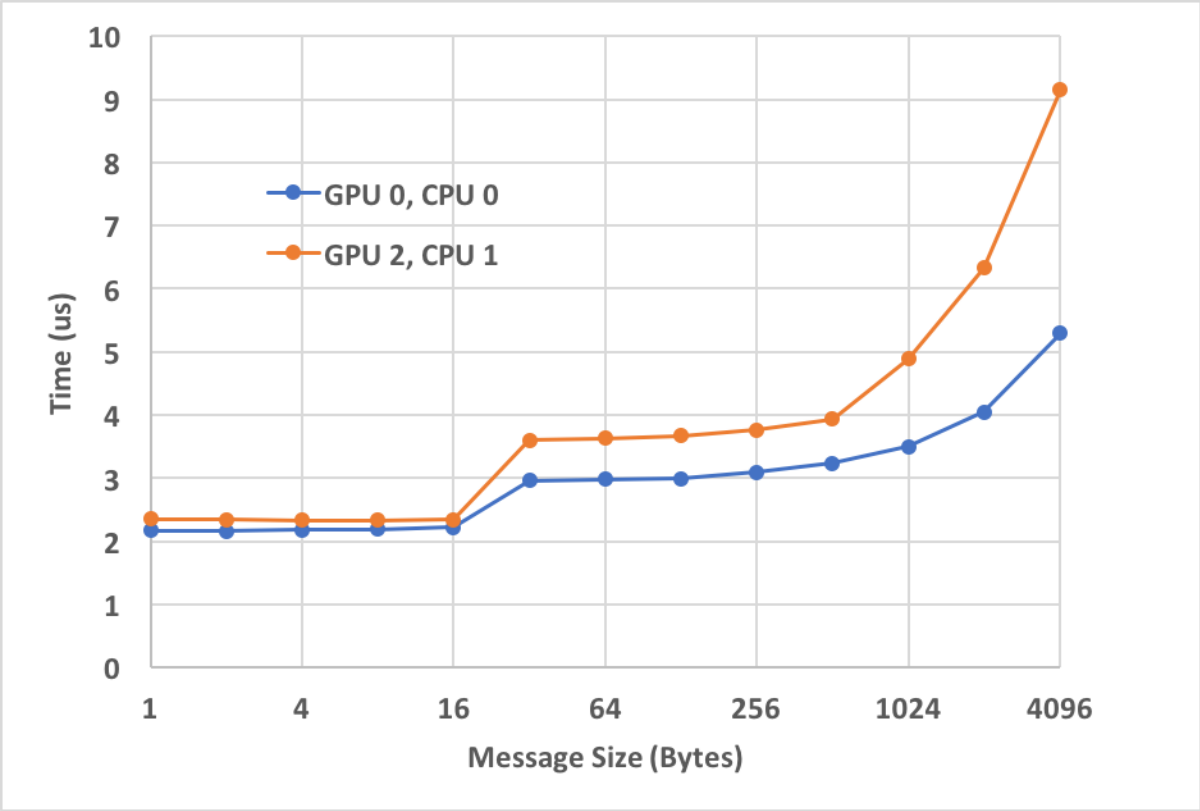


- Latency between GPU 0 , GPU 1: 2.73 μs
- Latency between GPU 2 , GPU 3: 2.95 μs
- Latency between GPU 1 , GPU 2: 3.13 μs

OSU Bandwidth (osu_bw) Benchmark Intra-node, P100 nodes



OSU Latency (osu_latency) Benchmark Inter-node, P100 nodes



- Latency between GPU 0 , process bound to CPU 0 on both nodes: 2.17 μs
- Latency between GPU 2 , process bound to CPU 1 on both nodes: 2.35 μs

References

- **Excellent tutorials from LLNL:**
  - https://computing.llnl.gov/tutorials/mpi/
  - https://computing.llnl.gov/tutorials/openMP/

- **MPI for Python:**
  - http://mpi4py.scipy.org/docs/usrman/tutorial.html

- **MVAPICH2 User Guide:**
  - http://mvapich.cse.ohio-state.edu/userguide/

- **MVAPICH2-GDR User Guide:**
  - http://mvapich.cse.ohio-state.edu/userguide/gdr/