

Message Passing Interface (MPI) Programming

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MPI: Standard parallel programming language



Preparation

Minimal knowledge required for the hands-on projects in this course:

- Able to log in & use the Discovery computing cluster at USC Center for Advanced Research Computing (CARC) at the level of its “getting started” tutorial:

<https://carc.usc.edu/user-information/user-guides/hpc-basics/getting-started-discovery>

- Use shell commands to interact with the operating system at the level of “Chapter 1—Introduction to the Command Line” of *Effective Computation in Physics* by Scopatz and Huff; USC students have free access to the book through Safari Online: <https://libraries.usc.edu/databases/safari-books>

Contents

Overview

Logging in to the login node

Organizing files

Transferring files

Creating and editing files

Installing and running software

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Getting help

Chapter 1. Introduction to the Command Line

The command line, or *shell*, provides a powerful, transparent interface between the user and the internals of a computer. At least on a Linux or Unix computer, the command line provides total access to the files and processes defining the state of the computer—including the files and processes of the operating system.

How to Use USC CARC Cluster

System: Intel/AMD-based computing cluster

<https://carc.usc.edu>

Log in

```
> ssh anakano@discovery.usc.edu
```

Alternatively, you can use `discovery2.usc.edu`

To use MPI library:

Use text editor like vim, nano, emacs

If using Bash shell, add these in .bashrc

```
module purge
```

```
module load usc
```

To set up standard
software environment

Compile an MPI program

```
> mpicc -o mpi_simple mpi_simple.c
```

Execute an MPI program

```
> mpirun -n 2 mpi_simple
```

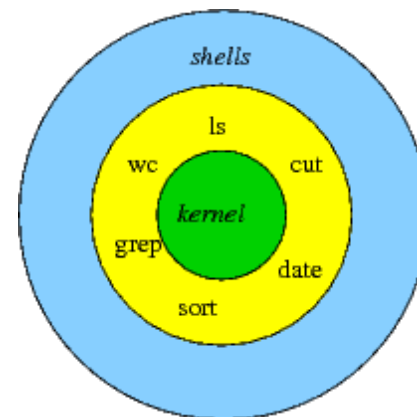
```
[anakano@discovery ~]$ which mpicc
```

To find absolute path to mpicc command

```
/spack/apps/linux-centos7-x86_64/gcc-8.3.0/openmpi-4.0.2-ipm3dnvlbtawpi4ifz7jma6jgr7mexq/bin/mpicc
```

```
[anakano@discovery ~]$ more /proc/cpuinfo
```

To find processor information



Shell is a language you speak with
the operating system

**Type `echo $0` to find
which shell you are using**

Email carc-support@usc.edu for assistance

Submit a Slurm Batch Job

Prepare a script file, mpi_simple.sl

```
#!/bin/bash
#SBATCH --nodes=1
#SBATCH --ntasks-per-node=2
#SBATCH --time=00:00:10
#SBATCH --output=mpi_simple.out
#SBATCH -A anakano_429
mpirun -n $SLURM_NTASKS ./mpi_simple
```

Slurm (Simple Linux Utility for Resource Management): Open-source job scheduler that allocates compute resources on clusters for queued jobs

Submit a Slurm job

discovery: **sbatch mpi_simple.sl**

Submitted batch job 63695

Class project account; type myaccount to check all accounts

Total number of processes = $\text{ntasks-per-node} \times \text{nodes}$

Check the status of a Slurm job

discovery: **squeue -u anakano**

JOBID	PARTITION	NAME	USER	ST	TIME	NODES	NODELIST(REASON)
63695	main	mpi_simple	anakano	PD	0:00	1	(Resources)

Cancel a Slurm job

discovery: **scancel 63695**

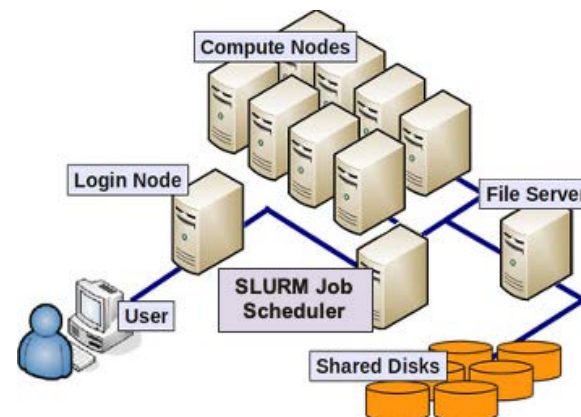
Check the output

discovery: `more mpi_simple.out`

n = 777

For detailed explanation, see the lecture note

<https://aiichironakano.github.io/cs596/02MPI.pdf>



Interactive Job at CARC

When debugging your MPI program, you may want to access computing nodes interactively, so that you can edit, compile & run MPI program in real time unlike the batch job

Reserve 2 processors for 20 minutes

```
[anakano@discovery cs596]$ salloc -n 2 -t 20
salloc: Granted job allocation 63754
salloc: Waiting for resource configuration
salloc: Nodes d05-05 are ready for job
[anakano@d05-05 cs596]$ mpirun -n 2 ./mpi_simple
n = 777
[anakano@d05-05 cs596]$ exit
exit
salloc: Relinquishing job allocation 63754
[anakano@discovery cs596]$
```

Note you are now using a computing node named d05-05

Back to the login node

Type `less /proc/cpuinfo` to find what kind of node you got

Symbolic Link to Work Directory

- Your home directory has very small quota (type `myquota` to confirm), so please use the scratch file system (`/scratch/anakano` for user `anakano`) instead
- It is convenient to make a symbolic link to a directory you use often, rather than typing its long absolute path every time

symbolic link

source

alias

```
[anakano@discovery ~]$ ln -s /scratch/anakano/cs596 cs596
[anakano@discovery ~]$ ls -lt
total 2
lrwxrwx--- 1 anakano anakano 22 Aug 23 12:14 cs596 -> /scratch/anakano/cs596
drwxrwx--- 3 anakano anakano  1 Aug 20 10:07 FFTW
lrwxrwx--- 1 anakano anakano 16 Aug 14 15:48 scr -> /scratch/anakano
[anakano@discovery ~]$ cd cs596
[anakano@discovery cs596]$ pwd -P
/scratch/anakano/cs596
```



This directory has been created as
`mkdir /scratch/anakano/cs596`

Instead of typing
`cd /scratch/anakano/cs596`

Print physical working directory

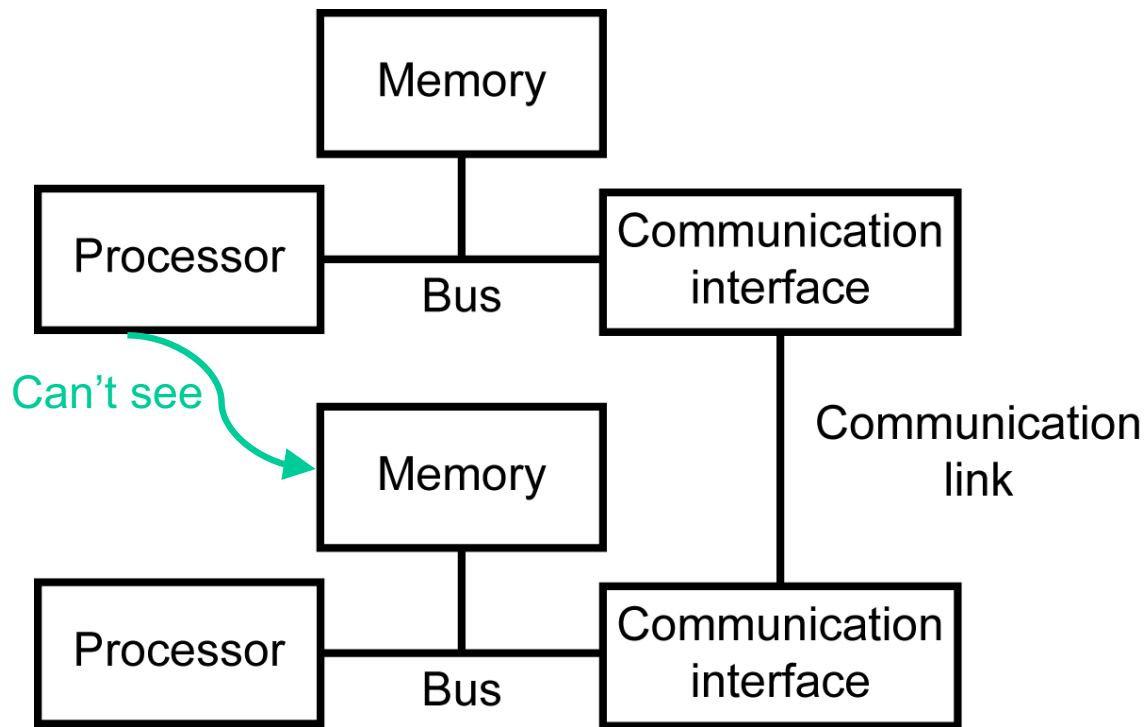
File Transfer

- Use secure file transfer protocol to transfer files between your laptop and Discovery

```
macbook-pro $ sftp anakano@discovery.usc.edu
Connected to discovery.usc.edu.
sftp> cd cs596
sftp> put md.*  Transfer files from local computer (your laptop)
to remote computer (Discovery)
sftp> ls  Check whether the files have been transferred
md.c      md.h      md.in
sftp> exit
macbook-pro $
```

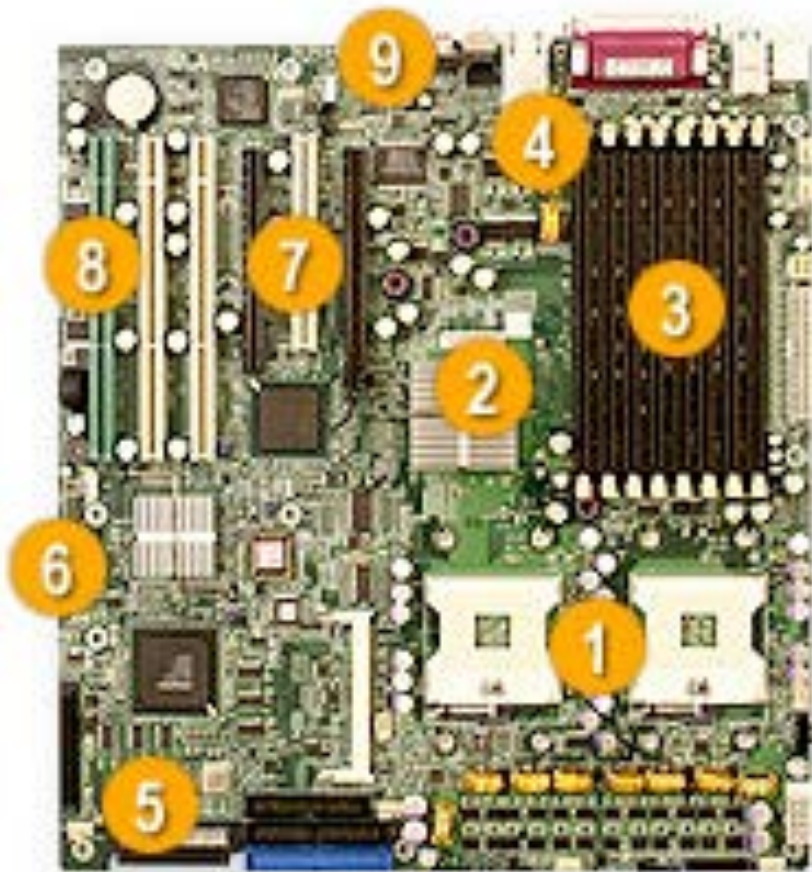
- To transfer files from remote computer to local computer, use **get** instead

Parallel Computing Hardware



- **Processor:** Executes arithmetic & logic operations.
- **Memory:** Stores program & data.
- **Communication interface:** Performs signal conversion & synchronization between communication link and a computer.
- **Communication link:** A wire capable of carrying a sequence of bits as electrical (or optical) signals.

