Introduction to MPI

Topics to be covered

- MPI *vs* shared memory
- Initializing MPI
- MPI concepts -- communicators, processes, ranks
- MPI functions to manipulate these
- Timing functions
- Barriers and the *reduction* collective operation

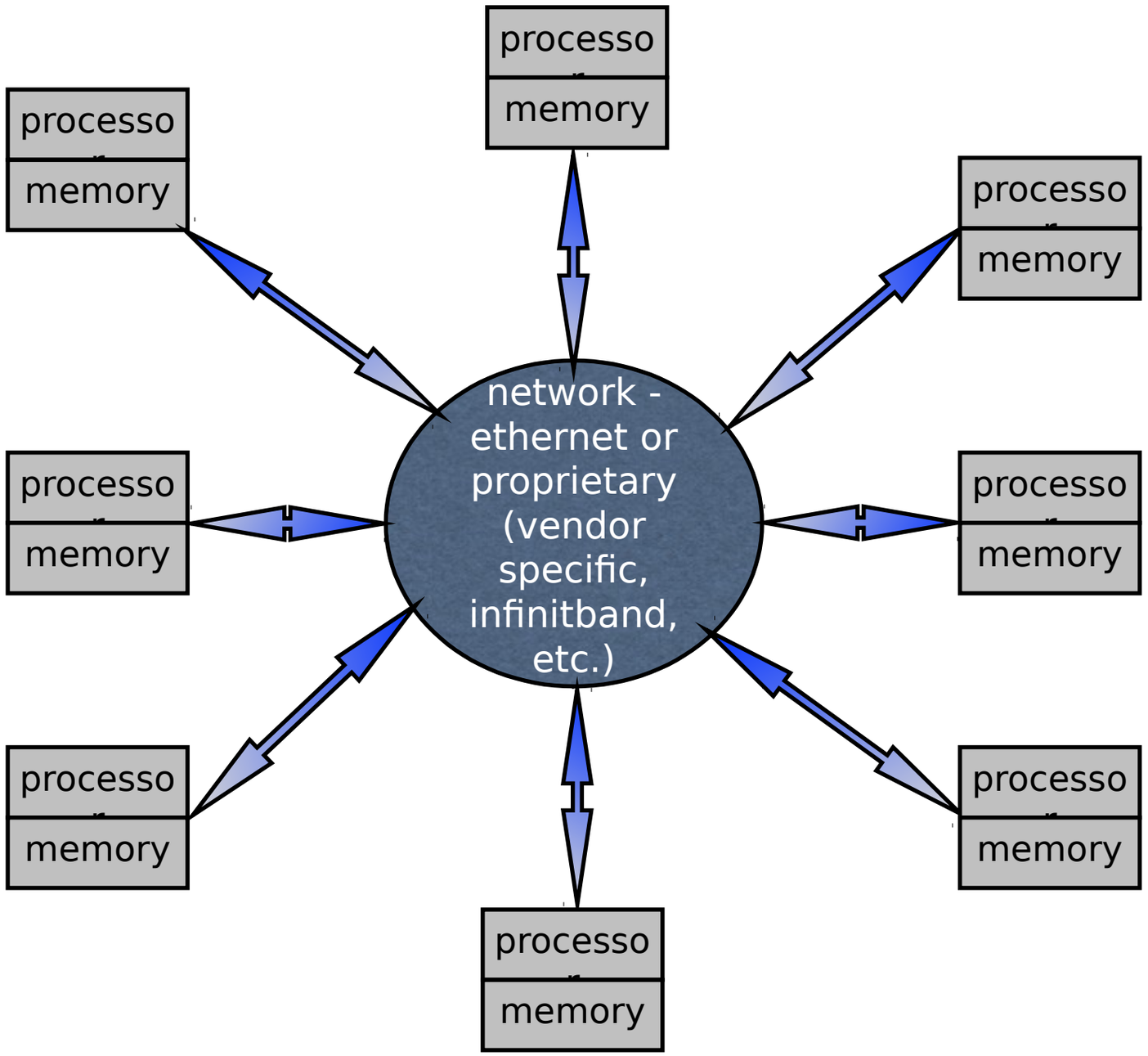
Shared and distributed memory

- **Shared memory**
  - automatically maintained a consistent image of memory according to some memory model
  - fine grained communication possible via loads, stores, and cache coherence
  - model and multicore hardware support well aligned
  - Programs can be converted piece-wise

Shared and distributed memory

- **Distributed memory**
  - Program executes as a collection of processes, all communication between processors explicitly specified by the programmer
  - Fine grained communication in general too expensive -- programmer must aggregate communication
  - Conversion of programs is all-or-nothing
  - Cost scaling of machines is better than with shared memory -- well aligned with economics of commodity rack mounted blades

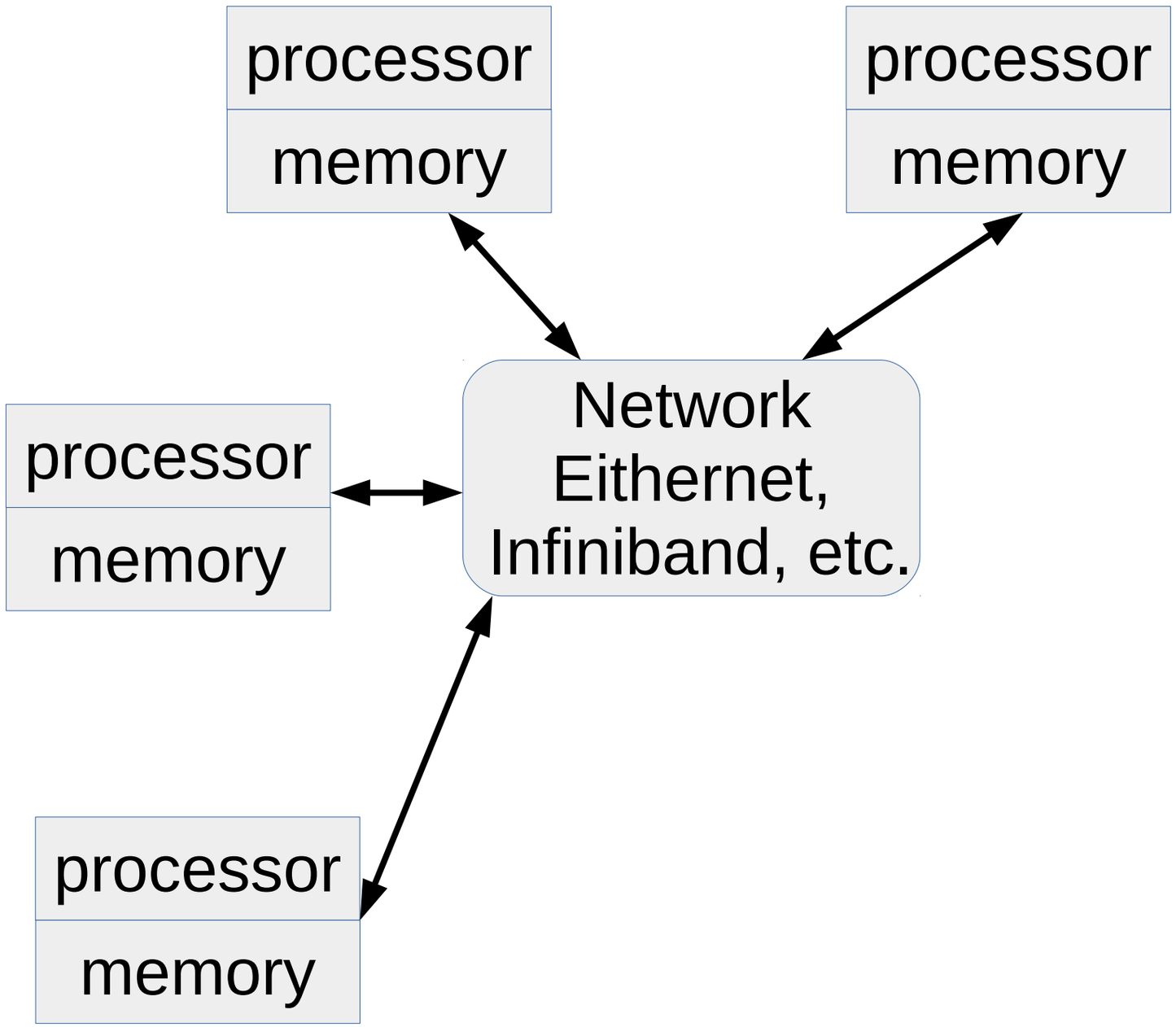
Message Passing Model



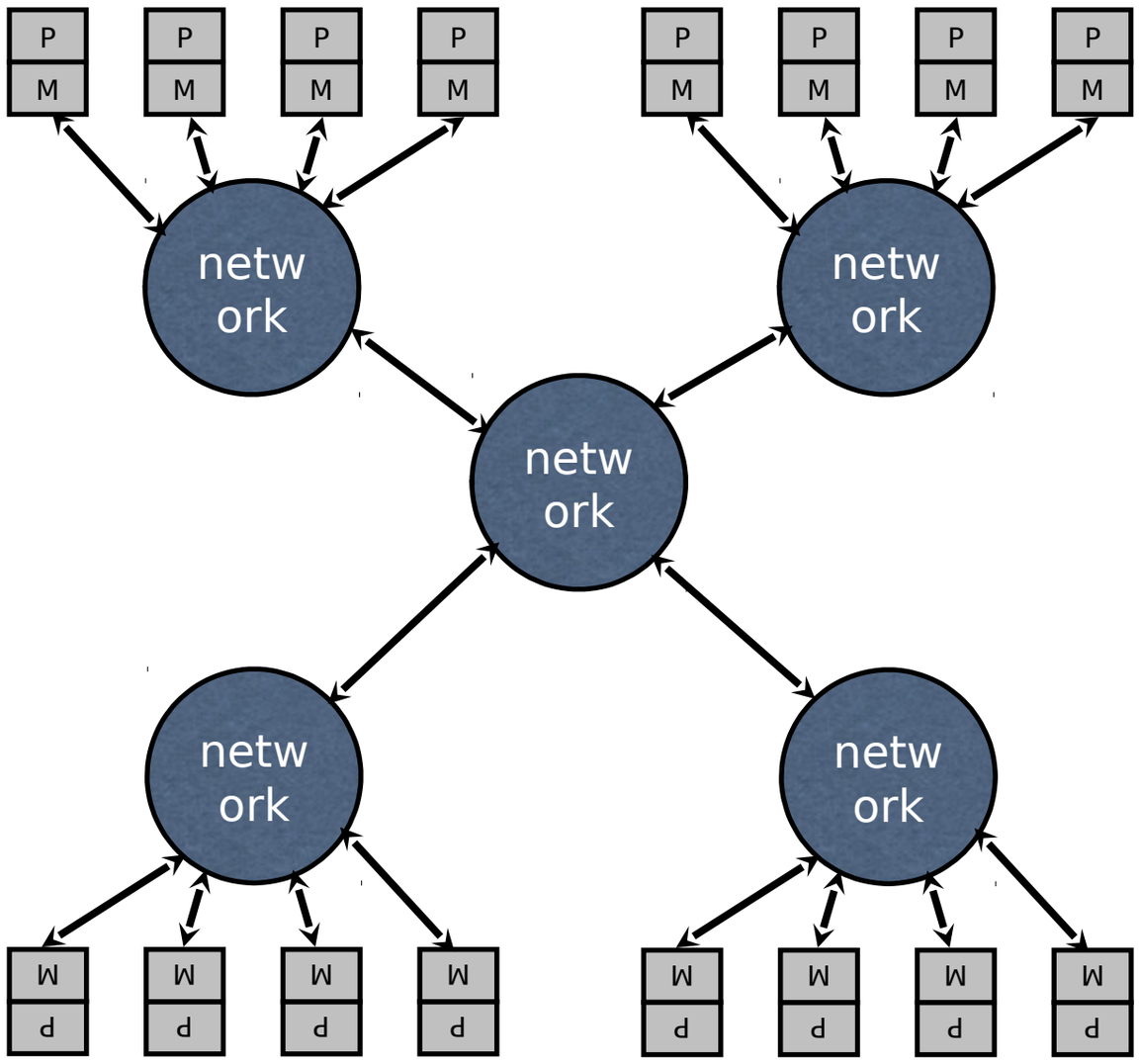
- This drawing implies that all processor are equidistant from one another
- This is often not the case -- the network topology and multicores make some processors closer than others
- programmers have to exploit

Message Passing Model

- This drawing implies that all processor are equidistant from one another
- This is often not the case -- the network topology and multicores make some processors closer than others
- programmers have to exploit this manually



Message Passing Model



- In reality, processes run on cores, and are closer to other processes on the same processor
- Across processors, some can be reached via a single hop on the network, others require multiple hops
- Not a big issue on small (several hundred processors), but it needs to be considered on large machines.

