

MPI

Message Passing Interfaces

OpenMP

- ▶ Basic data parallelism over for loops
 -) `#pragma omp parallel for`
 -) `#pragma omp parallel { #pragma omp for { } }`
- ▶ Avoiding race conditions
 -) `#pragma omp atomic`
 -) `#pragma omp atomic capture`
 -) `#pragma omp critical { }`
 -) `#pragma omp single { }`
 -) `#pragma omp master { }`
- ▶ Reductions
 -) `#pragma omp parallel for reduction(op:variable)`
 -) `op = +,-,min,max,etc. (see online resources for list)`



MPI

Message Passing
Interface



Outline

- Background
- Message Passing
- MPI
 - Group and Context
 - Communication Modes
 - Blocking/Non-blocking
 - Features
 - Programming / issues
- Tutorial



Distributed Computing Paradigms

- Communication Models:
 - Message Passing
 - Shared Memory
- Computation Models:
 - Functional Parallel
 - Data Parallel



Message Passing

- A process is a program counter and address space.
- Message passing is used for communication among processes.
- Inter-process communication:
 - Type:
Synchronous / Asynchronous
 - Movement of data from one process's address space to another's



Synchronous Vs. Asynchronous

- A synchronous communication is not complete until the **message** has been received.
- An asynchronous communication completes as soon as the **message** is on the way.

Synchronous Vs. Asynchronous (cont.)





What is message passing?

- Data transfer.
- Requires cooperation of sender and receiver
- Cooperation not always apparent in code

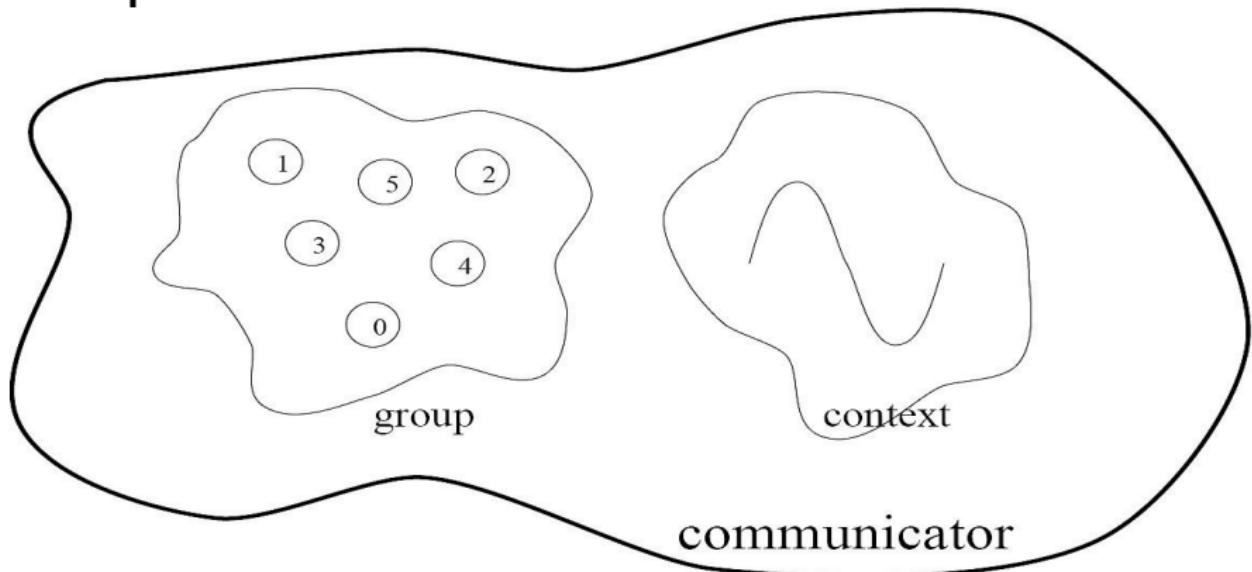


What is MPI?

- A message-passing library specifications:
 - Extended message-passing model
 - Not a language or compiler specification
 - Not a specific implementation or product
- For parallel computers, clusters, and heterogeneous networks.
- Communication modes: *standard*, *synchronous*, *buffered*, and *ready*.
- Designed to permit the development of parallel software libraries.
- Designed to provide access to advanced parallel hardware for
 - End users
 - Library writers
 - Tool developers



Group and Context



The context is what prevents an operation on one communicator from matching with a similar operation on another communicator. MPI keeps an ID for each communicator internally to prevent the mixups. The group is a little simpler to understand since it is just the set of all processes in the communicator. A communicator is a data object that specifies the scope of a communication operation, that is, the group of processes involved and the communication context. Contexts partition the communication space. A message sent in one context cannot be received in another context. Process ranks are interpreted with respect to the process group associated with a communicator.

Group and Context (cont.).

- ● ● Are two important and indivisible concepts of MPI.
- Group: is the set of processes that communicate with one another. It is an ordered collection of processes. If a group consists of p processes, each process in group is assigned a unique rank, which is a nonnegative integer in the range 0, 1, ..., $p-1$.
- Context: it is somehow similar to the frequency in radio communications. its the system-defined object that uniquely identifies a communicator. Two distinct communicators have different contexts, even if they have identical underlying groups.
- Communicator: is the central object for communication in MPI. Each communicator is associated with a group and a context. It provides a separate communication space.