Motherboard



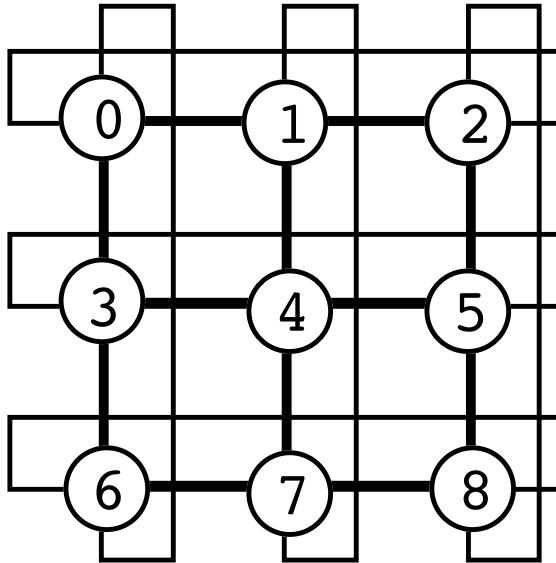
Key Features

1. Dual Intel® Xeon™ EM64T Support up to 3.60 GHz
2. Intel® E7525 (Tumwater) Chipset
3. Up to 16GB DDRII-400 SDRAM
4. Intel® 82546GB Dual-port Gigabit Ethernet Controller
5. Adaptec AIC-7902 Dual Channel Ultra320 SCSI
6. 2x SATA Ports via ICH5R SATA Controller
7. 1 (x16) & 1 (x4) PCI-Express, 1 x 64-bit 133MHz PCI-X, 2 x 64-bit 100MHz PCI-X, 1 x 32-bit 33MHz PCI Slots
8. Zero Channel RAID Support
9. AC'97 Audio, 6-Channel Sound

Supermicro X6DA8-G2

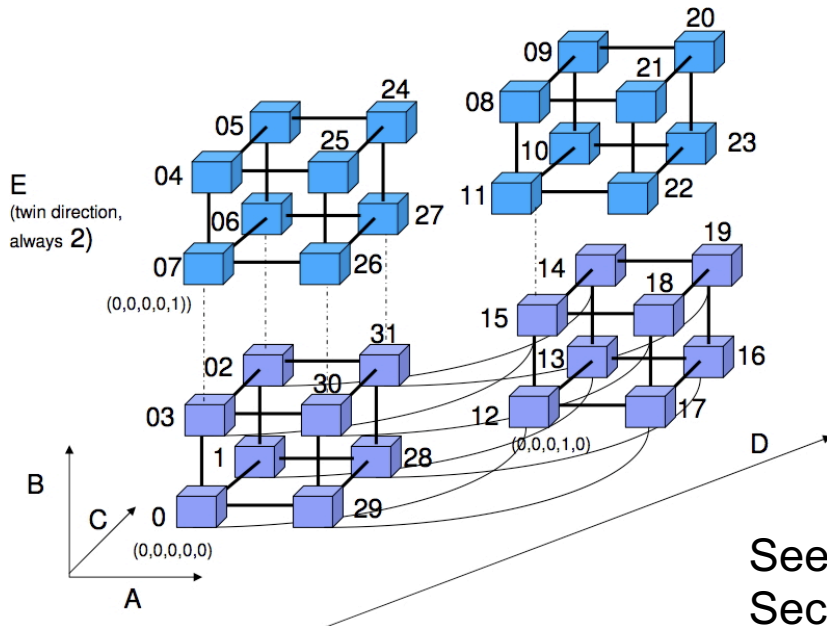
Communication Network

**Mesh
(torus)**

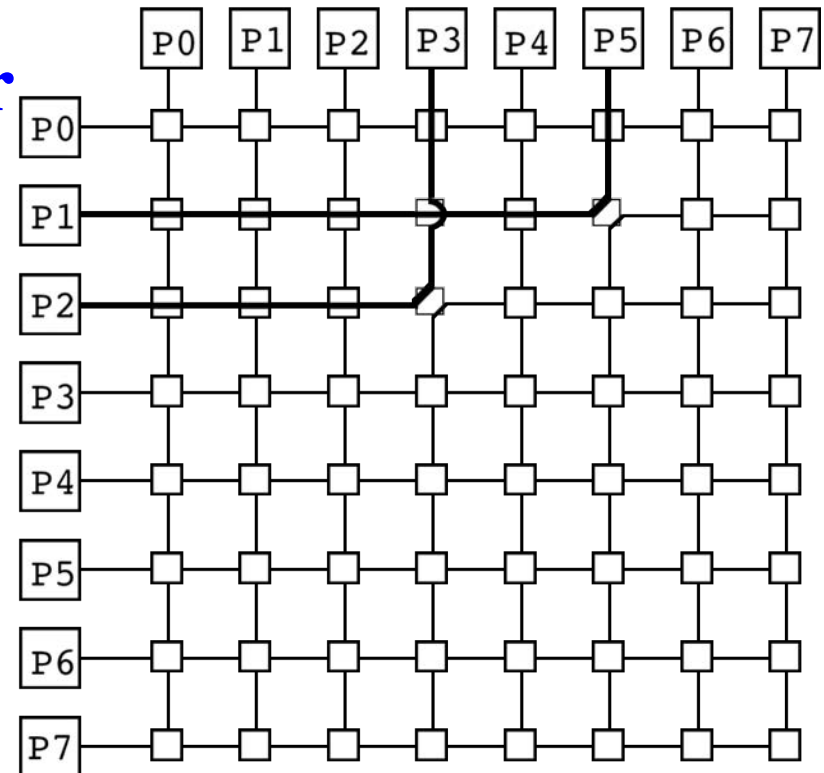


NEC Earth Simulator (640x640 crossbar)

IBM Blue Gene/Q (5D torus)



**Crossbar
switch**



See Grama,
Secs. 2.4.2-2.4.4

Message Passing Interface

MPI (Message Passing Interface)

A standard message passing system that enables us to write & run applications on parallel computers

Download for Unix & Windows:

<http://www.mcs.anl.gov/mpich>

Compile

```
> mpicc -o mpi_simple mpi_simple.c
```

Run

```
> mpirun -np 2 mpi_simple
```

MPI Programming

mpi_simple.c: Point-to-point message send & receive

```
#include "mpi.h"
#include <stdio.h>
int main(int argc, char *argv[]) {
    MPI_Status status;
    int myid;
    int n;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &myid);
    if (myid == 0) {
        n = 777;
        MPI_Send(&n, 1, MPI_INT, 1, 10, MPI_COMM_WORLD);
    }
    else {
        MPI_Recv(&n, 1, MPI_INT, 0, 10, MPI_COMM_WORLD, &status);
        printf("n = %d\n", n);
    }
    MPI_Finalize();
    return 0;
}
```

MPI rank

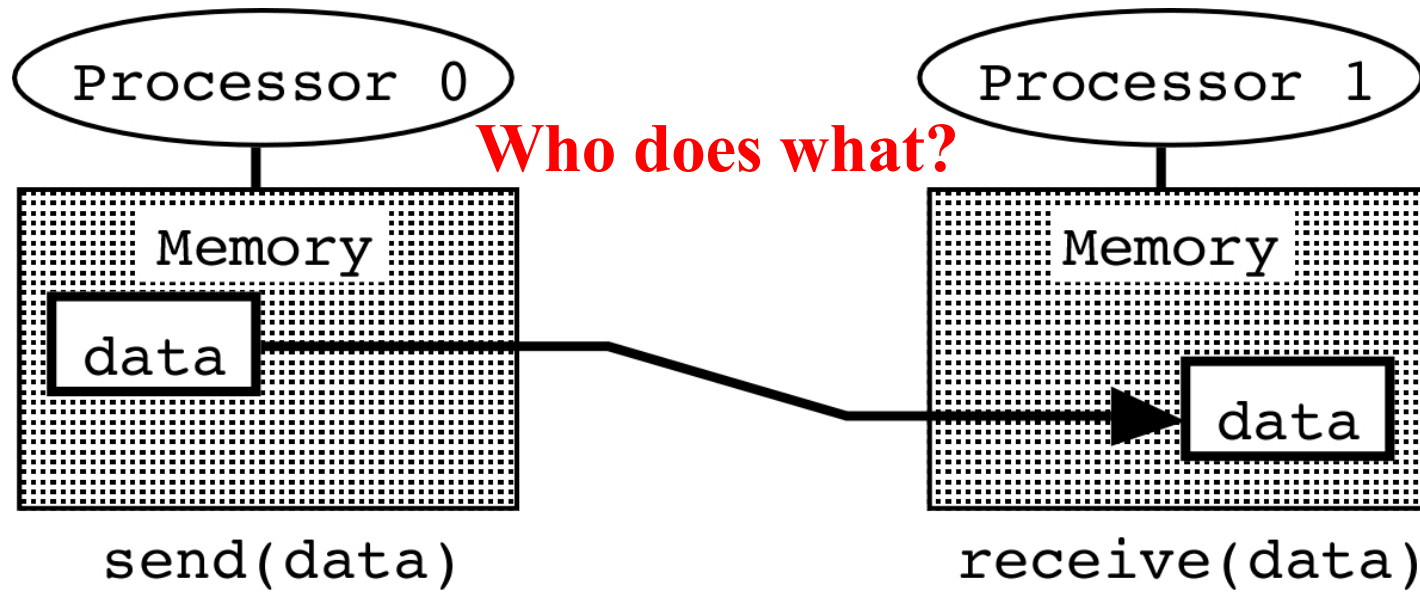
Matching message labels

Data triplet

To/from whom

```
graph TD
    P0((P0)) -- "send to 1" --> P1((P1))
    P1 -- "recv from 0" --> P0
    P0 -- "requests" --> MD((MPI daemon))
    P1 -- "requests" --> MD
```

Single Program Multiple Data (SPMD)