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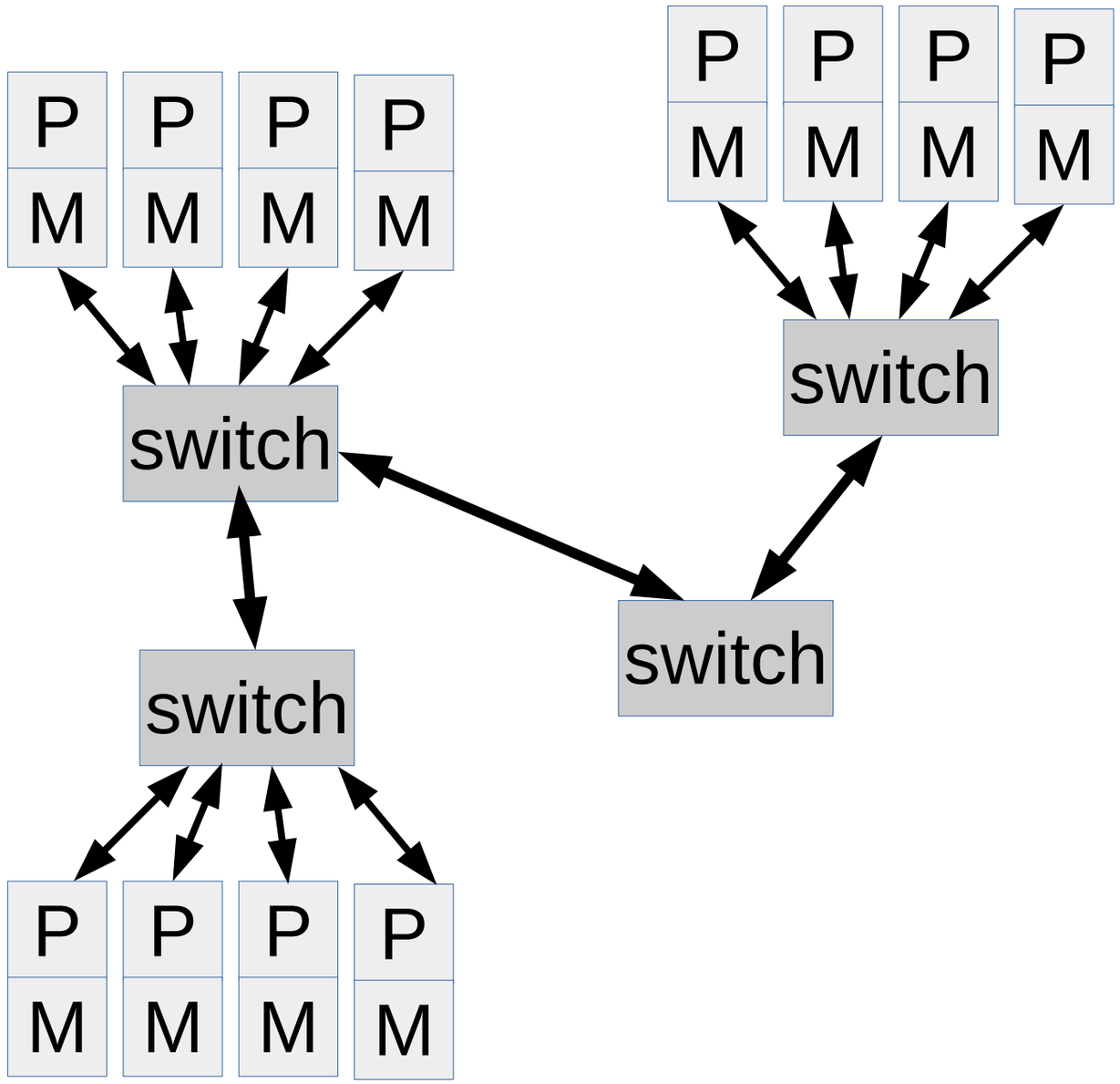


Cray-1 80 mhz, 138 – 250 MPFLOPs

Some Seymour Cray quotes

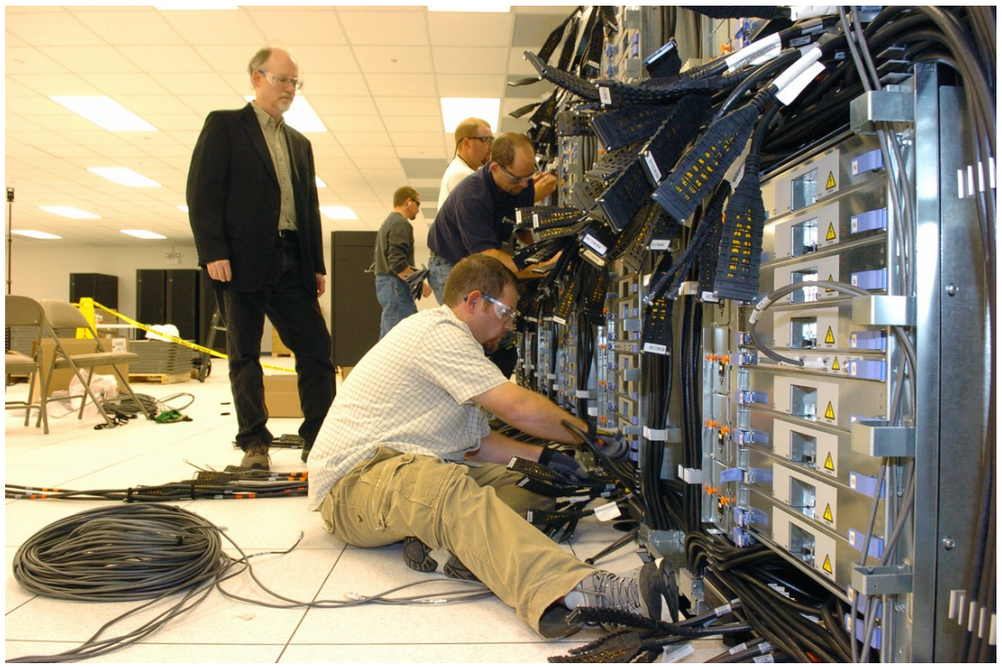
If you were plowing a field, which would you rather use? Two strong oxen or 1024 chickens?

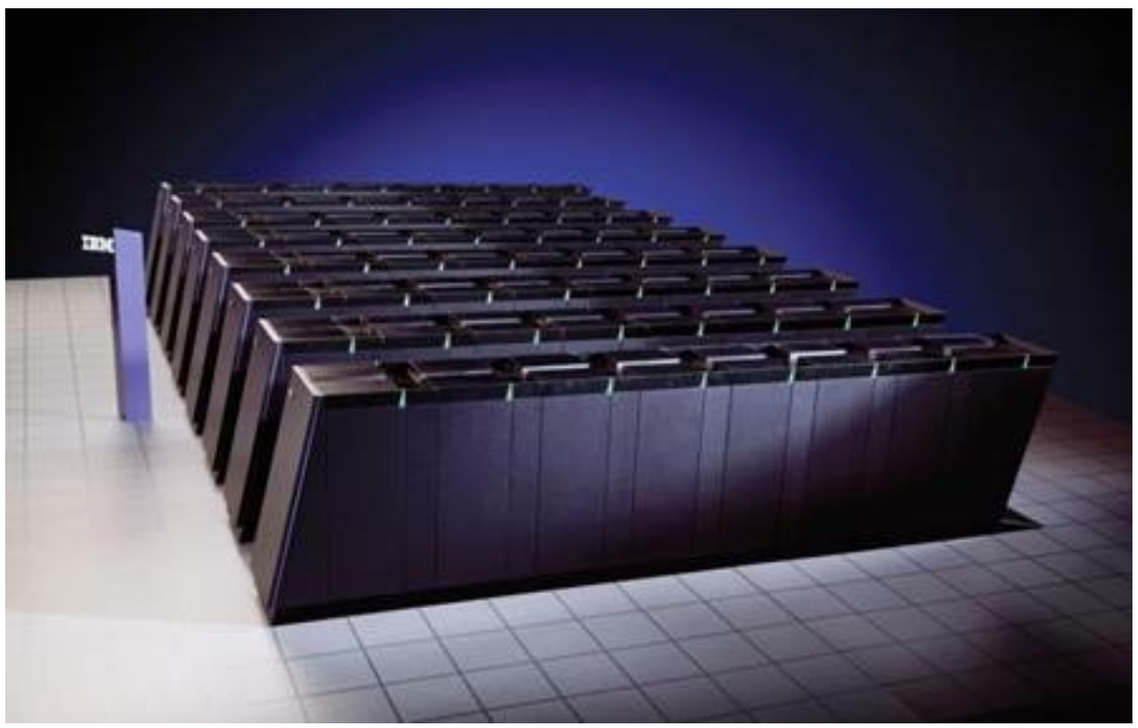
Anybody can build a fast CPU, the trick is to build a fast system.

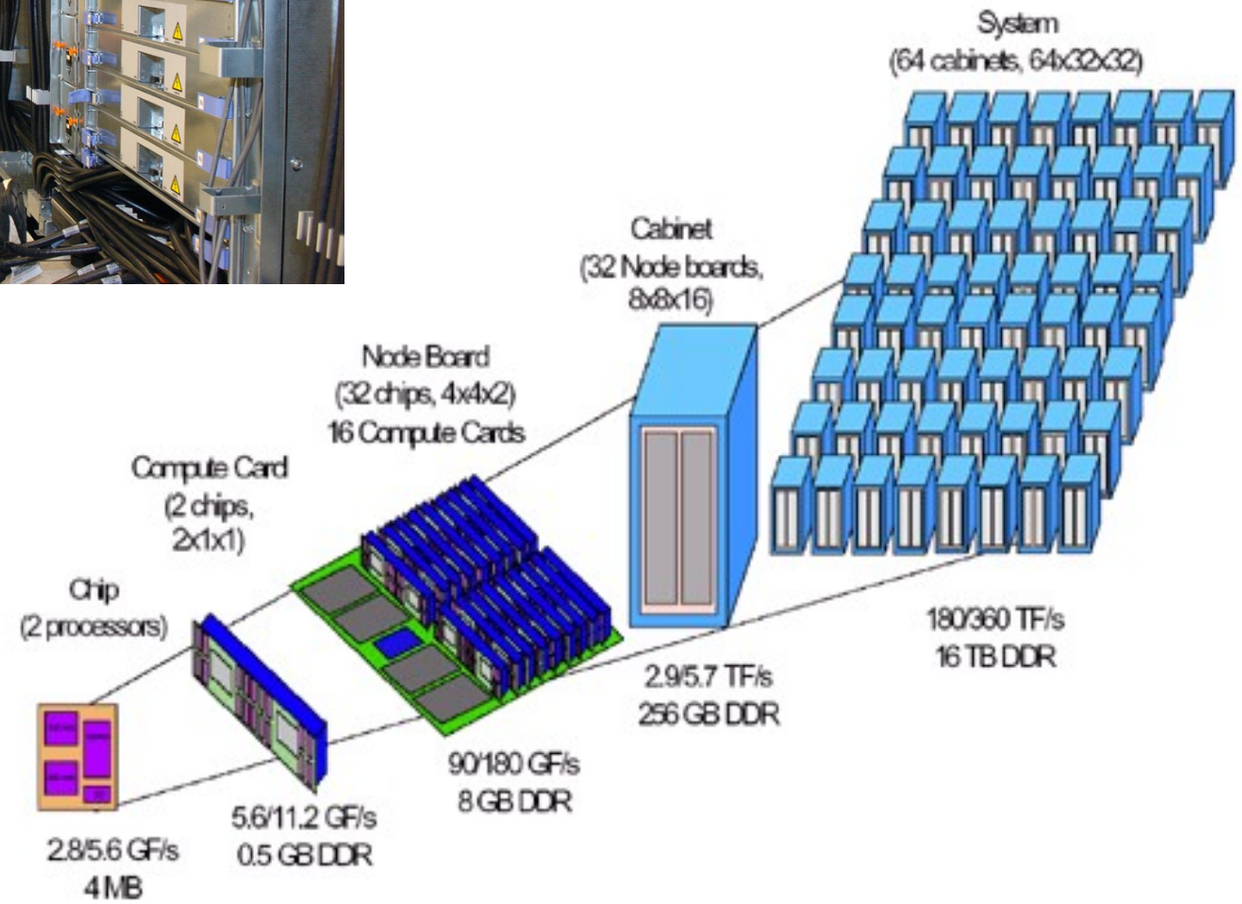
As long as we can make them smaller, we can make them faster.

Parity is for farmers.

