Announcements

- If you registered for the course recently, please email the TAs for a zaratan account
Shared memory architecture

- All processors/cores can access all memory as a single address space

Uniform Memory Access

Non-uniform Memory Access (NUMA)

https://computing.llnl.gov/tutorials/parallel_comp/#SharedMemory
Distributed memory architecture

- Each processor/core only has access to its local memory
- Writes in one processor’s memory have no effect on another processor’s memory
Distributed memory architecture

- Each processor/core only has access to its local memory
- Writes in one processor’s memory have no effect on another processor’s memory
Programming models

• Shared memory model: All threads have access to all of the memory
  • Pthreads, OpenMP

• Distributed memory model: Each process has access to their own local memory
  • Also sometimes referred to as message passing
    • MPI, Charm++

• Hybrid models: Use both shared and distributed memory models together
  • MPI+OpenMP, Charm++ (SMP mode)
Distributed memory programming models

- Each process only has access to its own local memory/address space.
- When it needs data from remote processes, it has to send messages.
Message passing

- Each process runs in its own address space
  - Access to only their memory (no shared data)
- Use special routines to exchange data
Message passing programs

- A parallel message passing program consists of independent processes
  - Processes created by a launch/run script
- Each process runs the same executable, but potentially different parts of the program
- Often used for SPMD style of programming
Message passing history

- PVM (Parallel Virtual Machine) was developed in 1989-1993
- MPI forum was formed in 1992 to standardize message passing models and MPI 1.0 was released around 1994
  - v2.0 - 1997
  - v3.0 - 2012
Message Passing Interface (MPI)

- It is an interface standard — defines the operations / routines needed for message passing
- Implemented by vendors and academics for different platforms
  - Meant to be “portable”: ability to run the same code on different platforms without modifications
- Some popular implementations are MPICH, MVAPICH, OpenMPI
Hello world in MPI

```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("Hello world! I'm %d of %d\n", rank, size);

    MPI_Finalize();
    return 0;
}
```
Compiling and running an MPI program

- Compiling:

  ```
  mpicc -o hello hello.c
  ```

- Running:

  ```
  mpirun -n 2 ./hello
  ```
Process creation / destruction

- `int MPI_Init( int argc, char **argv )`
  - Initializes the MPI execution environment
- `int MPI_Finalize( void )`
  - Terminates MPI execution environment
Process identification

- `int MPI_Comm_size( MPI_Comm comm, int *size )`
  - Determines the size of the group associated with a communicator

- `int MPI_Comm_rank( MPI_Comm comm, int *rank )`
  - Determines the rank (ID) of the calling process in the communicator

- **Communicator — a set of processes**
  - Default communicator: `MPI_COMM_WORLD`
Send a message

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

- `buf`: address of send buffer
- `count`: number of elements in send buffer
- `datatype`: datatype of each send buffer element
- `dest`: rank of destination process
- `tag`: message tag
- `comm`: communicator
Receive a message

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

- `buf`: address of receive buffer
- `status`: status object
- `count`: maximum number of elements in receive buffer
- `datatype`: datatype of each receive buffer element
- `source`: rank of source process
- `tag`: message tag
- `comm`: communicator
Semantics of point-to-point communication

- If a sender sends two messages to a destination, and both match the same receive, the second message cannot be received if the first is still pending
  - “No-overtaking” messages
  - True when processes are single-threaded
- Tags can be used to disambiguate between messages in case of non-determinism
int main(int argc, char *argv) {
    ...
    MPI_Comm_rank(MPI_COMM_WORLD, &rank);
    MPI_Comm_size(MPI_COMM_WORLD, &size);

    int data;
    if (rank == 0) {
        data = 7;
        MPI_Send(&data, 1, MPI_INT, 1, 0, MPI_COMM_WORLD);
    } else if (rank == 1) {
        MPI_Recv(&data, 1, MPI_INT, 0, 0, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
        printf("Process 1 received data %d from process 0\n", data);
    }

    ...
}
Basic MPI_Send and MPI_Recv

• MPI_Send and MPI_Recv routines are blocking
  • Only return when the buffer specified in the call can be used
  • Send: Returns once sender can reuse the buffer
  • Recv: Returns once data from Recv is available in the buffer

Process 0

Process 1

Time

MPI_Send

MPI_Recv
Basic MPI_Send and MPI_Recv

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![Diagram showing a deadlock between Process 0 and Process 1 during MPI_Send and MPI_Recv calls. The diagram indicates that Process 0 is sending to Process 1, and Process 1 is receiving from Process 0, leading to a deadlock symbolized by "Deadlock!".]
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Process 0

Process 1

Deadlock!

Time

MPI_Send

MPI_Recv
Example program

```c
int main(int argc, char *argv) {
    ...
    MPI_Comm_rank(MPI_COMM_WORLD, &rank);
    ...
    if (rank % 2 == 0) {
        data = rank;
        MPI_Send(&data, 1, MPI_INT, rank+1, 0, ...);
    } else {
        data = rank * 2;
        MPI_Recv(&data, 1, MPI_INT, rank-1, 0, ...);
    }
    ...
    printf("Process %d received data %d\n", data);
}
...
Example program

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int main(int argc, char *argv) {
    ...
    MPI_Comm_rank(MPI_COMM_WORLD, &rank);
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    }
    ...
    printf("Process %d received data %d\n", data);
}
...
MPI communicators

- Communicator represents a group or set of processes numbered 0, … , n-1
- Every program starts with MPI_COMM_WORLD (default communicator)
  - Defined by the MPI runtime, this group includes all processes
- Several MPI routines to create sub-communicators
  - MPI_Comm_split
  - MPI_Cart_create
  - MPI_Group_incl
MPI datatypes

• Can be a pre-defined one: MPI_INT, MPI_CHAR, MPI_DOUBLE, …

• Derived or user-defined datatypes:
  • Array of elements of another datatype
  • struct data type to accommodate sending multiple datatypes