Process 0

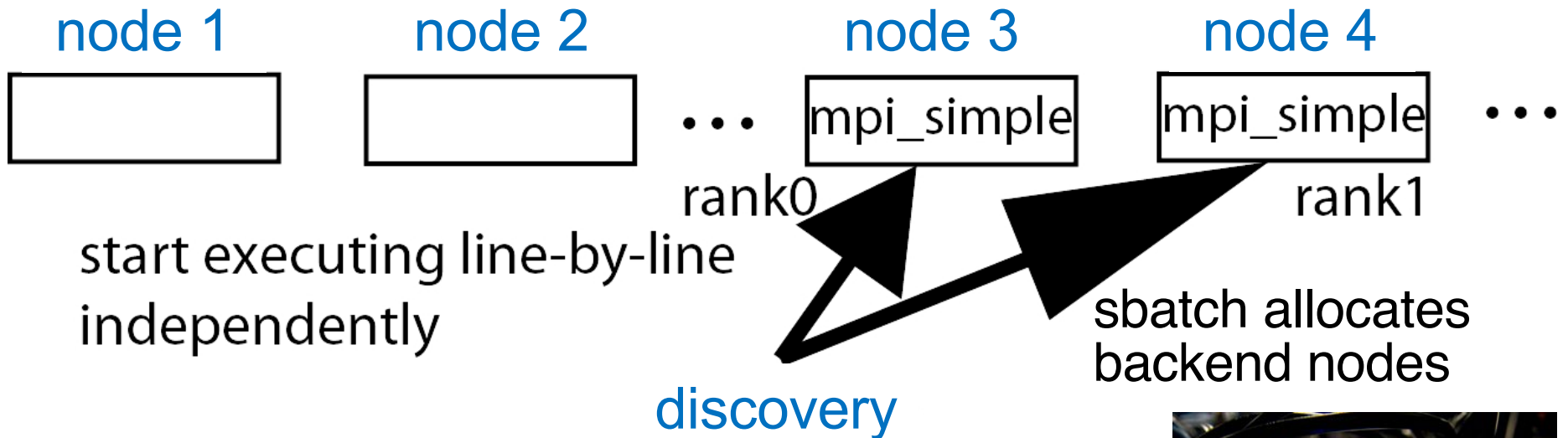
```
if (myid == 0) {  
    n = 777;  
    MPI_Send(&n, ...);  
}  
else {  
    MPI_Recv(&n, ...);  
    printf(...);  
}
```

Process 1

```
if (myid == 0) {  
    n = 777;  
    MPI_Send(&n, ...);  
}  
else {  
    MPI_Recv(&n, ...);  
    printf(...);  
}
```

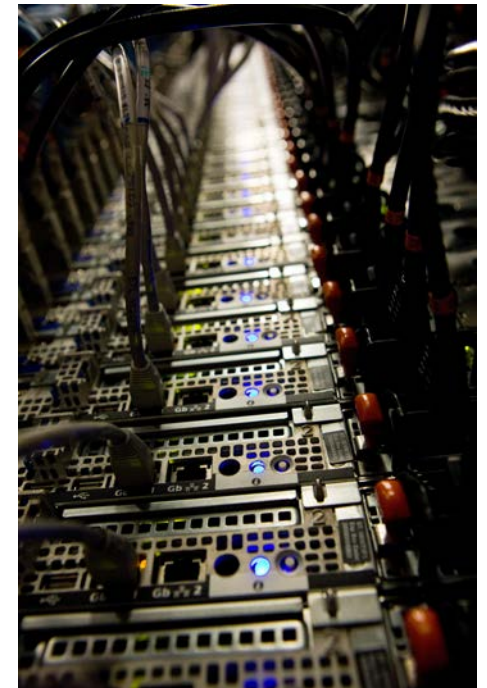

Single Program Multiple Data (SPMD)

What really happens?



```
%mpirun -n 2 mpi_simple
```

```
%ssh discovery.usc.edu  
My laptop
```



MPI Minimal Essentials

We only need **MPI_Send()** & **MPI_Recv()**
within **MPI_COMM_WORLD**

```
MPI_Send(&n, 1, MPI_INT, 1, 10, MPI_COMM_WORLD);
```

```
MPI_Recv(&n, 1, MPI_INT, 0, 10, MPI_COMM_WORLD, &status);
```



A blue bracket is positioned below the first three arguments of the MPI_Send function call: &n, 1, and MPI_INT.

Data triplet



A blue bracket is positioned below the next three arguments of the MPI_Send function call: 1, 10, and MPI_COMM_WORLD.

To/from whom



A blue bracket is positioned below the last argument of the MPI_Recv function call: &status.

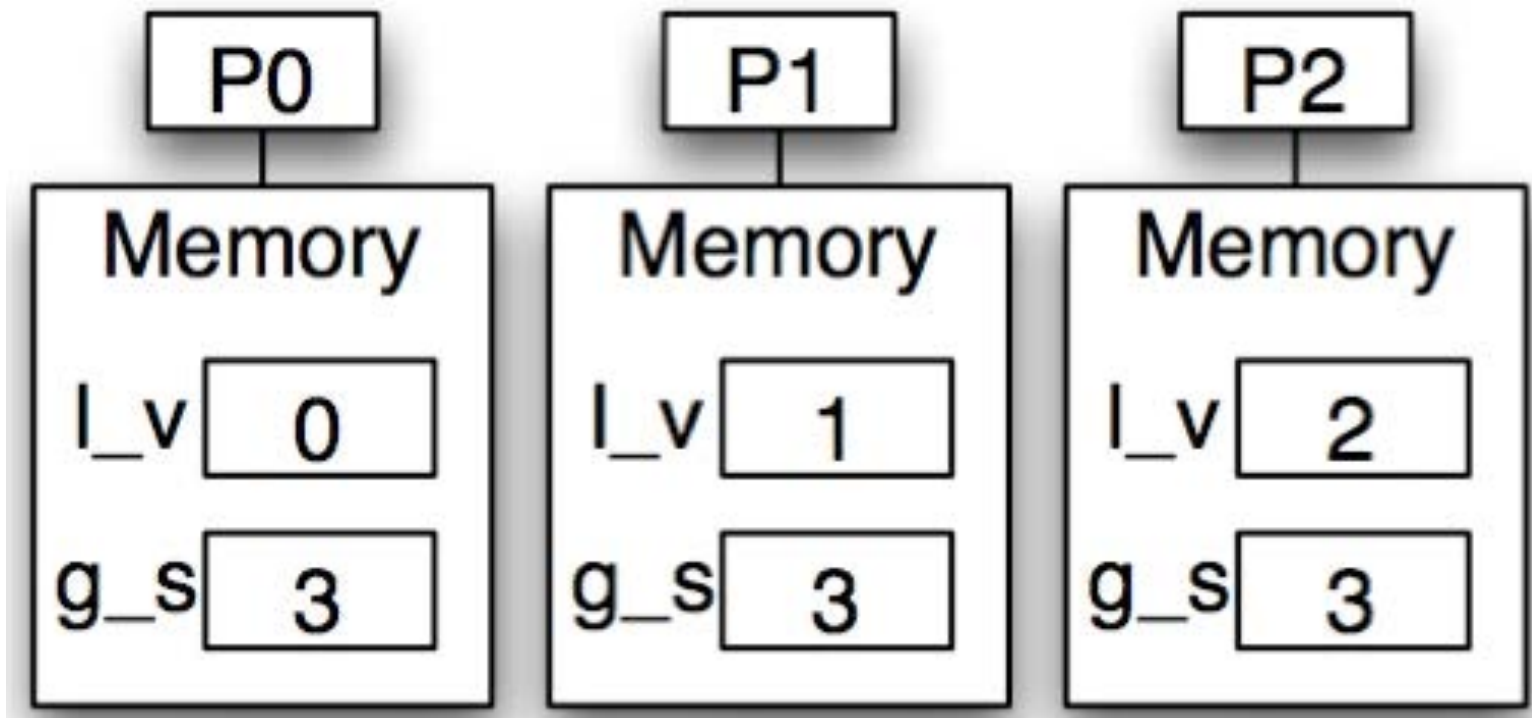
Information

Global Operation

All-to-all reduction: Each process contributes a partial value to obtain the global summation. In the end, all the processes will receive the calculated global sum.

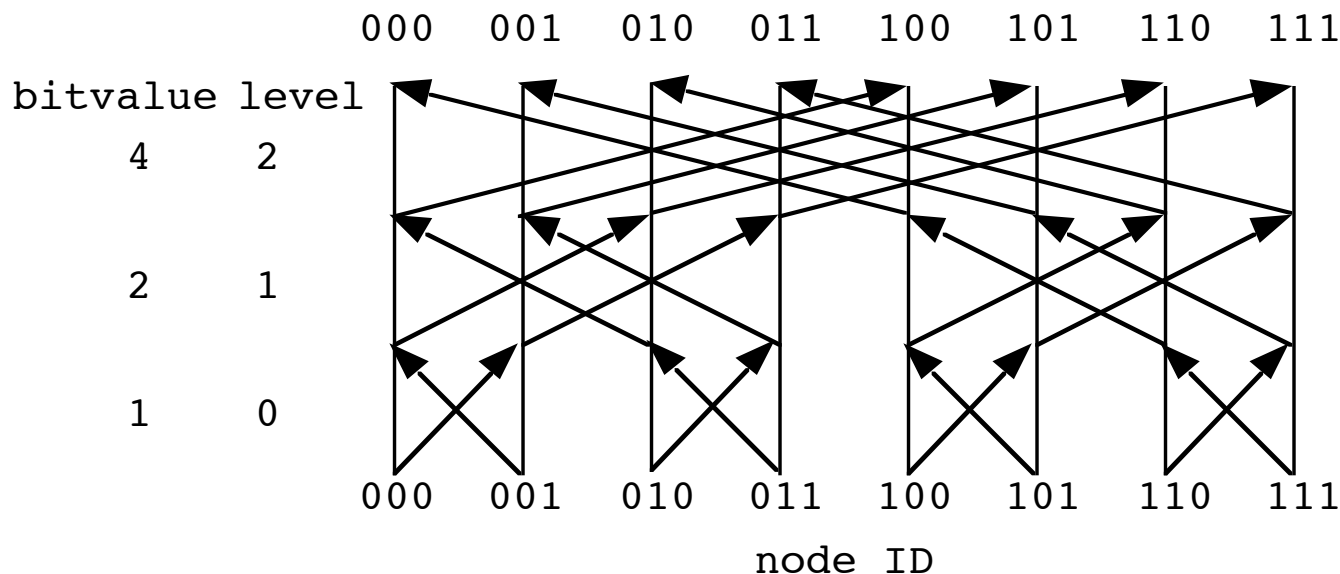
```
MPI_Allreduce(&local_value, &global_sum, 1, MPI_INT, MPI_SUM,  
MPI_COMM_WORLD)
```

```
int l_v, g_s; // local variable & global sum  
l_v = myid;   // myid is my MPI rank  
MPI_Allreduce(&l_v, &g_s, 1, MPI_INT, MPI_SUM, MPI_COMM_WORLD);
```



Hypercube Algorithm

Hypercube algorithm: Communication of a reduction operation is structured as a series of pairwise exchanges, one with each neighbor in a hypercube (**butterfly**) structure. Allows a computation requiring all-to-all communication among p processes to be performed in $\log_2 p$ steps.