131,072 cores BG/L (5.6 GFLOPS)







Tianhe-2, 40,960 processors, 10,649,600 cores, 33.9 PFLOPS

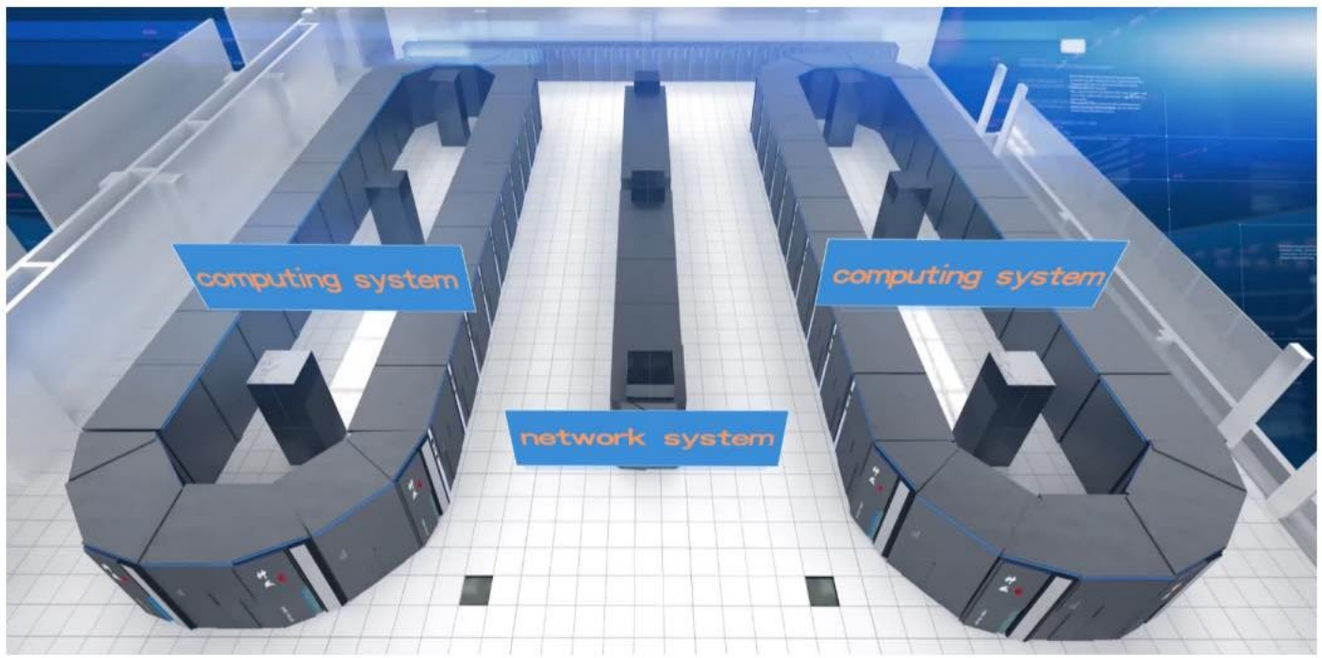
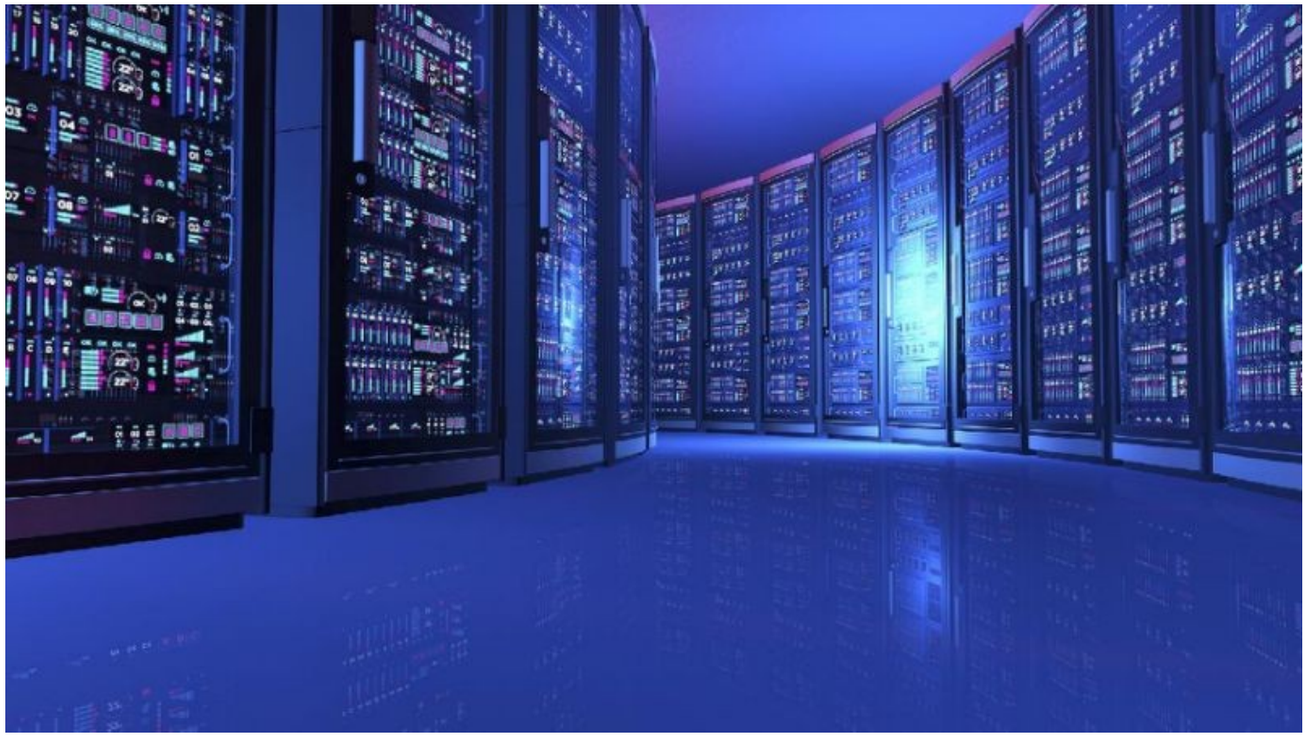


Figure 4: Overview of the Sunway TaihuLight System



TaihuLight has 125 PFLOPS peak performance, 93 PFLOPS on Linpack.

Why use message passing

- Allows control over data layout, locality and communication -- very important on large machines
- Portable across all machines *including shared memory machines* -- it's a universal parallel programming model. Sometimes called the assembly language of paralle programming
- Easier to write deterministic programs
  - simplifies debugging
  - easier to understand programs
- Style needed for efficient messages can lead to better performance than shared memory programs, even on shared memory systems.

Why not use it?

- All or nothing program development - generally need to make the entire program parallel to make any part parallel
- Information needed for messages low-level and sometimes hard to program
- Subtle bugs in message passing code can lead to performance problems and deadlock
- Message passing code disrupts the flow of algorithms

SPMD execution is often used with MPI

- *S*ingle *P*rogram *M*ultiple *D*ata
- Multiple copies of the same program operating on different parts of the data (typically different sections of an array)
- Each program copy executes in a process
- Different processes can execute different paths through the program

SPMD execution

```
for (i=0; i <= (n-1)/2; i++) {
   a[i] = i + 1;
}
for (i=0, i <= n-1; i++) {
   ... = a[i-1];
}
```

```
for (i=0; i <= n-1; i++) {
   a[i] = i + 1;
}
for (i=0, i <= n-1; i++) {
   ... = a[i-1];
}
```

0	1	...	n/2-1	n/2
1	2	...	49	50

Global index

Local index

0	1	...	n/2-1	n/2
1	2	...	49	50

```
for (i=0; i <= n-1; i++) {  // n = 100
   a[i] = i + 1;
}
for (i=0, i <= n-1; i++) {
   ... = a[i-1];
}
```

The original program

Work is done by processes

- Each process has a unique rank or process id (often called pid in programs) that is set when program begins executing
- The rank does NOT change during the execution of the program
- Each process has a unique identifier (often called *pid*) that is known to the program

- Typical program pattern is

Compute

communicate

compute

communicate ...

An simple MPI program: Radix sort

- Radix sort works well to sort lists of numbers
- Will assume integers have values from 0 to 65,535
- Have N >> 65,535 numbers to sort

A sequential radix sort

```
for (i=0; i < 65535; i++) {
   sorted[i] = 0;
}

for (i=0; i < n; i++) {
   sorted[data[i]]++;
}

for (i=0; i<65535; i++) {
   for (j=0; j < sort[i]; j+
+) {
      fprint(“%i\n”, i);
}}
```

Want to convert to SPMD message passing code

A sequential radix sort

```
for (i=0; i < 65535; i++) {
   sorted[i] = 0;
}

for (i=0; i < n; i++) {
   sorted[data[i]]++;
}

for (i=0; i<65535; i++) {
   for (j=0; j < sort[i]; j+
+) {
      fprint(“%i\n”, i);
}}
```

Note that data input not shown -- this can require some thought

Data often spread across multiple files to accommodate parallel I/O on large problems

Determining a data layout

Process pid = 0

data[0:N/4-1]
i,j
Sorted[0:65353]

Process pid = 1

data[n/4:2*N/4]
i,j
Sorted[0:65353]

Process pid = 2

data[2*N/4:3*N/4-1]
i,j
Sorted[0:65353]

Process pid = 2

data[3*n/4:N-1]
i,j
Sorted[0:65353]

Global indices are shown. The local indices used on each processor are, for data, pid*n/4:(pid+1)*n/4-1
For *replicated* data, global and local indices are the same

Change the program to SPMD

data[0:N/4-1] i,j Sorted[0:65353]	data[n/4:2*N/4] i,j Sorted[0:65353]	data[2*N/4:3*N/4-1] i,j Sorted[0:65353]	data[3*n/4:N-1] i,j Sorted[0:65353]

all processors execute this (replicated execution)

```
for (i=0; i < 65535; i++) {
    sorted[i] = 0;
}
```

each processor executes N/4 iterations (assume N mod 4 = 0)

```
for (i=0; i < N/4; i++) {
    sorted[data[i]]++;
}
```

this becomes a sum reduction over the sorted arrays on each processor, i.e. communication. This code does not show that yet.

```
for (i=0; i<65535; i++) {
    for (j=0; j < sort[i]; j++) {
        fprint("%i\n", i);
}}
```

Data management

data[0:N/4-1] i,j Sorted[0:65353]	data[n/4:2*N/4] i,j Sorted[0:65353]	data[2*N/4:3*N/4-1] i,j Sorted[0:65353]	data[3*n/4:N-1] i,j Sorted[0:65353]

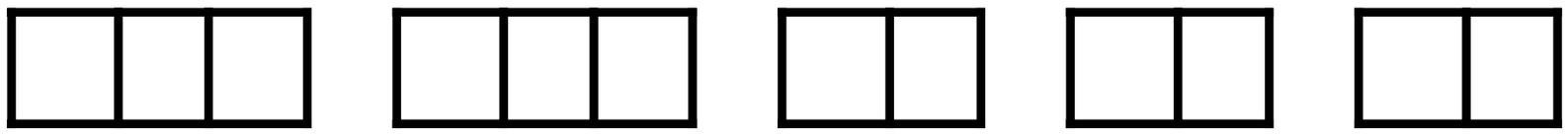
- All declared variables exist within each process
- There is a *global* and *local* logical index space for arrays
  - *globally*, data has *N* elements *pid*N:(pid+1)*N/4-1*
  - *locally*, each process has *N/4* elements numbered *0:N/4-1*(if $N \bmod 4 == 0$, otherwise $\lceil N/4 \rceil$or$\lfloor N/4 \rfloor$elements per processors with some processors having more or fewer elements than other processors
  - The concatenation of the local partitions of data arrays forms the global array data
- The array data is *block* distributed over the processors

Data bounds for block

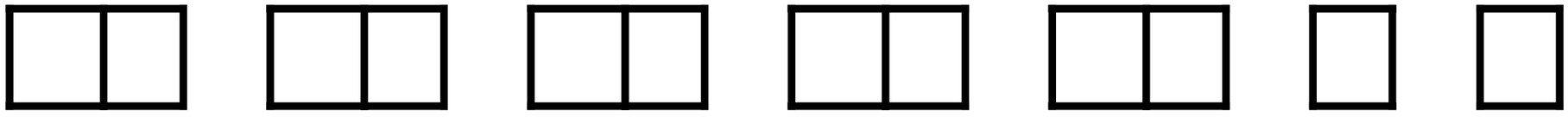
- Two “obvious” ways to compute
- Let n be the array size, P the number processors

First method

- Let P be the number of processes, n the number of array elements, $0 \le p \le P-1$ is a process id
- $r = n \bmod P$, $r = 0$, all blocks are the same size, otherwise, first r blocks have $\lceil n/P \rceil$ elements, last $P-r$ have $\lfloor n/P \rfloor$ elements
- First element on a process p is $p\lfloor n/P \rfloor + \min(p,r)$
- Last element on process p is $(p+1)\lfloor n/P \rfloor + \min(p+1,r) - 1$
- process with element i is $\min(\lfloor i/(\lfloor n/P \rfloor + 1) \rfloor, \lfloor i-r) / \lfloor n/P \rfloor \rfloor)$
- Example -- 12 elements over 5 processors, $2 = 12 \bmod 5$



- Example -- 12 elements over 7 processors, $5 = 12 \bmod 7$

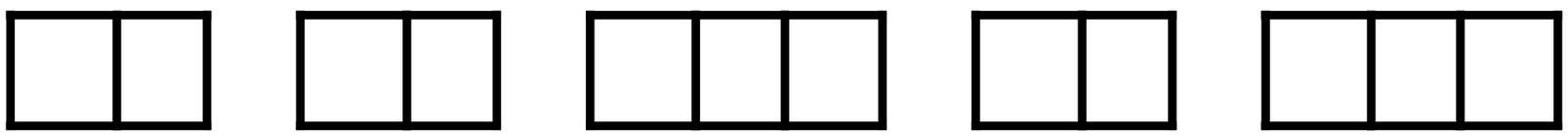


Second method

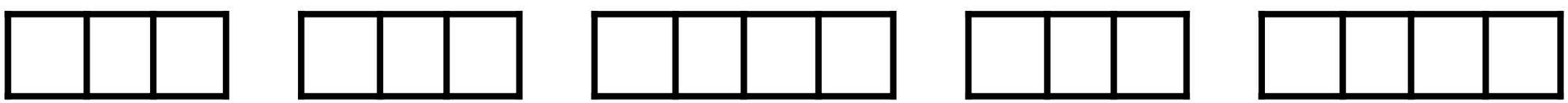
- First element controlled (or owned) by process p is $\lfloor p\ n/P \rfloor$ (first element and first process id p is 0
- Last element controlled by process p is one less that the first element controlled by process $p+1$ (the next process)

$$\lfloor (p+1)\ n/P \rfloor - 1$$

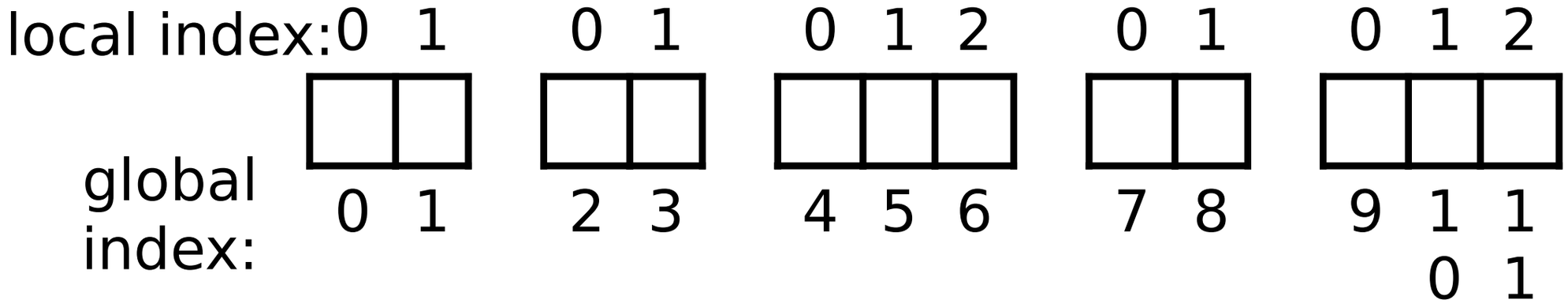
- Process controlling element i is $\lfloor (P(i+1)-1)/n \rfloor$
- Example -- 12 elements over 5 processors, $r = 2 = 12 \bmod 5$