Communication Modes

- Based on the type of send:
 - Synchronous: Completes once the acknowledgement is received by the sender.
 - Buffered send: completes immediately, unless if an error occurs.
 - Standard send: completes once the message has been sent, which may or may not imply that the message has arrived at its destination.
 - Ready send: completes immediately, if the receiver is ready for the message it will get it, otherwise the message is dropped silently.



Blocking vs. Non-Blocking

- Blocking, means the program will not continue until the communication is completed.
- Non-Blocking, means the program will continue, without waiting for the communication to be completed.



Features of MPI

- General
 - Communications combine context and group for message security.
 - Thread safety can't be assumed for MPI programs.



Features that are NOT part of MPI

- Process Management
- Remote memory transfer
- Threads
- Virtual shared memory



Why to use MPI?

- 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.
- Portable !!!!!!!!!!!!!!!
- Good way to learn about subtle issues in parallel computing



How big is the MPI library?

- Huge (125 Functions).

- Basic (6 Functions).



Basic Commands

Standard with blocking



Skeleton MPI Program

```
#include <mpi.h>

main( int argc, char** argv )
{
    MPI_Init( &argc, &argv );

    /* main part of the program */

    /*
        Use MPI function call depend on your data
        partitioning and the parallelization
        architecture
    */

    MPI_Finalize();
}
```



Initializing MPI

- The initialization routine `MPI_INIT` is the first MPI routine called.
- `MPI_INIT` is called once

```
int mpi_Init( int *argc, char **argv );
```



A minimal MPI program(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;
}
```



A minimal MPI program(c) (cont.)

- `#include "mpi.h"` provides basic MPI definitions and types.
- `MPI_Init` starts MPI
- `MPI_Finalize` exits MPI
- Note that all non-MPI routines are local; thus “printf” run on each process
- Note: MPI functions return error codes or `MPI_SUCCESS`



Error handling

- By default, an error causes all processes to abort.
- The user can have his/her own error handling routines.
- Some custom error handlers are available for downloading from the net.



Improved Hello (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;
}
```



Some concepts

- The default communicator is the `MPI_COMM_WORLD`

- A process is identified by its rank in the group associated with a communicator.



Data Types

- The data message which is sent or received is described by a triple (address, count, datatype).
- The following data types are supported by MPI:
 - Predefined data types that are corresponding to data types from the programming language.
 - Arrays.
 - Sub blocks of a matrix
 - User defined data structure.
 - A set of predefined data types



Basic MPI types

MPI datatype

MPI_CHAR
MPI_SIGNED_CHAR
MPI_UNSIGNED_CHAR
MPI_SHORT
MPI_UNSIGNED_SHORT
MPI_INT
MPI_UNSIGNED
MPI_LONG
MPI_UNSIGNED_LONG
MPI_FLOAT
MPI_DOUBLE
MPI_LONG_DOUBLE

C datatype

signed char
signed char
unsigned char
signed short
unsigned short
signed int
unsigned int
signed long
unsigned long
float
double
long double



Why defining the data types during the send of a message?

Because communications take place between heterogeneous machines. Which may have different data representation and length in the memory.



MPI blocking send

```
MPI_SEND(void *start, int  
        count, MPI_Datatype datatype, int dest,  
        int tag, MPI_Comm comm)
```

- The message buffer is described by (**start**, **count**, **datatype**).
- **dest** is the rank of the target process in the defined communicator.
- **tag** is the message identification number.



MPI blocking receive

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

- **Source** is the rank of the sender in the communicator.
- The receiver can specify a wildcard value for source (MPI_ANY_SOURCE) and/or a wildcard value for tag (MPI_ANY_TAG), indicating that any source and/or tag are acceptable
- **Status** is used for extra information about the received message if a wildcard receive mode is used.
- If the count of the message received is less than or equal to that described by the MPI receive command, then the message is successfully received. Else it is considered as a buffer overflow error.



MPI_STATUS

- Status is a data structure
- In C:

```
int recvd_tag, recvd_from, recvd_count;  
MPI_Status status;  
MPI_Recv(..., MPI_ANY_SOURCE, MPI_ANY_TAG,  
..., &status)  
recvд_tag = status.MPI_TAG;  
recvд_from = status.MPI_SOURCE;  
MPI_Get_count(&status, datatype,  
&recvд_count);
```



More info

- A receive operation may accept messages from an arbitrary sender, but a send operation must specify a unique receiver.
- Source equals destination is allowed, that is, a process can send a message to itself.



Why MPI is simple?