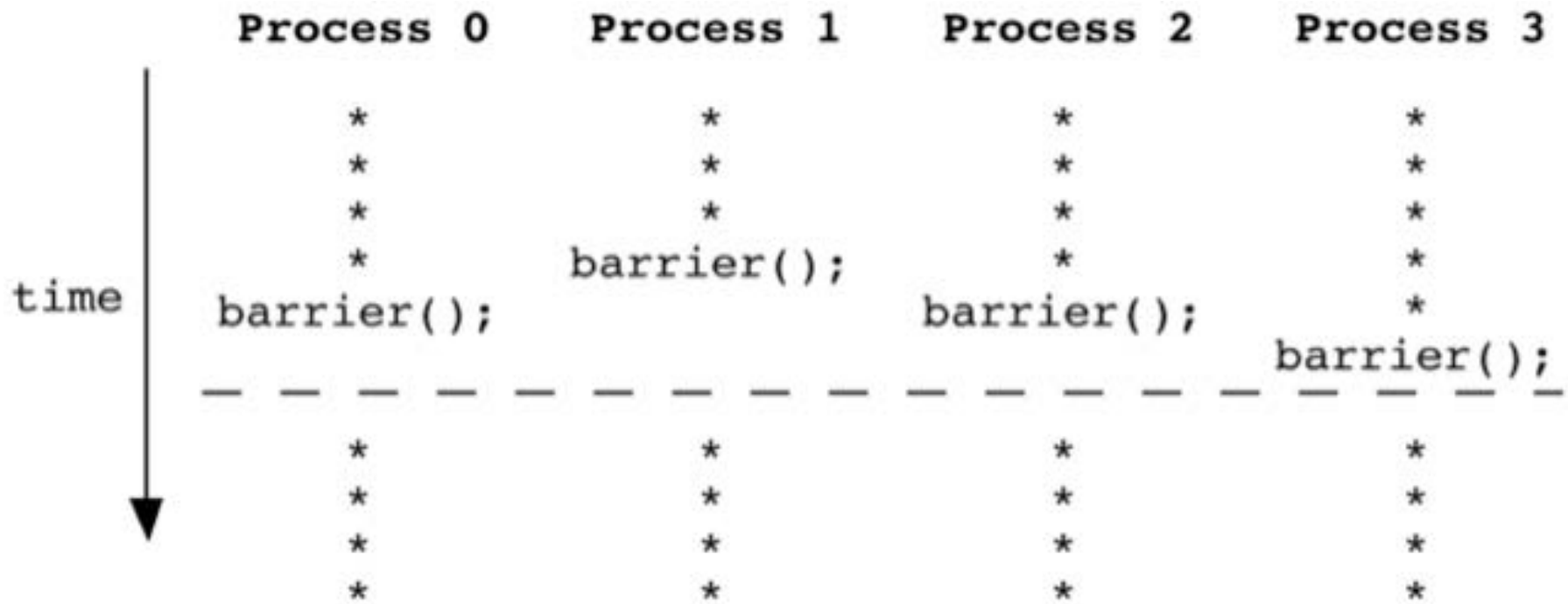
Butterfly network

$$\begin{aligned}
 & a000 + a001 + a010 + a011 + a100 + a101 + a110 + a111 \\
 = & ((a000 + a001) + (a010 + a011)) \\
 + & ((a100 + a101) + (a110 + a111))
 \end{aligned}$$

Below the equation, three circled numbers are shown: a purple circle with the number 2, a green circle with the number 1, and a red circle with the number 0.

Barrier

```
<A>;  
barrier();  
<B>;
```



MPI_Barrier(MPI_Comm communicator)

Useful for debugging (but would slow down the program)

MPI Communication

MPI communication functions:

1. Point-to-point

`MPI_Send()`

`MPI_Recv()`

2. Global

`MPI_Allreduce()`

`MPI_Barrier()`

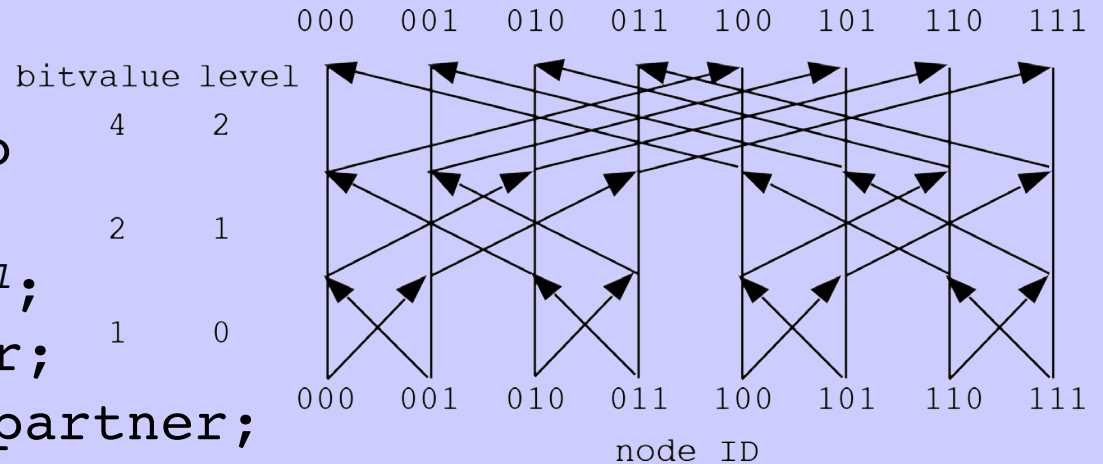
`MPI_Bcast()`

Hypercube Template

```

procedure hypercube(myid, input, log2P, output)
begin
  mydone := input;
  for l := 0 to log2P-1 do
  begin
    partner := myid XOR 2l;
    send mydone to partner;
    receive hisdone from partner;
    mydone = mydone OP hisdone
  end
  output := mydone
end

```



level	2^l	bitvalue
0	001	
1	010	
2	100	

Exclusive OR

a	b	a XOR b
0	0	0
0	1	1
1	0	1
1	1	0

Associative operator
(e.g., sum, max)

$$(a \text{ OP } b) \text{ OP } c = a \text{ OP } (b \text{ OP } c)$$

$$abcdefg \text{ XOR } 0000100 = abcd\bar{e}fg$$

In C, ^ (caret operator) is bitwise XOR applied to int

Driver for Hypercube Test

```
#include "mpi.h"
#include <stdio.h>
int nprocs; /* Number of processes */
int myid; /* My rank */

double global_sum(double partial) {
    /* Implement your own global summation here */
}

int main(int argc, char *argv[]) {
    double partial, sum, avg;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &myid); Who am I?
    MPI_Comm_size(MPI_COMM_WORLD, &nprocs); How big is the world? (see
    partial = (double) myid; p. 5 in lecture note)
    printf("Rank %d has %le\n", myid, partial);
    sum = global_sum(partial);
    if (myid == 0) {
        avg = sum/nprocs;
        printf("Global average = %d\n", avg);
    }
    MPI_Finalize();
    return 0;
}
```

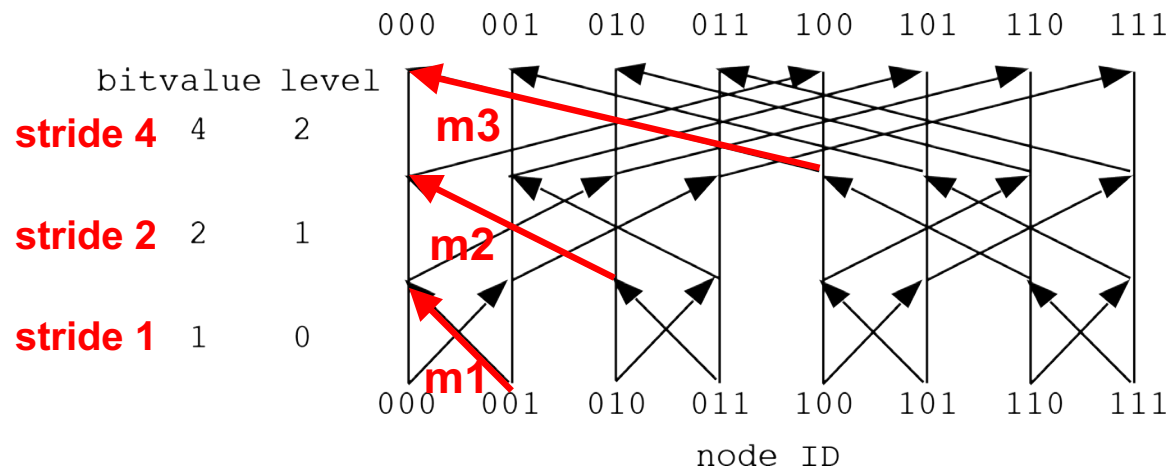
C Implementation of global_sum()

```
mydone = partial;
for (bitvalue=1; bitvalue<nprocs; bitvalue*=2)
{
    partner = myid ^ bitvalue;
    send mydone to partner;
    receive hisdone from partner;
    mydone = mydone + hisdone;
}
return mydone;
```

level	2^l	bitvalue
0	001	
1	010	
2	100	

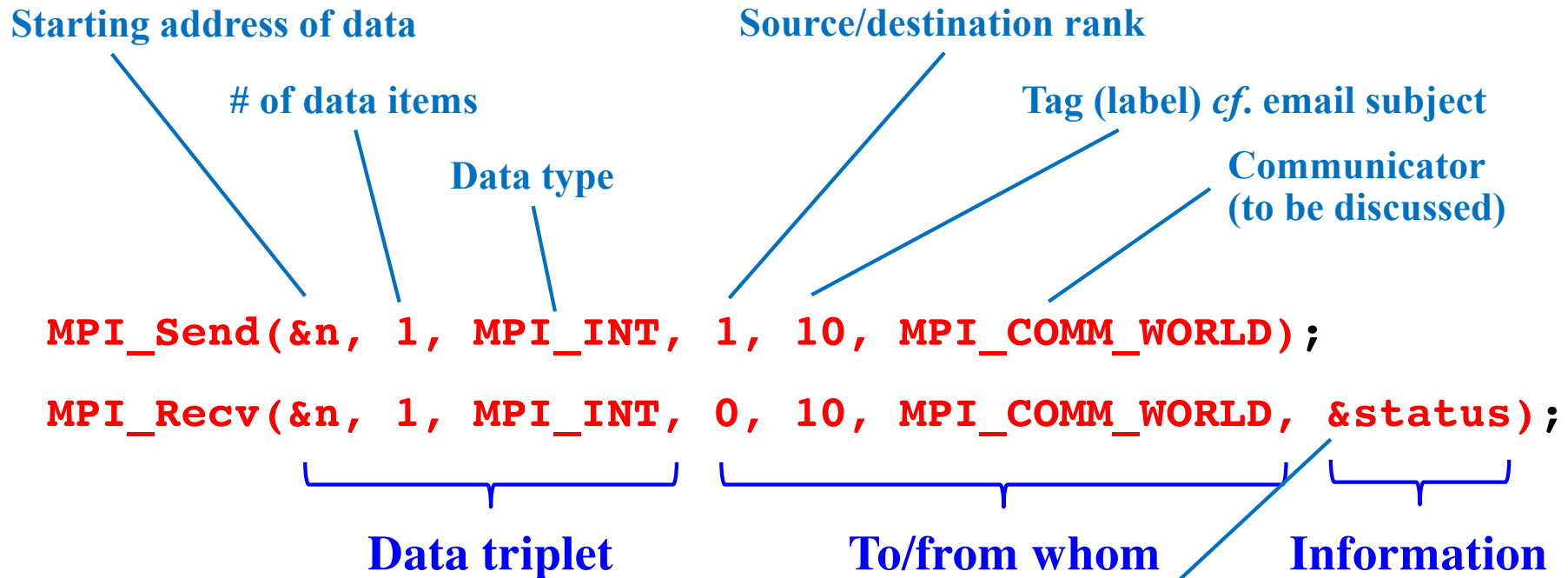
Implement with MPI_Send() & MPI_Recv()

Use *bitvalue* as **counter** & **bitmask**



It is recommended to use distinct labels (tags) for different messages, e.g. (bitmask = stride) as a tag

MPI Send & Receive Revisited



MPI_Datatype	C data type
MPI_CHAR	char
MPI_INT	int
MPI_FLOAT	float
MPI_DOUBLE	double
...	...