- Example -- 17 elements over 5 processors, $r = 2 = 17 \bmod 5$

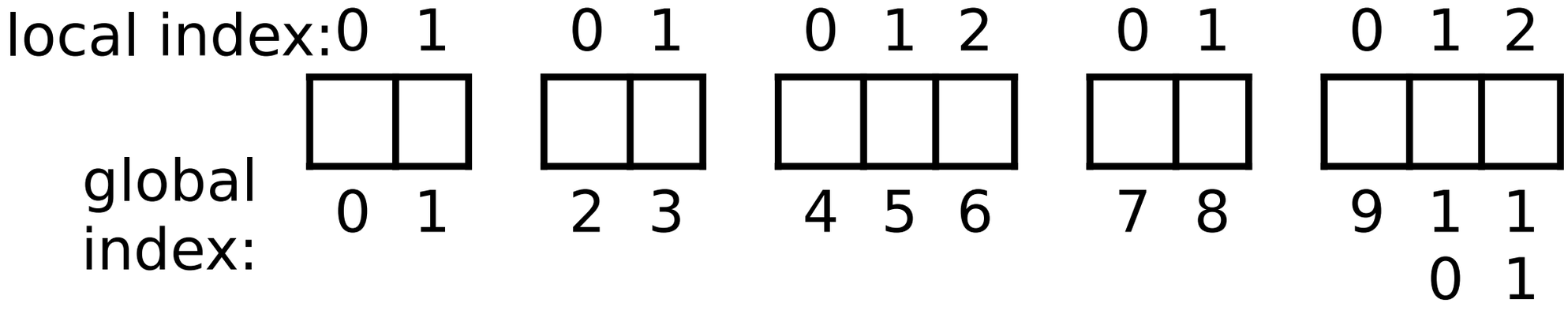


Global *vs* local indices



- Each part of an array within a process *must* be indexed as a local element of that array using the *local index.*
- Logically, each local element is a part of the global array, and within the problem domain has a *global index*
- It is the MPI *programmer's* responsibility (that means you) to maintain that mapping.

Use macros to access bounds



- Macros or functions can be used to compute these.
- Block lower bound: $LB(pid, P, n) = (pid*n/P)$
- Block upper bound: $UB(pid, P, n) = LB(pid+1, P, n)-1$
- Block size: $LB(pid+1, P, n) - LB(pid, P, n) + 1$
- Block owner: $Owner(i, P, n) = (P*(i+1)-1)/n$

Comparison of the two methods

Operations	First Method	Second Method
Low index	4	2
High index	6	4
Owner	7	4

Assumes floor is free (as it is with integer division although integer division itself may be expensive)

The *cyclic* distribution

P0	P1	P2	P3
Data[0:N:4] I,j Sorted[0:65353	Data[1:N:4] I,j Sorted[0:65353	Data[2:N:4] I,j Sorted[0:65353	Data[3:N:4] I,j Sorted[0:65353

- Let *A* be an array with *N* elements.
- Let the array be *cyclically distributed* over *P* processes
- Process *p* gets elements *p, p+P, p+2*P, p+3*P, ...*
- In the above
  - process 0 gets elements 0, 4, 8, 12, ... of data
  - process 1 gets elements 1, 5, 9, 13, ... of data
  - process 2 gets elements 2, 6, 10, 14, ... of data
  - process 3 gets elements 3, 7, 11, 15, ... of data

The *block-cyclic* distribution

- Let *A* be an array with *N* elements
- Let the array be *block-cyclically distributed* over *P* processes, with blocksize *B*
- Block *b, b = 0 ...,* on process *p* gets elements
  *b*B*P+p*B: b*B*P + (p+1)*B*)-1 elements
- With P=4, *B=3*
  - process 0 gets elements [0:2], [12:14], [24:26] of data
  - process 1 gets elements [3:5], [15:17],[27:29] of data
  - process 2 gets elements [6:8], [18:20],[30:32] of data
  - process 3 gets elements [9:11], [21:23],[33:35] of data

System initialization

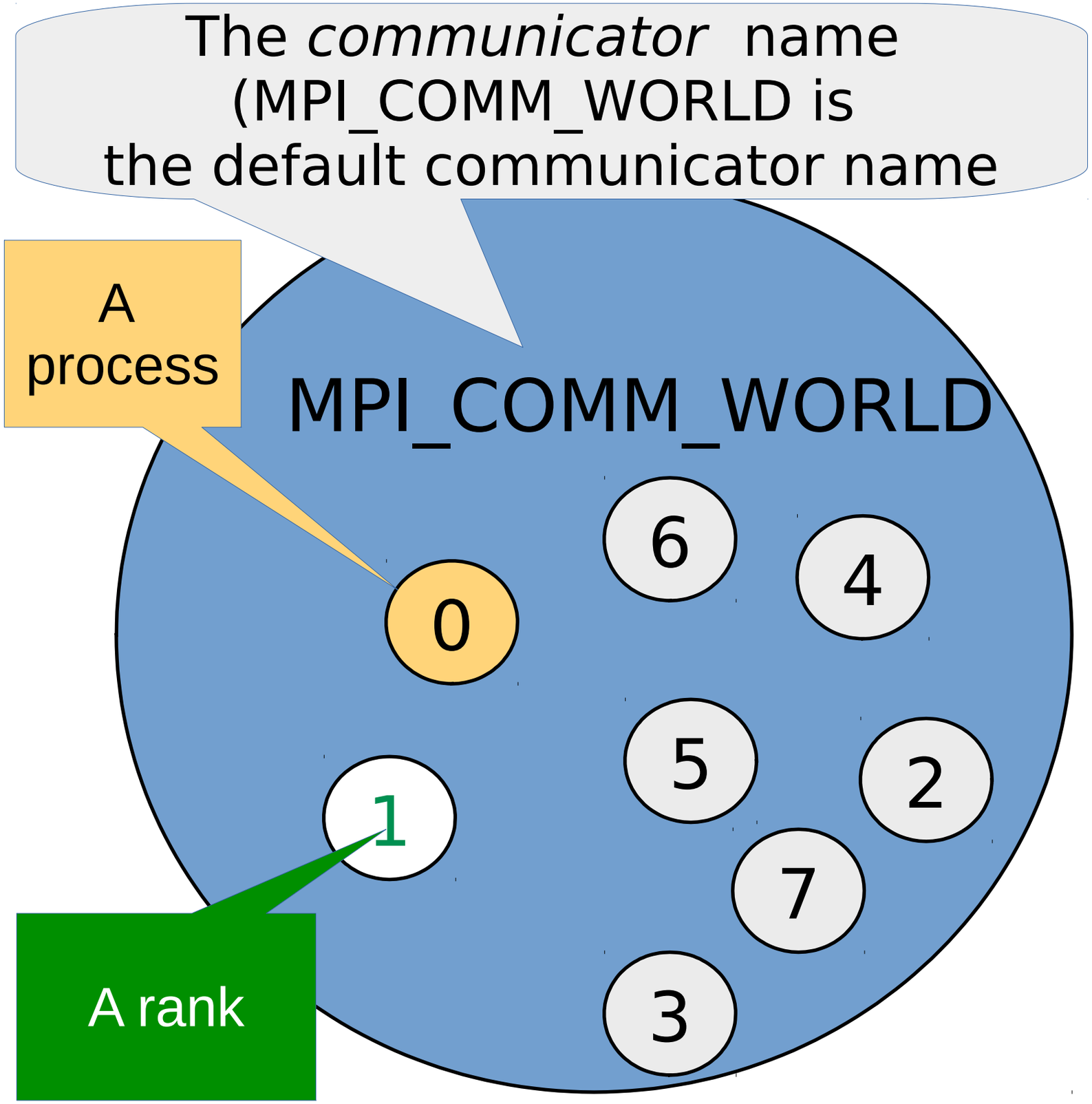
```
#include <mpi.h> /* MPI library prototypes, etc. */
#include <stdio.h>
// all processors execute this (replicated execution)
int main(int argc, char * argv[ ]) {
int pid; /* MPI process ID)
int numP; /* number of MPI processes */
int N;
extractArgv(&N, argv); // get N from the arg vector
int sorted[65536]; int data[N/4];
MPI_INIT(&argc, &argv); // argc and argv need to be passed in
for (i=0; i < 65535; i++) {
sorted[i] = 0;
}}
```

data[pid*n/4:pid*N/4-1]
i,j
Sorted[0:65353]

MPI_INIT

- Initialize the MPI runtime
- Does not have to be the first executable statement in the program, but it *must* be the first MPI call made
- Initializes the default MPI *communicator* (MPI_COMM_WORLD which includes all processes)
- Reads standard files and environment variables to get information about the system the program will execute on
  - e.g. what machines executes the program?

The MPI environment



A *communicator* defines a universe of processes that can exchange messages

Include files

P0	P1	P2	P3
Data[0:N:4] I,j Sorted[0:65353	Data[1:N:4] I,j Sorted[0:65353	Data[1:N:4] I,j Sorted[0:65353	Data[1:N:4] I,j Sorted[0:65353

```
#include <mpi.h> /* MPI library prototypes, etc. */
#include <stdio.h>
```

```
using mpi // Fortran 90
include “mpi.h” // Fortran 77
```

These may not be shown on later slides to make room for more interesting stuff

Communicator and process info

P0	P1	P2	P3
data[0:N/4-1] i,j Sorted[0:65353]	data[n/4:2*N/4] i,j Sorted[0:65353]	data[2*N/4:3*N/4-1] i,j Sorted[0:65353]	data[3*n/4:N-1] i,j Sorted[0:65353]

```
// all processors execute this (replicated execution)
int main(int argc, char * argv[ ]) {
    int pid; /* MPI process ID)
    int numP; /* number of MPI processes */
    int N;
    int lb = LB(pid, numP, N); int ub = UB(pid,numP,N);
    extractArgv(&N, argv);
    int sorted[65536]; int *data;
    MPI_INIT(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &numP);
    for (i=0; i < 65535; i++) {
        sorted[i] = 0;
}}
```

Getting the pid for each process

P0	P1	P2	P3
data[0:N/4-1] i,j Sorted[0:65353]	data[n/4:2*N/4] i,j Sorted[0:65353]	data[2*N/4:3*N/4-1] i,j Sorted[0:65353]	data[3*n/4:N-1] i,j Sorted[0:65353]

```
// all processors execute this (replicated execution)
int main(int argc, char * argv[ ]) {
    int pid; /* MPI process ID)
    int numP; /* number of MPI processes */
    int N;
    int lb = LB(pid, numP, N); int ub = UB(pid,numP,N);
    extractArgv(&N, argv);
    int sorted[65536]; int* data;
    MPI_INIT(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &numP);
    MPI_Comm_rank(MPI_COMM_WORLD, &pid);
    for (i=0; i < 65535; i++) {
        sorted[i] = 0;
}}
```

Getting the pid for each process

P0	P1	P2	P3
data[0:N/4-1] i,j Sorted[0:65353]	data[n/4:2*N/4] i,j Sorted[0:65353]	data[2*N/4:3*N/4-1] i,j Sorted[0:65353]	data[3*n/4:N-1] i,j Sorted[0:65353]

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int main(int argc, char * argv[ ]) {
    int pid; /* MPI process ID)
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    int lb = LB(pid, numP, N); int ub = UB(pid,numP,N);
    extractArgv(&N, argv);
    int sorted[65536]; int* data;
    MPI_INIT(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &numP);
    MPI_Comm_rank(MPI_COMM_WORLD, &pid);
    for (i=0; i < 65535; i++) {
        sorted[i] = 0;
}}
```

Allocating local storage

P0	P1	P2	P3
data[0:N/4-1] i,j Sorted[0:65353]	data[n/4:2*N/4] i,j Sorted[0:65353]	data[2*N/4:3*N/4-1] i,j Sorted[0:65353]	data[3*n/4:N-1] i,j Sorted[0:65353]

```
int main(int argc, char * argv[ ]) {
    int pid; /* MPI process ID)
    int numP; /* number of MPI processes */
    int N;
    int lb = LB(pid, numP, N); int ub = UB(pid,numP,N);
    extractArgv(&N, argv);
    int sorted[65536]; int* data;
    MPI_INIT(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &numP);
    MPI_Comm_rank(MPI_COMM_WORLD, &pid);
    Lb = LB(pid, numP, N); ub = LB(pid, numP, N)-1;
    data = malloc(sizeof(int)*(ub-lb+1)
    for (i=0; i < 65535; i++) {
        sorted[i] = 0;
}}
```

Terminating the MPI program

P0	P1	P2	P3
Data[0:N:4] I,j Sorted[0:65353	Data[1:N:4] I,j Sorted[0:65353	Data[1:N:4] I,j Sorted[0:65353	Data[1:N:4] I,j Sorted[0:65353