- Many parallel programs can be written using just these six functions, only two of which are non-trivial;
 - MPI_INIT
 - MPI_FINALIZE
 - MPI_COMM_SIZE
 - MPI_COMM_RANK
 - MPI_SEND
 - MPI_RECV



Simple full example

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

int main(int argc, char *argv[])
{
    const int tag = 42;          /* Message tag */
    int id, ntasks, source_id, dest_id, err, i;
    MPI_Status status;
    int msg[2]; /* Message array */

    err = MPI_Init(&argc, &argv); /* Initialize MPI */
    if (err != MPI_SUCCESS) {
        printf("MPI initialization failed!\n");
        exit(1);
    }
    err = MPI_Comm_size(MPI_COMM_WORLD, &ntasks); /* Get nr of tasks */
    err = MPI_Comm_rank(MPI_COMM_WORLD, &id); /* Get id of this process */
    if (ntasks < 2) {
        printf("You have to use at least 2 processors to run this program\n");
        MPI_Finalize(); /* Quit if there is only one processor */
        exit(0);
    }
}
```



Simple full example (Cont.)

```
if (id == 0) { /* Process 0 (the receiver) does this */
    for (i=1; i<ntasks; i++) {
        err = MPI_Recv(msg, 2, MPI_INT, MPI_ANY_SOURCE, tag, MPI_COMM_WORLD, \
                        &status); /* Receive a message */
        source_id = status.MPI_SOURCE; /* Get id of sender */
        printf("Received message %d %d from process %d\n", msg[0], msg[1], \
               source_id);
    }
} else { /* Processes 1 to N-1 (the senders) do this */
    msg[0] = id; /* Put own identifier in the message */
    msg[1] = ntasks; /* and total number of processes */
    dest_id = 0; /* Destination address */
    err = MPI_Send(msg, 2, MPI_INT, dest_id, tag, MPI_COMM_WORLD);
}

err = MPI_Finalize(); /* Terminate MPI */
if (id==0) printf("Ready\n");
exit(0);
return 0;
}
```



Collective Operations



Introduction to collective operations in MPI

- Collective operations are called by all processes in a communicator
- MPI_Bcast distributes data from one process(the root) to all others in a communicator.

Syntax:

```
MPI_Bcast(void *message, int count, MPI_Datatype  
datatype, int root, MPI_Comm comm)
```

- MPI_Reduce combines data from all processes in communicator or and returns it to one process

Syntax:

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

- In many numerical algorithm, send/receive can be replaced by Bcast/Reduce, improving both simplicity and efficiency.

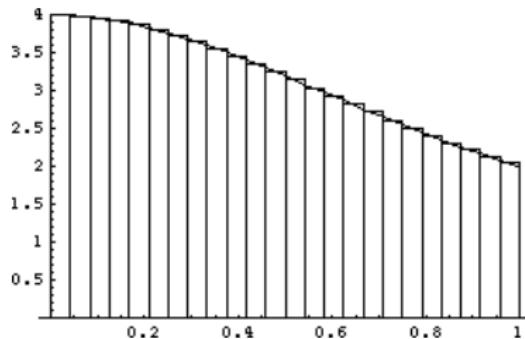


Collective Operations

MPI_MAX, MPI_MIN, MPI_SUM, MPI_PROD,
MPI LAND, MPI_BAND, MPI_LOR, MPI_BOR,
MPI_LXOR, MPI_BXOR, MPI_MAXLOC,
MPI_MINLOC

● ● ● Example: Compute $\text{PI} (0)$

$$\pi = \int_0^1 \frac{4}{1+x^2} dx$$



● ● ● Example: Compute PI (1)

```
#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)
    }
```



Example: Compute PI (2)

```
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\n", pi, fabs(pi - PI25DT));

MPI_Finalize();
return 0;
}
```



When to use MPI

- Portability and Performance
- Irregular data structure
- Building tools for others
- Need to manage memory on a per processor basis



Programming with MPI



Compile and run the code

- Compile using:

```
mpicc -o pi pi.c
```

Or

```
mpic++ -o pi pi.cpp
```

- mpirun -np # of procs -machinefile XXX pi
- -machinefile tells MPI to run the program on the machines of XXX.



MPI on ECE Solaris Machines (1)

- Log in to *draco.ece.arizona.edu*
- From outside the UofA first log in to *shell.ece.arizona.edu*
- Create a Text file and name it. For example ML, and have the following lines:

```
150.135.221.71
150.135.221.72
150.135.221.73
150.135.221.74
150.135.221.75
150.135.221.76
150.135.221.77
150.135.221.78
```



MPI on ECE Solaris Machines (2)

ex2.c

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

int main(argc,argv)
    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;
        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\n", pi, fabs(pi - PI25DT));
    }
    MPI_Finalize();
}
```



MPI on ECE Solaris Machines (3)

- How to compile:

```
mpicc ex2.c -o ex2 -lm
```

- How to run:

```
mpirun -np 4 -machinefile ml ex2
```



Where to get MPI library?

- MPICH (WINDOWS / UNICES)
 - <http://www-unix.mcs.anl.gov/mpi/mpich/>

- Open MPI (UNICES)
 - <http://www.open-mpi.org/>

Today's Biz

1. Review OpenMP
2. Talk about project
3. Talk about homework
4. MPI slides
5. **MPI tutorial**

MPI tutorial

1. Basic compilation
2. Environment
3. Send/Recv
4. Collective operations
5. Implementing BFS

**C++ Demonstration – Blank code and data available
on website**

www.cs.rpi.edu/~slotag/classes/FA16/index.html