MPI_Status status;
Filled with information about the received message

status.MPI_SOURCE	Source process rank
status.MPI_TAG	Tag of the received message
...	...


- Only tag-matching message passing between matching source/destination pair of ranks take place
- It is recommended to use distinct tags for different messages to avoid accidental receipt of unintended messages

Sample Slurm Script

Run two MPI runs in a single Slurm job

```
#!/bin/bash
#SBATCH --nodes=2
#SBATCH --ntasks-per-node=4
#SBATCH --time=00:00:59
#SBATCH --output=global.out
#SBATCH -A anakano_429      mpicc -o global_avg global_avg.c

mpirun -n $SLURM_NTASKS ./global_avg
mpirun -n 4 ./global
```



Total number of processors
= ntasks-per-node (4) × nodes (2) = 8

- **Type** sbatch global_avg.sl **in the directory where the executable global_avg resides, or** cd (change directory) to where it is

Output of global.c

- **4-processor job**

```
Rank 0 has 0.000000e+00
Rank 1 has 1.000000e+00
Rank 2 has 2.000000e+00
Rank 3 has 3.000000e+00
Global average = 1.500000e+00
```

- **8-processor job**

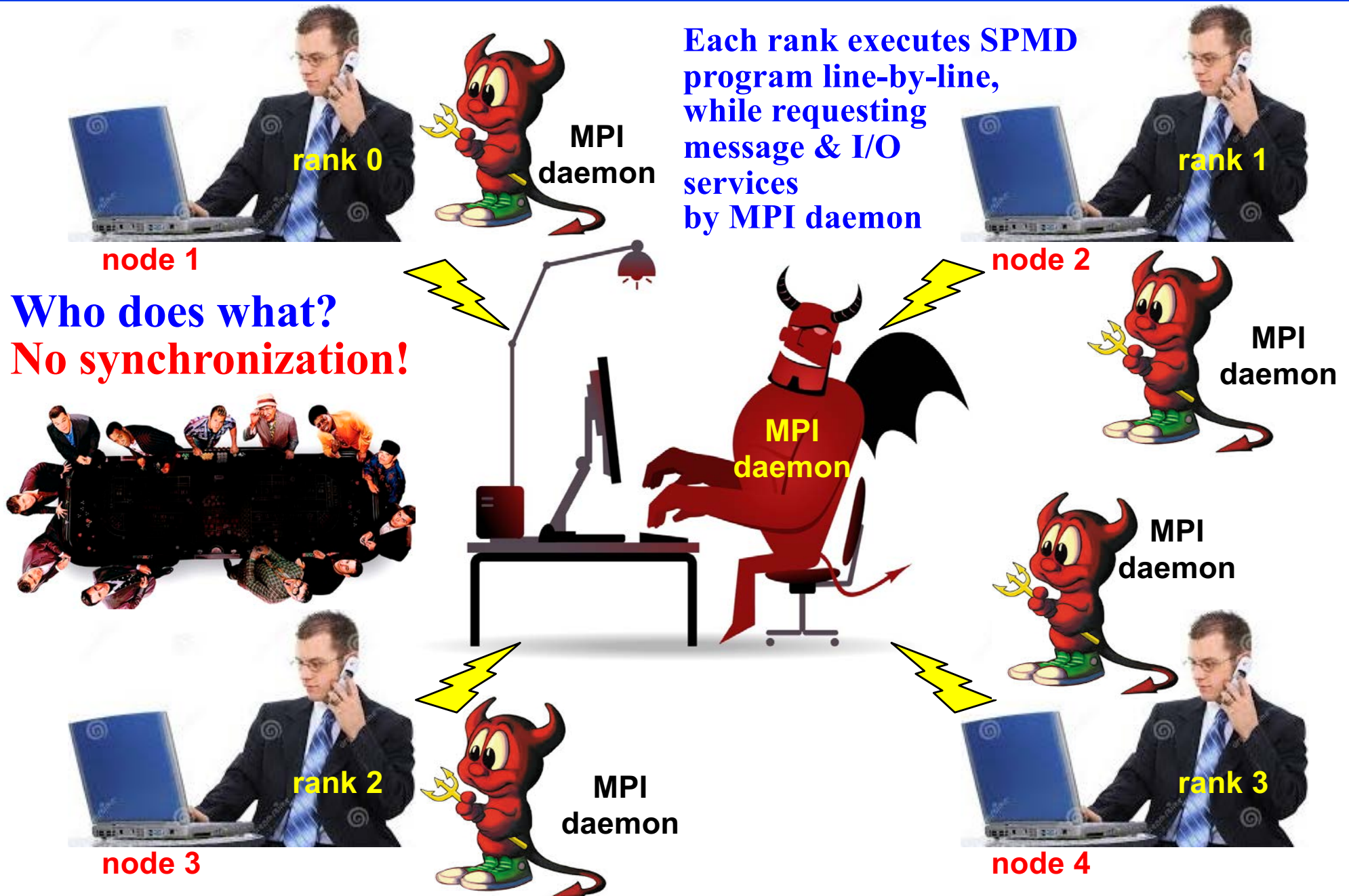
```
Rank 0 has 0.000000e+00
Rank 1 has 1.000000e+00
Rank 2 has 2.000000e+00
Rank 3 has 3.000000e+00
Rank 5 has 5.000000e+00
Rank 6 has 6.000000e+00
Rank 4 has 4.000000e+00
Rank 7 has 7.000000e+00
Global average = 3.500000e+00
```

**Actual output
is random
order in ranks
— Why?**

References on Hypercube Algorithms

1. [https://en.wikipedia.org/wiki/Hypercube_\(communication_pattern\)](https://en.wikipedia.org/wiki/Hypercube_(communication_pattern))
2. I. Foster, *Designing and Building Parallel Programs* (Addison-Wesley, 1995) Chap. 11 — Hypercube algorithms: <https://www.mcs.anl.gov/~itf/dbpp/text/node123.html>

Distributed-Memory Parallel Computing



Communicator

mpi_comm.c: Communicator = process group + context

```
#include "mpi.h"
#include <stdio.h>
#define N 64
int main(int argc, char *argv[]) {
    MPI_Comm world, workers;
    MPI_Group world_group, worker_group;
    int myid, nprocs;
    int server, n = -1, ranks[1];
    MPI_Init(&argc, &argv);
    world = MPI_COMM_WORLD;
    MPI_Comm_rank(world, &myid);
    MPI_Comm_size(world, &nprocs);
    server = nprocs-1;
    MPI_Comm_group(world, &world_group);
    ranks[0] = server;
    MPI_Group_excl(world_group, 1, ranks, &worker_group);
    MPI_Comm_create(world, worker_group, &workers);
    MPI_Group_free(&worker_group);
    if (myid != server)
        MPI_Allreduce(&myid, &n, 1, MPI_INT, MPI_SUM, workers);
    printf("process %2d: n = %6d\n", myid, n);
    MPI_Comm_free(&workers);
    MPI_Finalize();
    return 0;
}
```

Usage

- **Avoid accidental match of unintended Send-Receive pairs**
- **Global operations in a subgroup of processes**

Code at <https://aiichironakano.github.io/cs596/src/mpi/>
For detail, see p. 4 in <https://aiichironakano.github.io/cs596/02MPI.pdf>

Example: Ranks in Different Groups

World Rank	Institution*	Country /Region	National Rank	Total Score	Score on Alumni ▾
1	Harvard University		1	100	100
2	Stanford University		2	72.1	41.8
3	Massachusetts Institute of Technology (MIT)		3	70.5	68.4
4	University of California-Berkeley		4	70.1	66.8
5	University of Cambridge		1	69.2	79.1
51	University of Southern California		33	31	31.7

`MPI_Comm_rank(world, &usc_world);`
`MPI_Comm_rank(us, &usc_national);`

Rank is relative in each communicator!

Output from mpi_comm.c

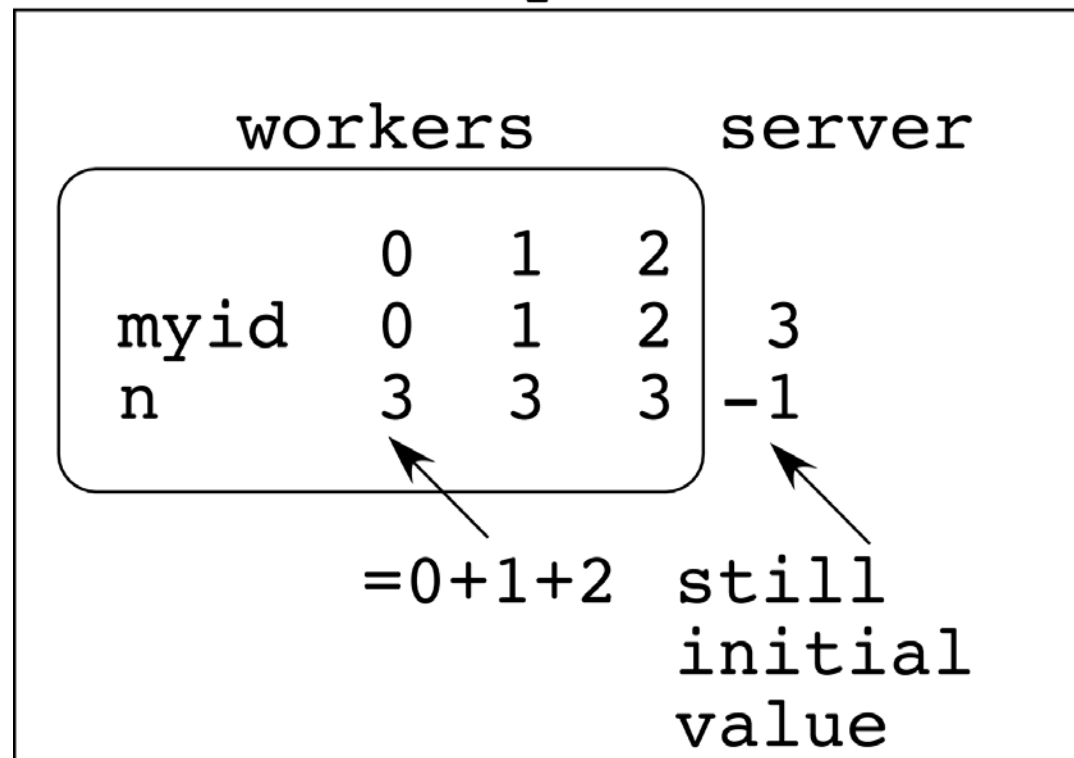
**Slurm
script**

```
#SBATCH --nodes=2
#SBATCH --ntasks-per-node=2
...
mpirun -n $SLURM_NTASKS./mpi_comm
```

```
process 3: n = -1
process 0: n = 3
process 1: n = 3
process 2: n = 3
```