```
int main(int argc, char * argv[ ]) {
    int pid; /* MPI process ID)
    int numP; /* number of MPI processes */
    int N;
    int lb = LB(pid, numP, N); int ub = UB(pid,numP,N);
    extractArgv(&N, argv);
    int sorted[65536]; int* data;
    MPI_INIT(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &numP);
    MPI_Comm_rank(MPI_COMM_WORLD, &pid);
    Lb = LB(pid, numP, N); ub = LB(pid, numP, N)-1;
    data = malloc(sizeof(int)*(ub-lb+1)
    for (i=0; i < 65535; i++) {
       sorted[i] = 0;
   MPI_Finalize( );
}
```

Time to do something useful

P0	P1	P2	P3
Data[0:N:4] I,j Sorted[0:65353	Data[1:N:4] I,j Sorted[0:65353	Data[1:N:4] I,j Sorted[0:65353	Data[1:N:4] I,j Sorted[0:65353

```
int main(int argc, char * argv[ ]) {
    int pid; /* MPI process ID)
    int numP; /* number of MPI processes */
    int N;
 int lb = LB(pid, numP, N); int ub = UB(pid,numP,N);
 extractArgv(&N, argv);
 int sorted[65536]; int* data;
 MPI_INIT(&argc, &argv);
 MPI_Comm_size(MPI_COMM_WORLD, &numP);
 MPI_Comm_rank(MPI_COMM_WORLD, &pid);
 Lb = LB(pid, numP, N); ub = LB(pid, numP, N)-1;
 data = malloc(sizeof(int)*(ub-lb+1)
 for (i=0; i < 65535; i++) {
    sorted[i] = 0;
 sort(data, sort, ub-lb+1);
MPI_Finalize( );}
```

The sequential radix sort

```
void sort (sort[ ], data[ ], int N) {
   for (i=0; i < N; i++) {
      sorted[data[i]]++;
   }

   for (i=0; i<65535; i++) {
      for (j=0; j < sort[i]; j++) {
         fprint(“%i\n”, i);
      }
   }
}
```

The parallel radix sort

```
void sort (sort[ ], data[ ], int localN) {
   for (i=0; i < N; i++) {
      sorted[data[i]]++;
   }
   // pid == 0 only has its results!  We
   // need to combine the results here.
   If (pid == 0) {
      for (i=0; i<65535; i++) {
         for (j=0; j < sort[i]; j++) {
            fprint("%i\n", i);
         }
      }
}
```

Each process sorts the local N elements that it owns. The results from each process need to be combined and sent to a single process for printing, say, the process with *pid==0*.

MPI_Reduce(...)

```
MPI_Reduce(
   void *opnd,  // data to be reduced
   void *result, // result of the reduction
   int count,     // # of elements to be reduced
   MPI_Datatype type, // type of the elements
                      // being reduced
   MPI_Operator op, // reduction operation
   int root, // pid of the process getting the
             // result of the reduction
   MPI_Comm comm // communicator over
                 // which the reduction is
                 // performed
);
```

MPI_Datatype

Defined as constants in the mpi.h header file

Types supported are

MPI_CHAR

MPI_DOUBLE

MPI_FLOAT

MPI_INT

MPI_LONG

MPI_LONG_DOUBLE

MPI_SHORT

MPI_UNSIGNED_CHAR

MPI_UNSIGNED

MPI_UNSIGNED_LONG

MPI_UNSIGNED_SHORT

MPI_Datatype

Defined as constants in the mpi.h header file

Types supported are

MPI_CHAR
MPI_FLOAT
MPI_LONG
MPI_SHORT
MPI_UNSIGNED
MPI_UNSIGNED_SHORT
MPI_DOUBLE
MPI_INT
MPI_LONGDOUBLE
MPI_UNSIGNED_CHAR
MPI_UNSIGNED_LONG

MPI_Op

- Defined as constants in the mpi.h header file
- Types supported are

MPI_BAND
MPI_EXOR
MPI_LAND
MPI_LXOR
MPI_MAXLOC
MPI_MINLOC
MPI_SUM
MPI_BOR
MPI_BXOR
[MPI_LOR
MPI_MAX
MPI_MIN
MPI_PROD

Example of reduction

sorted, p=0

sorted, p=1

sorted, p=2

sorted, p=3

sorted, p=0

3	5	2	9	8	11	20	4
8	3	6	8	38	5	27	6
1	0	9	0	2	1	2	40
13	15	12	19	18	21	42	3
25	23	39	36	64	38	91	53

```
MPI_Reduce(MPI_IN_PLACE, sorted, 8, MPI_INT,
           MPI_SUM, 0, MPI_COMM_WORLD);
```

Example of reduction

P0 data	1	2	3	4
P1 data	2	4	6	8
P2 data	3	6	9	12
P3 data	4	8	12	16

P0 res				
P1 res				
P2 res	10			
P3 res				

```
MPI_Reduce(data, res, 1,
                    MPI_INT,
                    MPI_SUM, 2,
                    MPI_COMM_WORLD);
```

Example of reduction

P0 data	1	2	3	4

P0 res	10	20	30	

P1 data	2	4	6	8

P1 res				

P2 data	3	6	9	12

P2 res				

P3 data	4	8	12	16

P0 res				

```
MPI_Reduce(data, res, 3,
                    MPI_INT,
                    MPI_SUM, 0,
                    MPI_COMM_WORLD);
```

Example of reduction

Before reduction

P0 data	1	2	3	4
P1 data	2	4	6	8
P2 data	3	6	9	12
P3 data	4	8	12	16

After reduction

P0 data	10	20	30	4
P1 data	2	4	6	8
P2 data	3	6	9	12
P3 data	4	8	12	16

```
MPI_Reduce(MPI_IN_PLACE, data, 3,
                    MPI_INT,
                    MPI_SUM, 0,
                    MPI_COMM_WORLD);
```

Add the reduction

```
void sort (sort[ ], data[ ], int pid, int numP) {
   for (i=0; i < N; i++) {
      sorted[data[i]]++;
   }
   // can merge all of the "sorted" arrays here
   if (pid == 0) {
      MPI_Reduce(MPI_IN_PLACE, sorted, 65353, MPI_INT,
                        MPI_SUM, 0, MPI_COMM_WORLD);
   } else {
      MPI_Reduce(sorted, (void *) null, 65353, MPI_INT,
                        MPI_SUM, 0, MPI_COMM_WORLD);
    // print out the sorted array on process pid==0
```

Alternatively, could allocate a buffer for final sorted result. Buffer would be the same size as sorted.

Measure program runtime

```
int main(int argc, char * argv[ ]) {
double elapsed;
int pid;
int numP;
int N;
. . .
MPI_Barrier( );
   elapsed = -MPI_Wtime( );
   sort(data, sort, pid, numP);
   elapsed += MPI_Wtime( );
   if (pid == 0) printSort(final);
   MPI_Finalize( );
}
```

Wtick( ) returns a *double* that holds the number of seconds between clock ticks - 10^{-3} is milliseconds

- MPI_Barrier - barrier synchronization
- MPI_Wtick - returns the clock resolution in seconds
- MPI_Wtime - current time

Wtick( ) gives the clock resolution

MPI_WTick returns the resolution of MPI_WTime in seconds. That is, it returns, as a double precision value, the number of seconds between successive clock ticks.

```
double tick = MPI_WTick( );
```

Thus, a millisecond resolution timer will return 10^{-3}

This can be used to convert elapsed time to seconds

Sieve of Erosthenes

- Look at block allocations
- Performance tuning
- MPI_Bcast function

Finding prime numbers

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100

To find primes

1. start with two, mark all multiples
2. find the next unmarked u -- it is a prime
3. mark all multiples of u between k^2 and n until $k^2 > n$
4. repeat 2 & 3 until finished

Mark off multiples of primes

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100

To find primes

3 is prime

mark all multiples of 3 > 9

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100

To find primes

5 is prime

mark all multiples of 5 > 25

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100

To find primes

7 is prime

mark all multiples of 7 > 49

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100

To find primes

11 is prime

mark all multiples of 11 > 121

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100

To find primes

~~1~~, 2, 3, 5, 7, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89 and 97 are prime.

Want to parallelize this

- Because we are message passing, obvious thing to look at it domain decomposition, i.e. how can we break up the domain being operated on over multiple processors
  - partition data across processors
  - associate tasks with data
- In general, try to find fundamental operations and associate them with data

Find the fundamental operation(s)?

- Marking of the multiples of the last prime found
- if *v* a multiple of *k* then *v mod k == 0*
- *min*-reduction to find the next prime (i.e. smallest unmarked value) across all processes
- *broadcast* the value to all tasks

```
forall (v = k; v < n+1; v++) {
   if (v mod k != 0) a[v] = 1;
}
```

To make this efficient . . .

- Combine as many tasks as possible onto a single process
- Make the amount of work done by each process similar, i.e. *load balance*
- Make the communication between tasks efficient

Combining work/data partitioning

- Because processes work on data that they own (the *owners compute rule,* Rogers and Pingali), the two problems are tightly inter-related.
- Each element is *owned* by a process
- It is the process that owns the consistent, i.e., up-to-date value of a variable
- All updates to the variable are made by the owner
- All requests for the value of the variable are to the owner

Combining work/data partitioning

- Because processes update the data that they own
- Cyclic distributions have the property that for all elements *i* on some process *p*, *i mod p* = *c* holds, where *c* is some integer value
  - Although cyclic usually gives better load balance, it doesn’t in this case
  - Lesson -- don’t apply rules-of-thumb blindly
- Block, in this case, gives a better load balance
  - computation of indices will be harder

Interplay of decomposition and implementation

- Decomposition affects how we design the implementation
- More abstract issues of parallelization can affect the implementation
- In the current algorithm, let Φ be the highest possible prime
  - At most, only first $\sqrt{\Phi}$ values may be used to mark off (sieve) other primes
- if P processes, n elements to a process, then if $n/P > \sqrt{\Phi}$ only elements in $p=0$ will be used to sieve. This means we only need to look for lowest unmarked elements in $p=0$ and only $p=0$ needs to send this out, saving a reduction operation.

Use of block partitioning affects marking

- Can mark $j, j+k, j+2k, \ldots$ where j is the first prime in the block
- Using the parallel method described in earlier psuedo-code, would need to use an expensive mod

```
for all e in the block
    if e mod k = 0, mark e
```

- We would like to eliminate this.

Sketch of the algorithm

1. Create list of possible primes
2. On each process, set $k = 2$
3. Repeat
    1. On each process, mark all multiples of k
    2. On process *0*, find smallest unmarked number u, set $k=u$
    3. On process 0, *broadcast* k to all processes
4. Until $k^2 > \Phi$ (the highest possible prime)
5. Perform a sum reduction to determine the number of primes

Data layout, primes up to 28

array element

number being checked for "primeness"

	$i=$ 0	1	2	3	4	5	6	7	8
P=0	2	3	4	5	6	7	8	9	10
P=1	11	12	13	14	15	16	17	18	19
P=2	20	21	22	23	24	25	26	2	28

Algorithm 1/4

```
#include <mpi.h>
#include <math.h>
#include <stdio.h>
#include "MyMPI.h"
#define MIN(a,b)  ((a)<(b)?(a):(b))

int main (int argc, char *argv[])
{
   ...
   MPI_Init (&argc, &argv);
   MPI_Barrier(MPI_COMM_WORLD);
   elapsed_time = -MPI_Wtime();
   MPI_Comm_rank (MPI_COMM_WORLD, &id);
   MPI_Comm_size (MPI_COMM_WORLD, &p);
   if (argc != 2) {
      if (!id) printf ("Command line: %s <m>\n", argv[0]);
      MPI_Finalize(); exit (1);
   }
```

Algorithm, 2/4

```
n = atoi(argv[1]);
low_value = 2 + BLOCK_LOW(id,p,n-1);
high_value = 2 + BLOCK_HIGH(id,p,n-1);
size = BLOCK_SIZE(id,p,n-1);
proc0_size = (n-1)/p;
if ((2 + proc0_size) < (int) sqrt((double) n)) {
   if (!id) printf ("Too many processes\n");
   MPI_Finalize();
   exit (1);
}

marked = (char *) malloc (size);
if (marked == NULL) {
   printf ("Cannot allocate enough memory\n");
   MPI_Finalize();
   exit (1);
}
```

Get min and max possible prime on *p* in global space

Figure out if too many processes for √Φ candidates on *p=0*

allocate array to use to mark primes

Block Low

Block hIGH

$i =$	0	1	2	3	4	5	6	7	8
P=0	2	3	4	5	6	7	8	9	10

$i =$	9	10	11	12	13	14	15	16	17
P=1	11	12	13	14	15	16	17	18	19

$i =$	18	19	20	21	22	23	24	25	26
P=2	20	21	22	23	24	25	26	2	28

Low value

High value

Algorithm 3/4 (a)

for (i = 0; i < size; i++) marked[i] = 0; // initialize marking array
if (!id) index = 0; // *p=0* action, find first prime
prime = 2;
do { // prime = 2 first time through, sent by *bcast* on later iterations
    Find first element to mark on each procesor
    Mark that element and every kth element on the processor
    Find the next unmarked element on P0. This is the next prime
    Send that prime to every other processor
} while (prime * prime <= n);

Algorithm 3/4 (b)

Initialize array and find first prime
  // Find first element to mark on each procesor
  do { // prime = 2 first time through, sent by *bcast* on later iterations
    if (prime * prime > low_value) // find first value to mark
      first = prime * prime - low_value; // first item in this block
    else {
      if (!(low_value % prime)) first = 0; // first element divisible
                                           // by prime
      else first = prime - (low_value % prime);
    }
    Find first element to mark on each procesor
    Mark that element and every kth element on the processor
    Find the next unmarked element on P0. This is the next prime
    Send that prime to every other processor
} while (prime * prime <= n);

Algorithm 3/4 (c)

Initialize array and find first prime

do { // prime = 2 first time through, sent by *bcast* on later iterations

Find first element to mark on each procesor

// Mark that element and every kth element on the processor

for (i = first; i < size; i += prime) marked[i] = 1; // mark every k^{th} item

Find the next unmarked element on P0. This is the next prime

Send that prime to every other processor

} while (prime * prime <= n);

Algorithm 3/4 (d)

Initialize array and find first prime