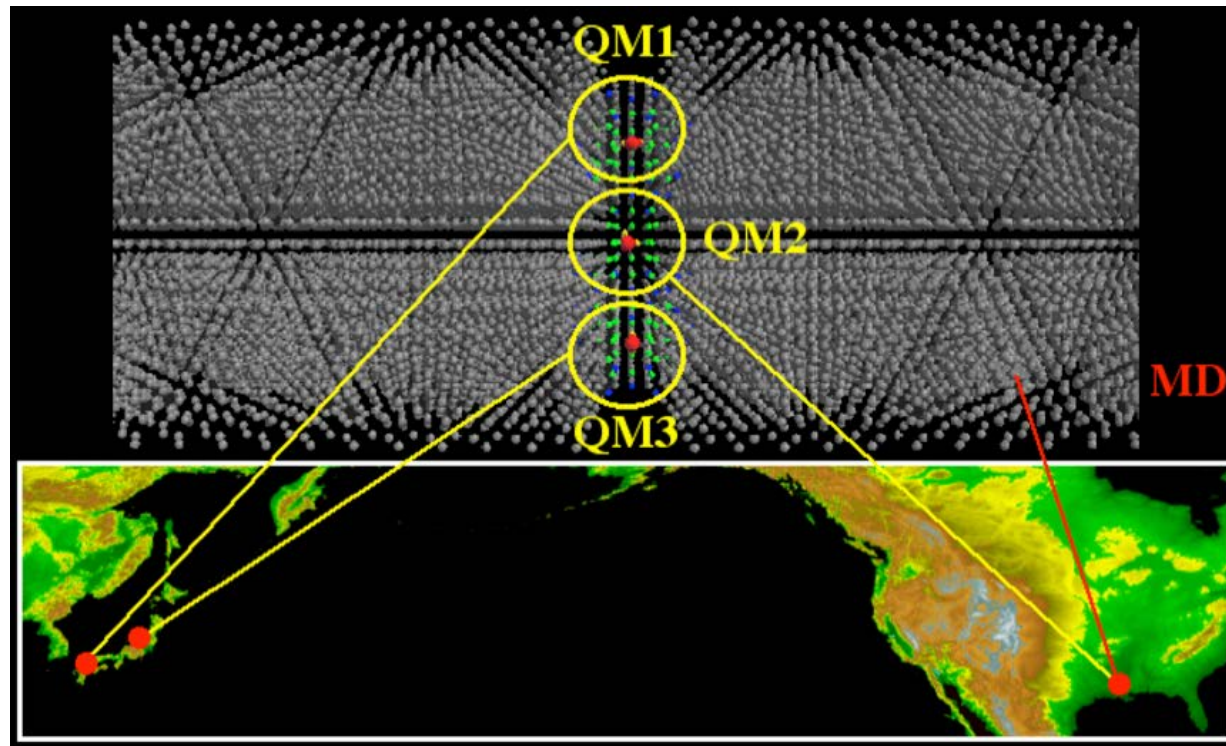
world: nprocs = 4

**What Has
Happened?**



Grid Computing & Communicators

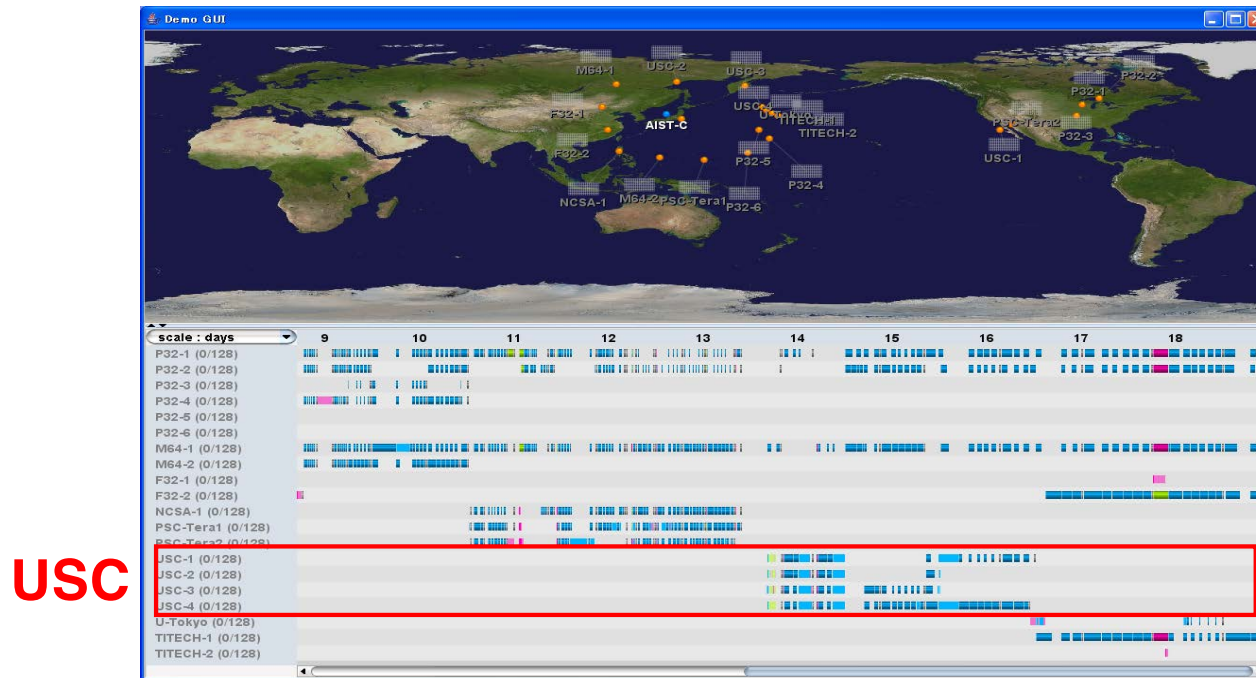
H. Kikuchi *et al.*, “Collaborative simulation Grid: multiscale quantum-mechanical/classical atomistic simulations on distributed PC clusters in the US & Japan, *IEEE/ACM SC02*”



Communicator = a nice migration path to distributed computing

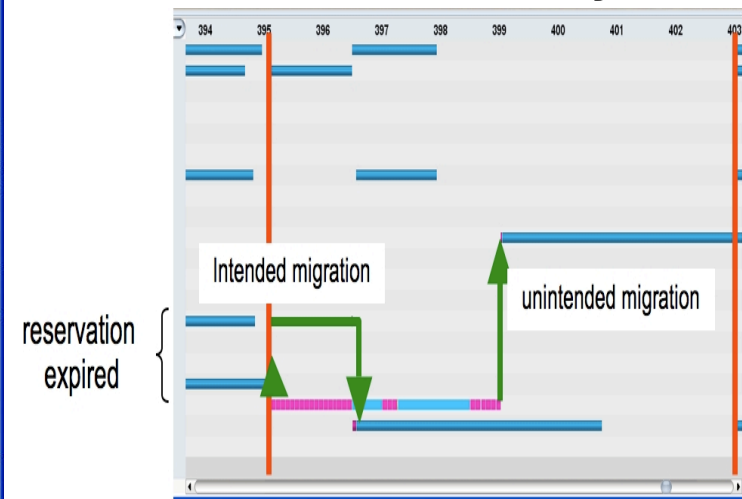
- Single MPI program run with the Grid-enabled MPI implementation, MPICH-G2
- Processes are grouped into MD & QM groups by defining multiple MPI communicators as subsets of MPI_COMM_WORLD; a machine file assigns globally distributed processors to the MPI processes

- *One of the largest (153,600 cpu-hrs) sustained Grid supercomputing*
at 6 sites in the US (USC, Pittsburgh, Illinois) & Japan (AIST, U
Tokyo, Tokyo IT)



USC

Automated resource migration & fault recovery



東京大学
THE UNIVERSITY OF TOKYO



USC



PITTSBURGH
SUPERCOMPUTING
CENTER

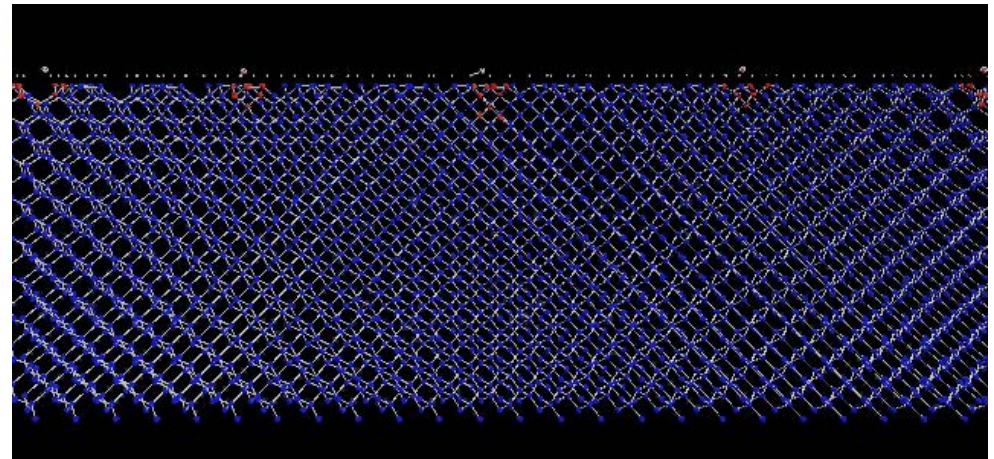
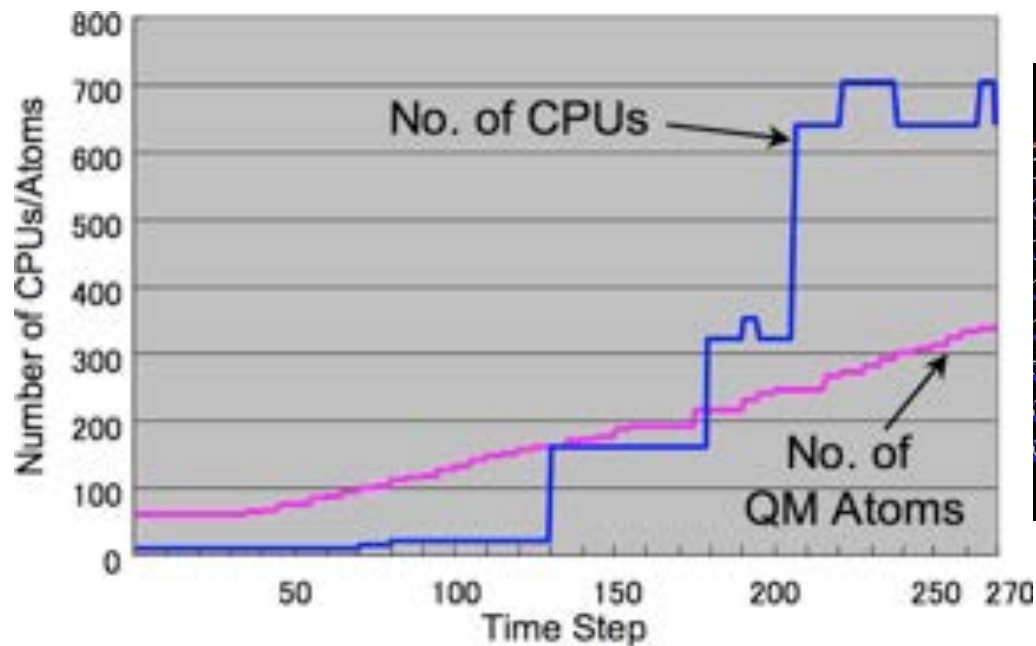
Takemiya *et al.*, "Sustainable adaptive Grid supercomputing: multiscale simulation of semiconductor processing across the Pacific," *IEEE/ACM SC06*