```
   do { // prime = 2 first time through, sent by bcast on later iterations
        Find first element to mark on each procesor
       Mark that element and every kth element on the processor
       // Find the next unmarked element on P0.  This is the next prime

      if (!id) { // p=0 action, find next prime by finding unmarked element
         while (marked[++index]);
         prime = index + 2;
      }
      // Send that prime to every other processor
      MPI_Bcast (&prime,  1, MPI_INT, 0, MPI_COMM_WORLD);
} while (prime * prime <= n);
```

Algorithm 3/4 full code

```
for (i = 0; i < size; i++) marked[i] = 0; // initialize marking array
if (!id) index = 0; // p=0 action, find first prime
prime = 2;
do { // prime = 2 first time through, sent by bcast on later iterations
   if (prime * prime > low_value) // find first value to mark
      first = prime * prime - low_value; // first item in this block
   else {
      if (!(low_value % prime)) first = 0; // first element divisible by prime
      else first = prime - (low_value % prime);
   }
   for (i = first; i < size; i += prime) marked[i] = 1; // mark every kth item
   if (!id) { // p=0 action, find next prime by finding unmarked element
      while (marked[++index]);
      prime = index + 2;
   }
   MPI_Bcast (&prime,  1, MPI_INT, 0, MPI_COMM_WORLD);
} while (prime * prime <= n);
```

First prime

index = 0
prime = 2

*2 * 2 > 2*
*first = 2 * 2 - 2*
first = 2

local i = 0 1 2 3 4 5 6 7 8

P=0 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

*not 2 * 2 > 11*
11 % 2 == 1
first = 2 - (11 % 2)
first = 1

local i = 0 1 2 3 4 5 6 7 8

P=0 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |

*not 2 * 2 > 20*
20 % 2 == 0
first = 0

local = 0 1 2 3 4 5 6 7 8

P=0 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 2 | 28 |

third prime

index = 3
prime = 5

*5 * 5 > 2*
*first = 5 * 5 - 2*
first = 23

local i = 0 1 2 3 4 5 6 7 8

P=0 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

5 * 5 > 11
first = 5 * 5 - 11
first = 16

local i = 0 1 2 3 4 5 6 7 8

P=0 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |

*5 * 5 > 20*
*first = 5 * 5 - 20*
first = 5

local = 0 1 2 3 4 5 6 7 8

P=0 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 2 | 28 |

Mark every prime elements starting with *first*

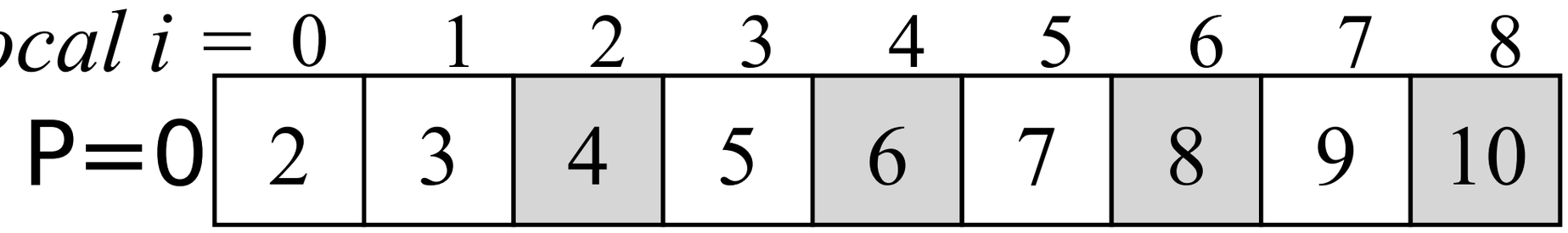
index = 0

prime = 2

*2 * 2 > 4*

*first = 2 * 2 - 2*

*first = **2***

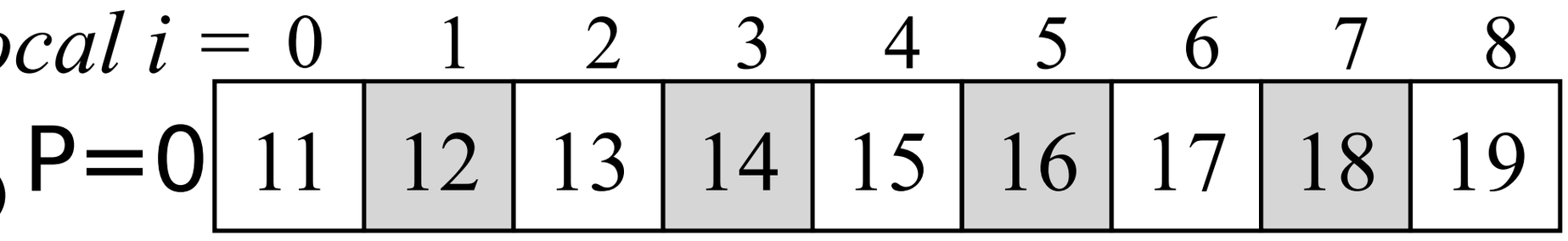


*not 2 * 2 > 11*

11 % 2 == 1

first = 2 - (11 % 2)

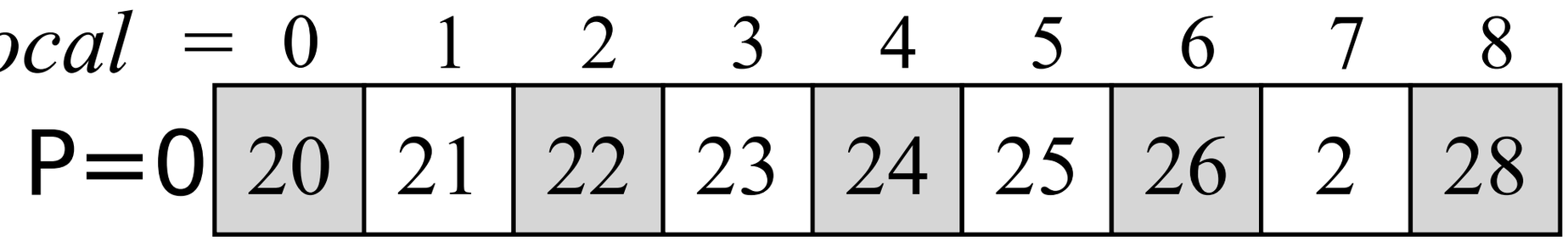
first = 1



*not 2 * 2 > 20*

20 % 2 == 0

first = 0



Algorithm 4/4

```
// on each processor count the number of primes, then reduce this total
count = 0;
for (i = 0; i < size; i++) if (!marked[i]) count++;
MPI_Reduce (&count, &global_count, 1, MPI_INT, MPI_SUM,
                        0, MPI_COMM_WORLD);
elapsed_time += MPI_Wtime();
   if (!id) {
      printf ("%d primes are less than or equal to %d\n",
                global_count, n);
      printf ("Total elapsed time: %10.6f\n", elapsed_time);
   }
   MPI_Finalize ();
   return 0;
}
```

index = 0

prime = 2

global_count = 1 + 4 + 2

count = 1 P=0

2	3	4	5	6	7	8	9	10

count = 4 P=0

11	12	13	14	15	16	17	18	19

count = 2 P=0

20	21	22	23	24	25	26	27	28

Other MPI environment management routines

- **MPI_Abort (comm, errorcode)**
  - Aborts all processors associated with communicator *comm*
- **MPI_Get_processor_name(&name, &length)**
  - MPI version of *gethostname*, but what it returns is implementation dependent. *gethostname* may be more portable.
- **MPI_Initialized(&flag)**
  - Returns **true** if MPI_Init has been called, **false** otherwise

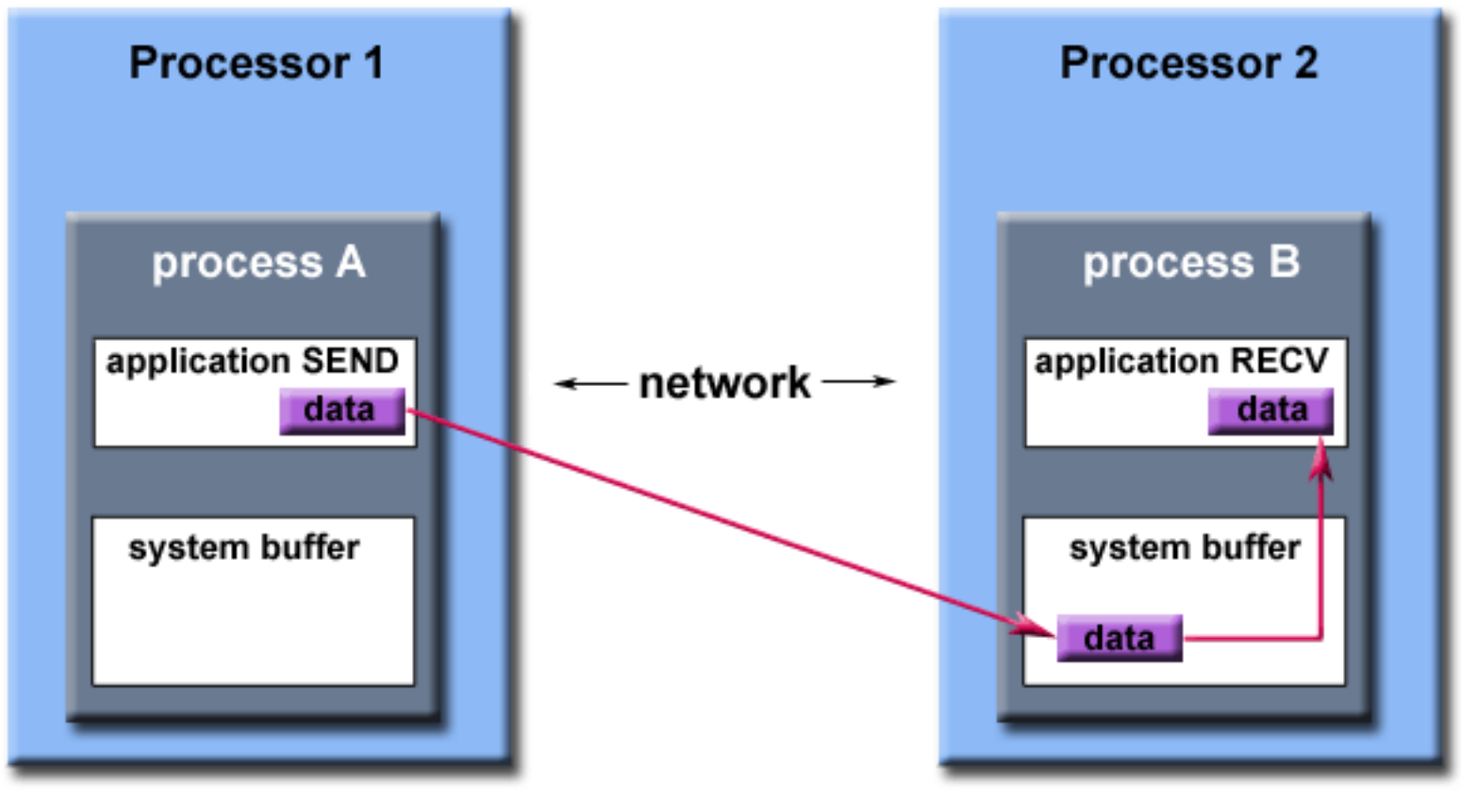
point-to-point communication

- Most MPI communication is between a pair of processors
  - send/receive transmits data from the sending process to the receiving process
- MPI point-to-point communication has many flavors:
  - Synchronous send
  - Blocking send / blocking receive
  - Non-blocking send / non-blocking receive
  - Buffered send
  - Combined send/receive
  - "Ready" send (matching receive already posted.)
- All types of sends can be paired with all types of receive

Buffering

What happens when

- A send occurs before the receiving process is ready for the data
- The data from multiple sends arrive at the receiving task which can only accept one at a time



Path of a message buffered at the receiving process

System buffer space

Not part of the standard -- an “implementation detail

- Managed and controlled by the MPI library
- Finite
- Not well documented -- size maybe a function of install parameters, consequences of running out not well defined
- Both sends and receives can be buffered

Helps performance by enabling asynchronous send/recvs

Can hurt performance because of memory copies

Program variables are called *application buffers* in MPI-speak

Blocking and non-blocking point-to-point communication

Blocking

- Most point-to-point routines have a blocking and non-blocking mode
- A blocking send call returns only when it is safe to modify/reuse the application buffer. Basically the data in the application buffer has been copied into a system buffer or sent.
- Blocking send can be synchronous, which means call to send returns when data is safely delivered to the recv process
- Blocking send can be asynchronous by using a send buffer
- A blocking receive call returns when sent data has arrived and is ready to use

Blocking and non-blocking point-to-point communication

Non-blocking

- Non-blocking send and receive calls behave similarly and return almost immediately.
- Non-blocking operations request the MPI library to perform the operation when it is able. It cannot be predicted when the action will occur.
- You should not modify any application buffer *(program variable)* used in non-blocking communication until the operation has finished. *Wait* calls are available to test this.
- Non-blocking communication allows overlap of computation with communication to achieve higher performance

Synchronous and buffered sends and receives

- synchronous send operations block until the receiver begins to receive the data
- buffered send operations allow specification of a buffer used to hold data (this buffer is not the *application* buffer that is the variable being sent or received)
  - allows user to get around system imposed buffer limits
  - for programs needing large buffers, provides portability
  - One buffer/process allowed
  - synchronous and buffered can be *matched*

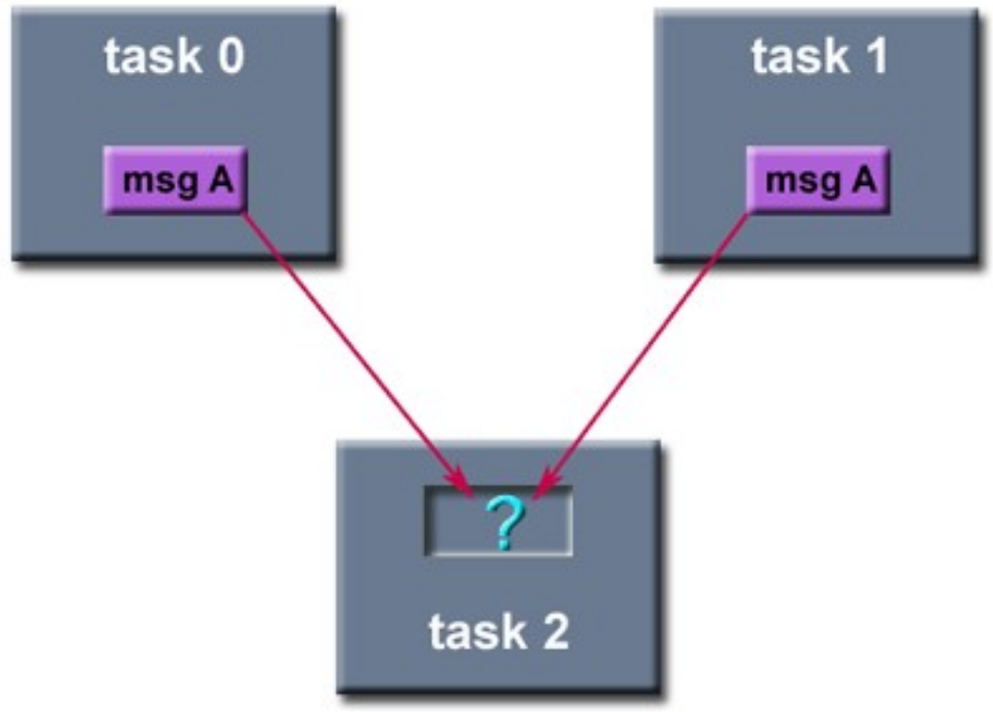
Ordering of messages and fairness

- Messages received in-order
- If a sender sends two messages, (*m1* and *m2*) to the same destination, and both match the same kind of receive, *m1* will be received before *m2*.
- If a receiver posts two receives (*r1* followed by *r2*), and both are looking for the same kind of messages, *r1* will receive a message before *r2*.
- *Operation starvation* is possible
  - *task2* performs a single receive. *task0* and *task3* both send a message to *task2* that matches the receive. Only one of the sends will complete if the receive is only executed once.
  - It is the programmer's job to ensure this doesn't happen

Operation starvation

Only one of the *sends* will complete.

Networks are generally not deterministic, cannot be predicted whose message will arrive at *task2* first, and which will complete.



Basic sends and receives

- MPI_send(buffer, count, type, dest, tag, comm)
- MPI_Isend(buffer, count, type, dest, tag, comm,request)
- MIP_Recv(buffer, count, type, source, tag, comm, status)
- MPI_Irecv(buffer, count, type, source, tag, comm, request)

I forms are non-blocking

Basic sends/recv arguments (*I* forms are non-blocking)

- MPI_send(buffer, count, type, dest, tag, comm)
- MPI_Isend(buffer, count, type, dest, tag, comm, request)
- MIP_Recv(buffer, count, type, source, tag, comm, status)
- MPI_Irecv(buffer, count, type, source, tag, comm, request)
- buffer: pointer to the data to be sent or where received (a program variable)
- count: number of data elements of type (*not bytes!*) to be sent
- type: an MPI_Type
- tag: the message type, any unsigned integer 0 - 32767.
- comm: sender and receiver communicator

Basic send/recv arguments

- MPI_send(buffer, count, type, dest, tag, comm)
- MPI_Isend(buffer, count, type, dest, tag, comm, request)
- MIP_Recv(buffer, count, type, source, tag, comm, status)
- MPI_Irecv(buffer, count, type, source, comm, request)
- dest: rank of the receiving process
- source: rank of the sending process
- request: for non-blocking operations, a handle to an MPI_Request structure for the operation to allow *wait* type commands to know what send/recv they are waiting on
- status: the source and tag of the received message. This is a pointer to the structure of type MPI_Status with fields MPI_SOURCE and MPI_TAG.

Blocking send/recv/etc.

MPI_Send: returns after *buf* is free to be reused. Can use a system buffer but not required, and can be implemented by a system send.

MPI_Recv: returns after the requested data is in *buf*.

MPI_Ssend: blocks sender until the application buffer is free and the receiver process started receiving the message

MPI_Bsend: permits the programmer to allocate buffer space instead of relying on system defaults. Otherwise like *MPI_Send*.

MPI_Buffer_attach (&buffer,size): allocate a message buffer with the specified size

MPI_Buffer_detach (&buffer,size): frees the specified buffer

~~**MPI_Rsend:** blocking ready send, copies directly to the receive application space buffer, but the receive must be posted before being invoked. Archaic.~~

MPI_Sendrecv: performs a blocking send and a blocking receive. Processes can swap without deadlock

Example of blocking send/recv

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

int main(argc,argv)
int argc;
char *argv[];  {
int numtasks, rank, dest, source, rc, count, tag=1;
char inmsg, outmsg='x';
MPI_Status Stat; // status structure

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

Example of blocking send/recv

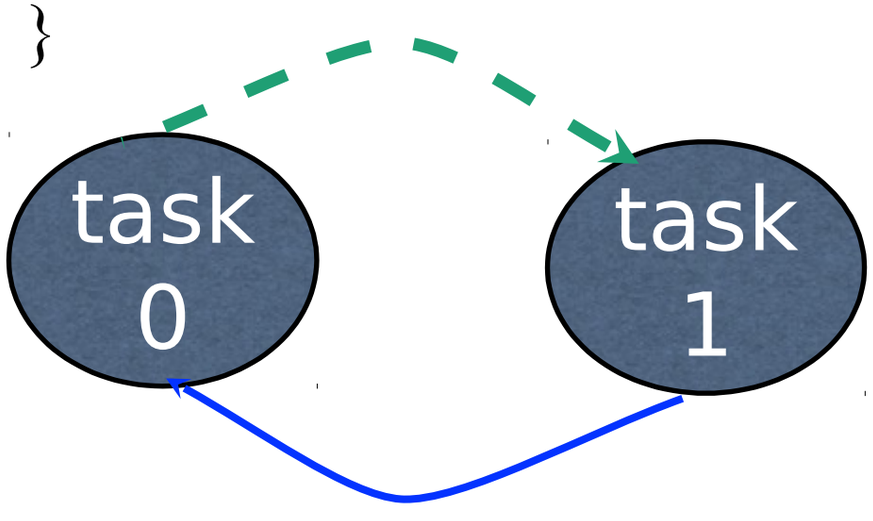
```
if (rank == 0) {
   dest = 1;
   source = 1;
   rc = MPI_Send(&outmsg, 1, MPI_CHAR, dest, tag, MPI_COMM_WORLD);
   rc = MPI_Recv(&inmsg, 1, MPI_CHAR, source, tag, MPI_COMM_WORLD,
&Stat);
} else if (rank == 1) {
   dest = 0;
   source = 0;
   rc = MPI_Recv(&inmsg, 1, MPI_CHAR, source, tag, MPI_COMM_WORLD,
&Stat);
   rc = MPI_Send(&outmsg, 1, MPI_CHAR, dest, tag, MPI_COMM_WORLD);
}

rc = MPI_Get_count(&Stat, MPI_CHAR, &count); // returns # of type received
printf("Task %d: Received %d char(s) from task %d with tag %d \n",
          rank, count, Stat.MPI_SOURCE, Stat.MPI_TAG);

MPI_Finalize( );
}
```

Example of blocking send/recv

```
if (rank == 0) {
   dest = 1;
   source = 1;
   rc = MPI_Send(&outmsg, 1, MPI_CHAR, dest, tag, MPI_COMM_WORLD);
   rc = MPI_Recv(&inmsg, 1, MPI_CHAR, source, tag, MPI_COMM_WORLD,
&Stat);
} else if (rank == 1) {
   dest = 0;
   source = 0;
   rc = MPI_Recv(&inmsg, 1, MPI_CHAR, source, tag, MPI_COMM_WORLD,
&Stat);
   rc = MPI_Send(&outmsg, 1, MPI_CHAR, dest, tag,
MPI_COMM_WORLD);
}
```



green/italic
send
blue/bold send

Why the reversed send/recv orders?

```
if (rank == 0) {
   dest = 1;
   source = 1;
   rc = MPI_Send(&outmsg, 1, MPI_CHAR, dest, tag, MPI_COMM_WORLD);
   rc = MPI_Recv(&inmsg, 1, MPI_CHAR, source, tag, MPI_COMM_WORLD, &Stat);
} else if (rank == 1) {
   dest = 0;
   source = 0;
   rc = MPI_Recv(&inmsg, 1, MPI_CHAR, source, tag, MPI_COMM_WORLD, &Stat);
   rc = MPI_Send(&outmsg, 1, MPI_CHAR, dest, tag, MPI_COMM_WORLD);
}
```

From stackoverflow
http://stackoverflow.com/questions/20448283/deadlock-with-mpi

MPI_Send may or may not block *[until a recv is posted]*. It will block until the sender can reuse the sender buffer. Some implementations will return to the caller when the buffer has been sent to a lower communication layer. Some others will return to the caller when there's a matching MPI_Recv() at the other end. So it's up to your MPI implementation whether if this program will deadlock or not.

Non-blocking operations

- **MPI_Isend, MPI_Irecv, MPI_Issend, Ibsend, Irsend**: similar to *MPI_Send, MPI_Recv, MPI_Ssend, Bsend, Rsend* except that a Test or Wait must be used to determine that the operation has completed and the buffer may be read (in the case of a recv) or written (in the case of a send)

Wait and probe

MPI_Wait (&request, &status): wait until the operation specified by *request* (specified in an *Isend/Irecv* finishes)

MPI_Waitany (count, &array_of_requests, &index,&status): wait for any blocking operations specified in *&array_of_requests* to finish

MPI_Waitall (count, &array_of_requests, &array_of_statuses): wait for all blocking operations specified in *&array_of_requests* to finish

MPI_Waitsome (incount, &array_of_requests, &outcount, &array_of_offsets, &array_of_statuses): wait for at least one request to finish, the number is returned in *outcount*.

MPI_Probe (source, tag, comm, &status): performs a blocking test but doesn't require a corresponding receive to be posted.

Non-blocking operations

- MPI_Test (&request, &flag,&status)
- MPI_Testany (count, &array_of_requests, &index, &flag, &status)
- MPI_Testall (count,&array_of_requests,&flag, &array_of_statuses)
- MPI_Testsome (incount, &array_of_requests, &outcount, &array_of_offsets, &array_of_statuses)
- Like the wait operations, but do not block

Non-blocking example

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

int main(argc,argv)
int argc;
char *argv[];  {
int numtasks, rank, next, prev, buf[2], tag1=1, tag2=2;
MPI_Request reqs[4];
MPI_Status stats[4];

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

Non-blocking example

```
prev = rank-1;
next = rank+1;
if (rank == 0)  prev = numtasks - 1;
if (rank == (numtasks - 1))  next = 0;

MPI_Irecv(&buf[0], 1, MPI_INT, prev, tag1, MPI_COMM_WORLD, &reqs[0]);
MPI_Irecv(&buf[1], 1, MPI_INT, next, tag2, MPI_COMM_WORLD, &reqs[1]);

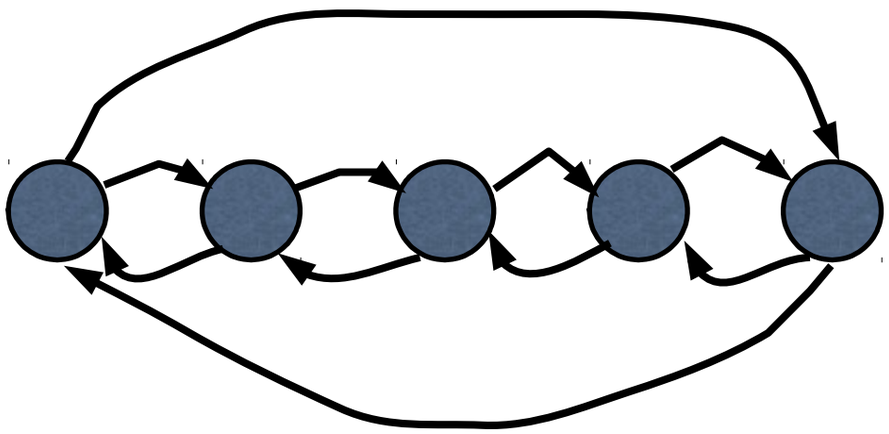
MPI_Isend(&rank, 1, MPI_INT, prev, tag2, MPI_COMM_WORLD, &reqs[2]);
MPI_Isend(&rank, 1, MPI_INT, next, tag1, MPI_COMM_WORLD, &reqs[3]);