Sustainable Grid Supercomputing

- Sustained (> months) supercomputing (> 10^3 CPUs) on a Grid of geographically distributed supercomputers
- Hybrid Grid remote procedure call (GridRPC) + message passing (MPI) programming
- Dynamic allocation of computing resources on demand & automated migration due to reservation schedule & faults



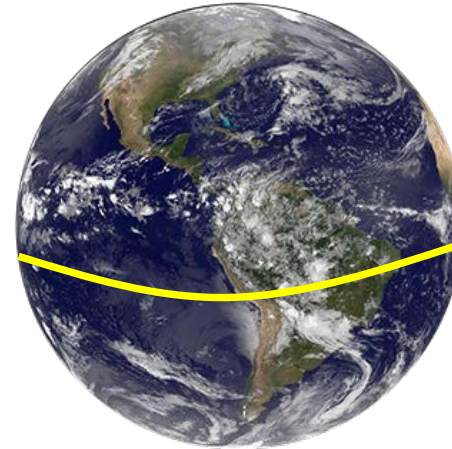
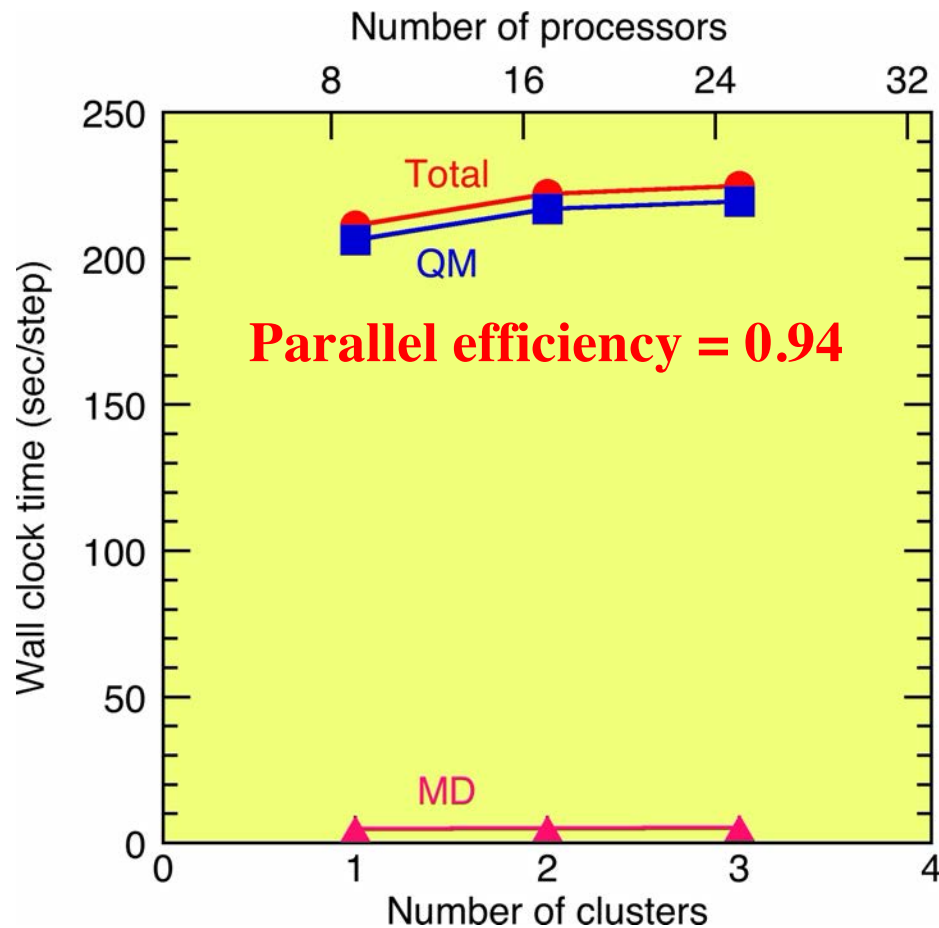
Ninf-G GridRPC: ninf.apgrid.org; MPICH: www.mcs.anl.gov/mpi



Multiscale QM/MD simulation of high-energy beam oxidation of Si

Computation-Communication Overlap

H. Kikuchi *et al.*, “Collaborative simulation Grid: multiscale quantum-mechanical/classical atomistic simulations on distributed PC clusters in the US & Japan, *IEEE/ACM SC02*”



$$\frac{\text{Earth's circumference}}{\text{Light speed}} = \frac{40,000 \text{ [km]} = 4 \times 10^7 \text{ [m]}}{3 \times 10^8 \text{ [m]}} = 0.1 \text{ s} = 100 \text{ ms}$$

Try on Discovery:

`tracert www.u-tokyo.ac.jp`
vs. `ping hpc-transfer.usc.edu`

- **How to overcome 200 ms latency & 1 Mbps bandwidth?**
- **Computation-communication overlap:** To hide the latency, the communications between the MD & QM processors have been overlapped with the computations using **asynchronous messages**

Synchronous Message Passing

MPI_Send () : (blocking), synchronous

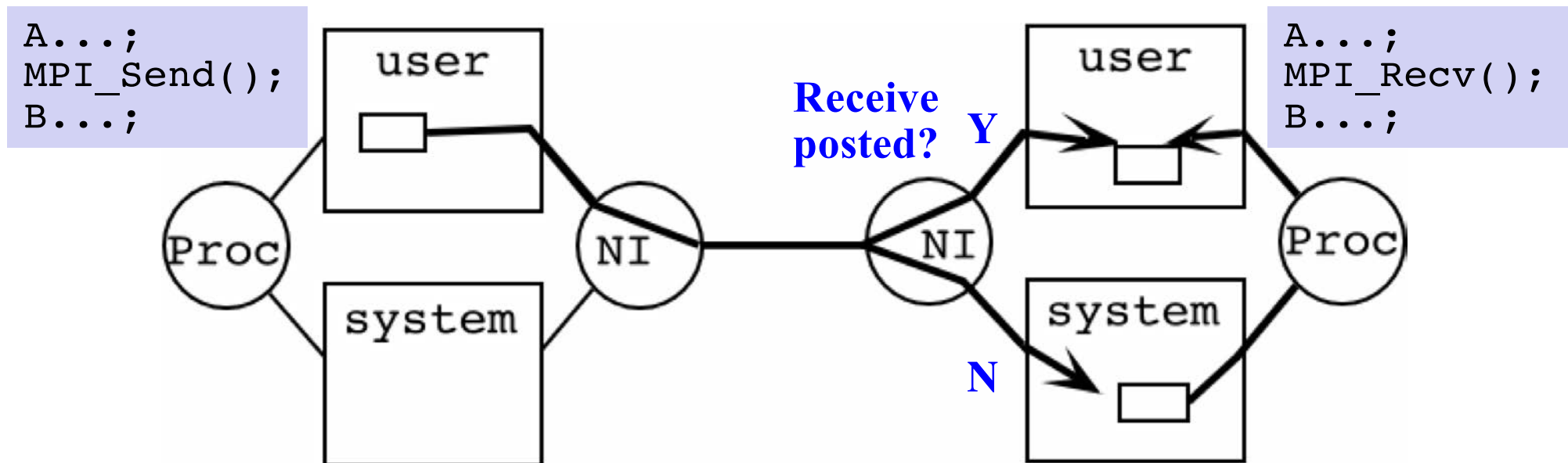
- Safe to modify original data immediately on return
- Depending on implementation, it may return whether or not a matching receive has been posted, or it may block (especially if no buffer space available)

MPI_Recv () : blocking, synchronous

- Blocks for message to arrive
- Safe to use data on return



Experienced a lot of blocking on iPSC/860 with 12 MB user & 4 MB system memory per node



Asynchronous Message Passing

Allows computation-communication overlap

MPI_Isend() : non-blocking, asynchronous

- Returns immediately whether or not a matching receive has been posted
- Not safe to modify original data immediately (use **MPI_Wait()** system call)

MPI_Irecv() : non-blocking, asynchronous

- Does not block for message to arrive
- Cannot use data before checking for completion with **MPI_Wait()**

MPI_Irecv() is just a “request” for data delivery, when a matching message arrives

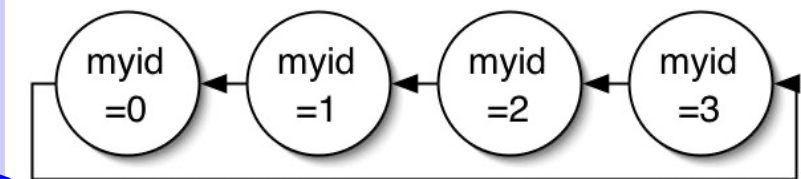
```
A...;  
MPI_Isend();  
B...;  
MPI_Wait();  
C...; // Reuse the send buffer
```

```
A...;  
MPI_Irecv();  
B...;  
MPI_Wait();  
C...; // Use the received message
```

Program `irecv_mpi.c`

```
#include "mpi.h"
#include <stdio.h>
#define N 1000
int main(int argc, char *argv[]) {
    MPI_Status status;
    MPI_Request request;
    int send_buf[N], recv_buf[N];
    int send_sum = 0, recv_sum = 0;
    long myid, left, Nnode, msg_id, i;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &myid);
    MPI_Comm_size(MPI_COMM_WORLD, &Nnode);
    left = (myid + Nnode - 1) % Nnode;
    for (i=0; i<N; i++) send_buf[i] = myid*N + i;
    MPI_Irecv(recv_buf, N, MPI_INT, MPI_ANY_SOURCE, 777, MPI_COMM_WORLD,
              &request); /* Post a receive */
    /* Perform tasks that don't use recv buf */
    MPI_Send(send_buf, N, MPI_INT, left, 777, MPI_COMM_WORLD);
    for (i=0; i<N; i++) send_sum += send_buf[i];
    MPI_Wait(&request, &status); /* Complete the receive */
    /* Now it's safe to use recv_buf */
    for (i=0; i<N; i++) recv_sum += recv_buf[i];
    printf("Node %d: Send %d Recv %d\n", myid, send_sum, recv_sum);
    MPI_Finalize();
    return 0;
}
```

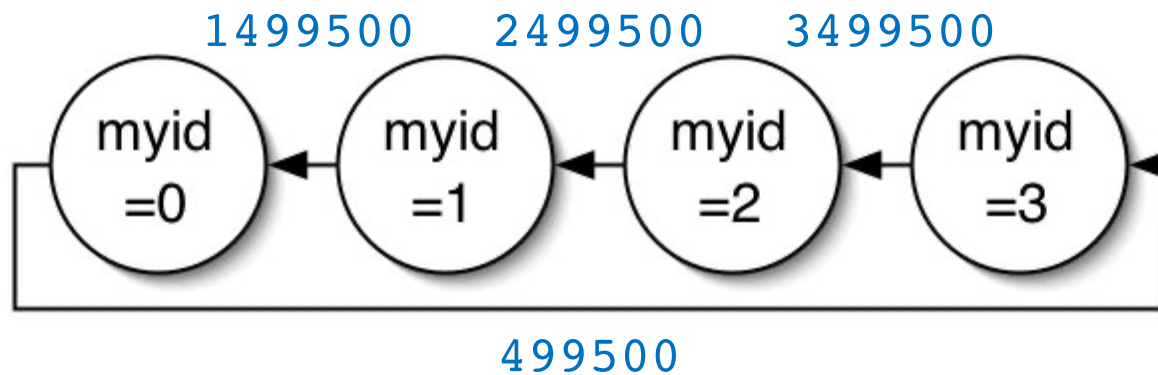
Wrap-around/torus
via modulo (%) operator
(cf. periodic boundary condition)



Code at <https://aiichironakano.github.io/cs596/src/mpi/>

Output from `irecv_mpi.c`

```
Node 1: Send 1499500 Recv 2499500
Node 3: Send 3499500 Recv 499500
Node 0: Send 499500 Recv 1499500
Node 2: Send 2499500 Recv 3499500
```

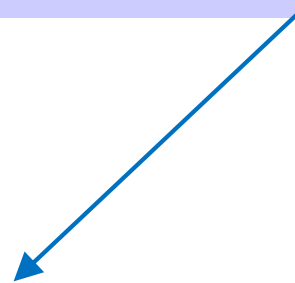


Multiple Asynchronous Messages

```
MPI_Request requests[N_message];
MPI_Status statuses[N_message];
MPI_Status status;
int index;

/* Wait for all messages to complete */
MPI_Waitall(N_message, requests, statuses);

/* Wait for any specified messages to complete */
MPI_Waitany(N_message, requests, &index, &status);
```



returns the index ($\in [0, N_message-1]$) of the message that completed

Polling MPI_Irecv

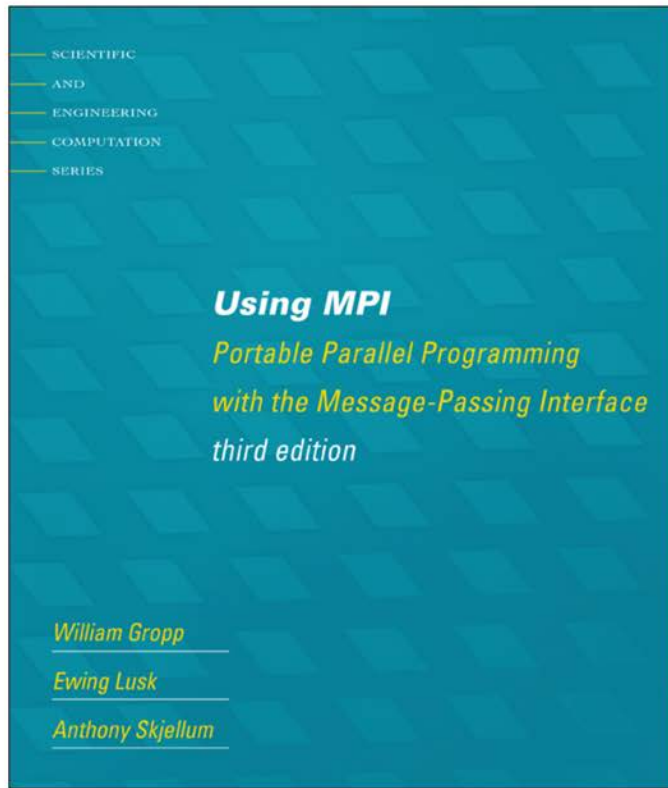
```
int flag;

/* Post an asynchronous receive */
MPI_Irecv(recv_buf, N, MPI_INT, MPI_ANY_SOURCE, 777,
          MPI_COMM_WORLD, &request);

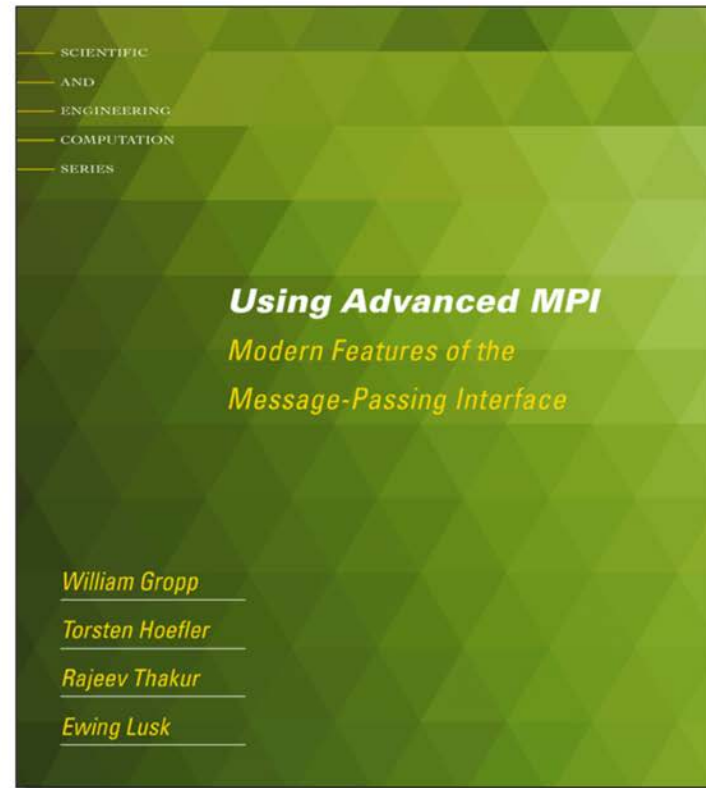
/* Perform tasks that don't use recv_buf */
...

/* Polling */
MPI_Test(&request, &flag, &status); /* Check completion */
if (flag) { /* True if message received */
    /* Now it's safe to use recv_buf */
    ...
}
```

Where to Go from Here



Basic MPI



Advanced MPI, including MPI-3

- **Complete MPI reference at <http://www.netlib.org/utk/papers/mpi-book/mpi-book.html>**
- **MPI is evolving (MPI-2 to MPI-3) to include advanced features like remote memory access (`MPI_Put()` & `MPI_Get()`; cf. `sftp`), parallel I/O and dynamic process management**
- **Various versions of MPI standard are specified at <https://www.mpi-forum.org/docs/>**

MPI Basics: Recap

- **Parallel computing = Who does what**
- **Single program multiple data (SPMD) programming: Do it with MPI rank (who am I) & selection constructs (`if`, *etc.*)**
- **Only need `MPI_Send()` & `MPI_Recv()` within communicators to implement any distributed-memory parallel computing**
- **Asynchronous message passing (`MPI_Isend()` & `MPI_Irecv()`) to overlap computation & communication**
- **You can survive professionally only with a few global communication functions, *e.g.*, `MPI_Allreduce()`, `MPI_Barrier()` & `MPI_Bcast()`**

Start using MPI for your research & projects!

20 Years-Unleashing the Power of HPC

SC2001

2001 Chair
Charles Slocumb
Denver, CO



2001

Notable Systems first mentioned this year
in the proceedings:

- SGI Origin 3000
- Sun Fire 6000
- ASCI White
- Blue Horizon
- ASCI Blue Mountain

Notable Processors:

- MIPS R 12000
- Intel Pentium 4
- Intel Itanium

Noteworthy Architecture Topics:

- Cache coherence through snooping
- Application speedups through custom on-the-fly FPGA function units
- Interactive program steering
- Grid-enabled parallel computing

Notable Programming Languages:

- HDL
- PThreads

Research Machines:

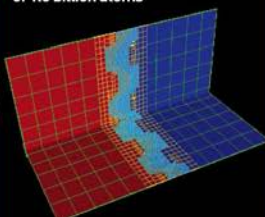
- CPlant



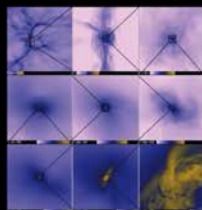
A WINE-2 system board



A discrete particle simulation
of 1.5 billion atoms



Adaptive mesh simulation of
advecting sinusoidal density contours



Adaptive mesh simulation of
star formation



The MDM system

Adaptive mesh simulation of
a spherical shock

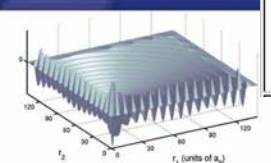
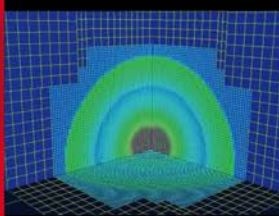


Figure 10. Real part of wavefunction for three-body system. In this example $\ell = 1$, so the radial function is constant.



Best Paper

Aiichiro Nakano, Rajiv K. Kalia, Priya Vashishta, Timothy J. Campbell, Shuji Ogata, Fuyuki Shimojo, and Subhash Saini
[Scalable atomistic simulation algorithms for materials research](#)

Best Student Paper

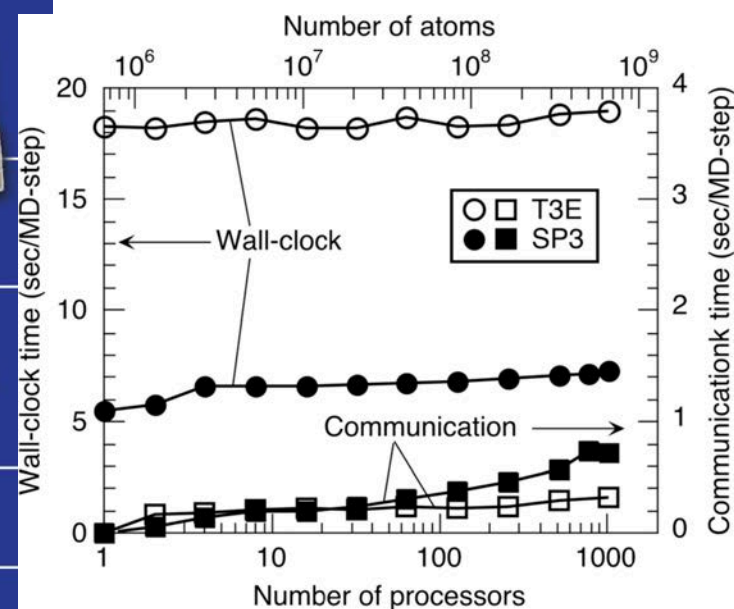
Shava Smullen, Henri Cazsanova and Francine Berman
[Applying Scheduling and Tuning to On-line Parallel Tomography](#)

ACM Gordon Bell Prize

See list of [ACM Gordon Bell Prize winners](#)

Best Research Poster

Sumir Chandra, Johan Steensland, and Manish Parashar
??? If you know, please contact chair@SIGHPC.org



Solution of a three
body quantum
mechanics problem