    {  do some work that does not depend on the data being received  }

MPI_Waitall(4, reqs, stats);

MPI_Finalize();
}
```

Nearest neighbor exchange
in a ring topology



Collective communication routines

- Use these when communicating among processes with a well defined pattern
- Some can be used to allow all processes to communicate
- Some perform computation during the communication (reductions)
- Involve all processes in the specified communicator, even if a particular processor has no data to send
- Can only be used with MPI predefined types, not *derived types.*
- The programmer has to make sure all processes participate in the collective operation

All processors participate in the collective operation

```
if (pid % 2) {
   MPI_Reduce(..., MPI_COMM_WORLD);
}
```

This program will deadlock, as the MPI_Reduce will wait forever for even processes to begin executing it.

If you want to only involve odd processes, add them to a new communicator.

Groups and communicators

- Two terms used in MPI documentation are *groups* and *communicators.*
- A *communicator* is a group of processes that can communicate with each other
- A *group* is an ordered set of processes
- Programmers can view groups and communicators as being identical

Collective routines

MPI_Barrier (comm): tasks block upon reaching the barrier until every task in the group has reached it

MPI_Bcast (&buffer,count,datatype,root,comm): process *root* sends a copy of its data to every other processor. Should be log2(comm_size) operation.

MPI_Scatter (&sendbuf,sendcnt,sendtype,&recvbuf, recvcnt,recvtype,root,comm): distributes a unique message from *root* to every process in the group.

Collective routines

MPI_Gather(&sendbuf, sendcnt, sendtype, &recvbuf, recvcount, recvtype, root, comm):
opposite of scatter, every process in the group sends a unique message to the *root*.

MPI_Allgather (&sendbuf,sendcount,sendtype,&recvbuf, recvcount,recvtype,comm): each tasks performs a one-to-all broadcast to every other process in the group These are concatenated together in the *recvbuf.*

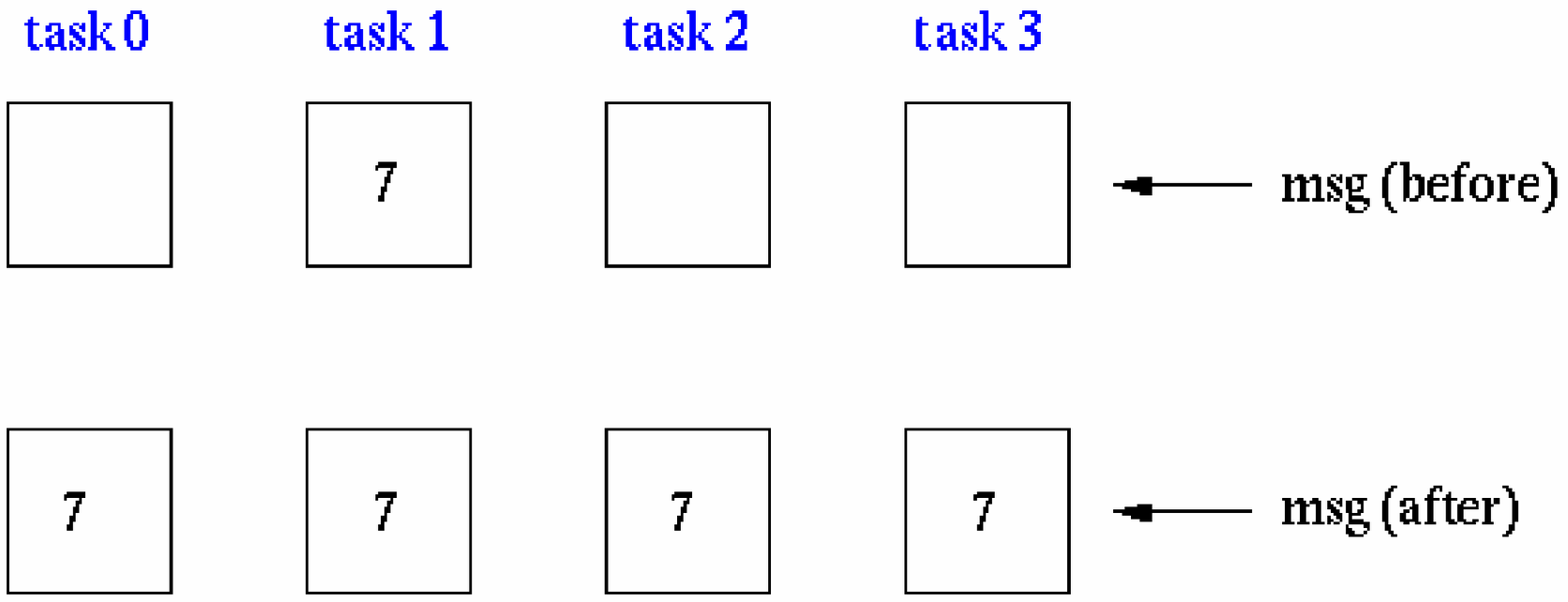
MPI_Reduce (&sendbuf,&recvbuf,count,datatype,op,root,comm): performs a reduction using operation *op* and places the result into *recvbuf* on the *root* process.

MPI_Bcast

MPI_Bcast

Broadcasts a message to all other processes of that group

```
count = 1;
source = 1;                    broadcast originates in task 1
MPI_Bcast(&msg, count, MPI_INT, source, MPI_COMM_WORLD);
```



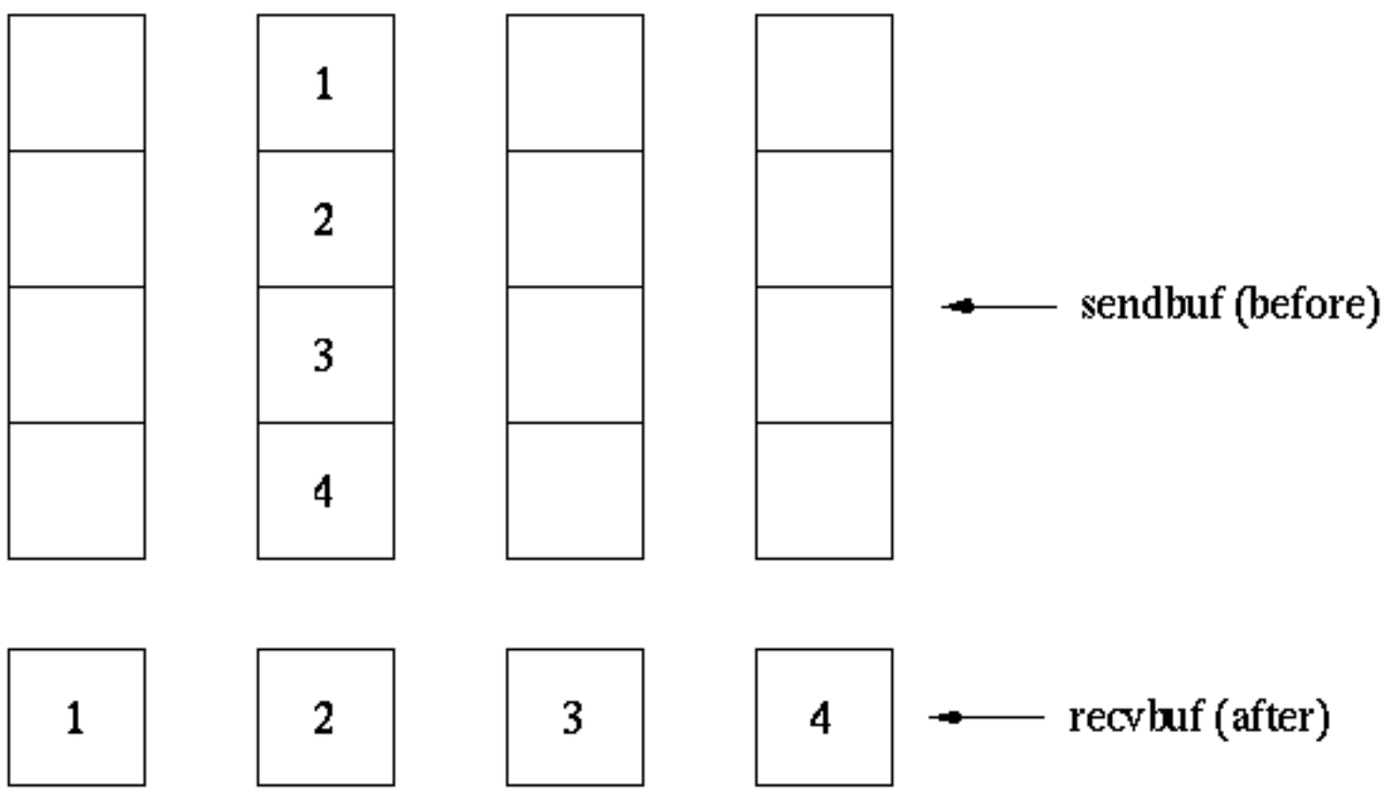
MPI_Scatter

Equivalent to
MPI_Send(sendbuf+i*sendcount*extent(sendtype), sendcount, sendtype, i, ...)
MPI_Recv(recvbuf, recvcount, recvtype, i, sendcount, sendtype, i, ...)

MPI_Scatter

Sends data from one task to all other tasks in a group

```
sendcnt = 1;
recvcnt = 1;
src  = 1;                    task 1 contains the message to be scattered
MPI_Scatter(sendbuf, sendcnt, MPI_INT,
            recvbuf, recvcnt, MPI_INT,
            src, MPI_COMM_WORLD);
```



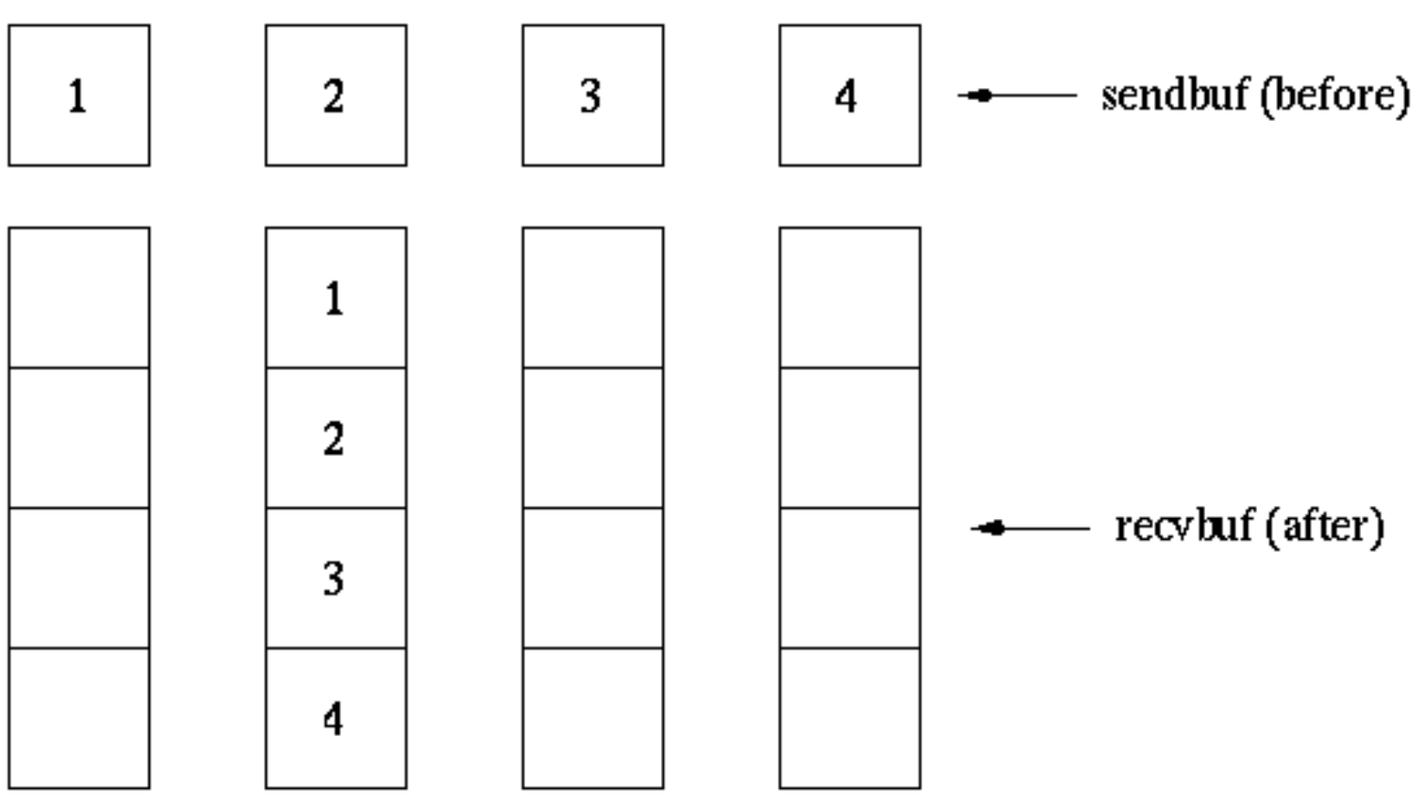
MPI_Gather

Equivalent to MPI_Send(sendbuf, sendcount, sendtype, root, ...)
MPI_Recv(recvbuf+i*recvcount*extent(recvtype), recvcount, recvtype, i, …)
With the results of each recv stored in rank order of the sending process

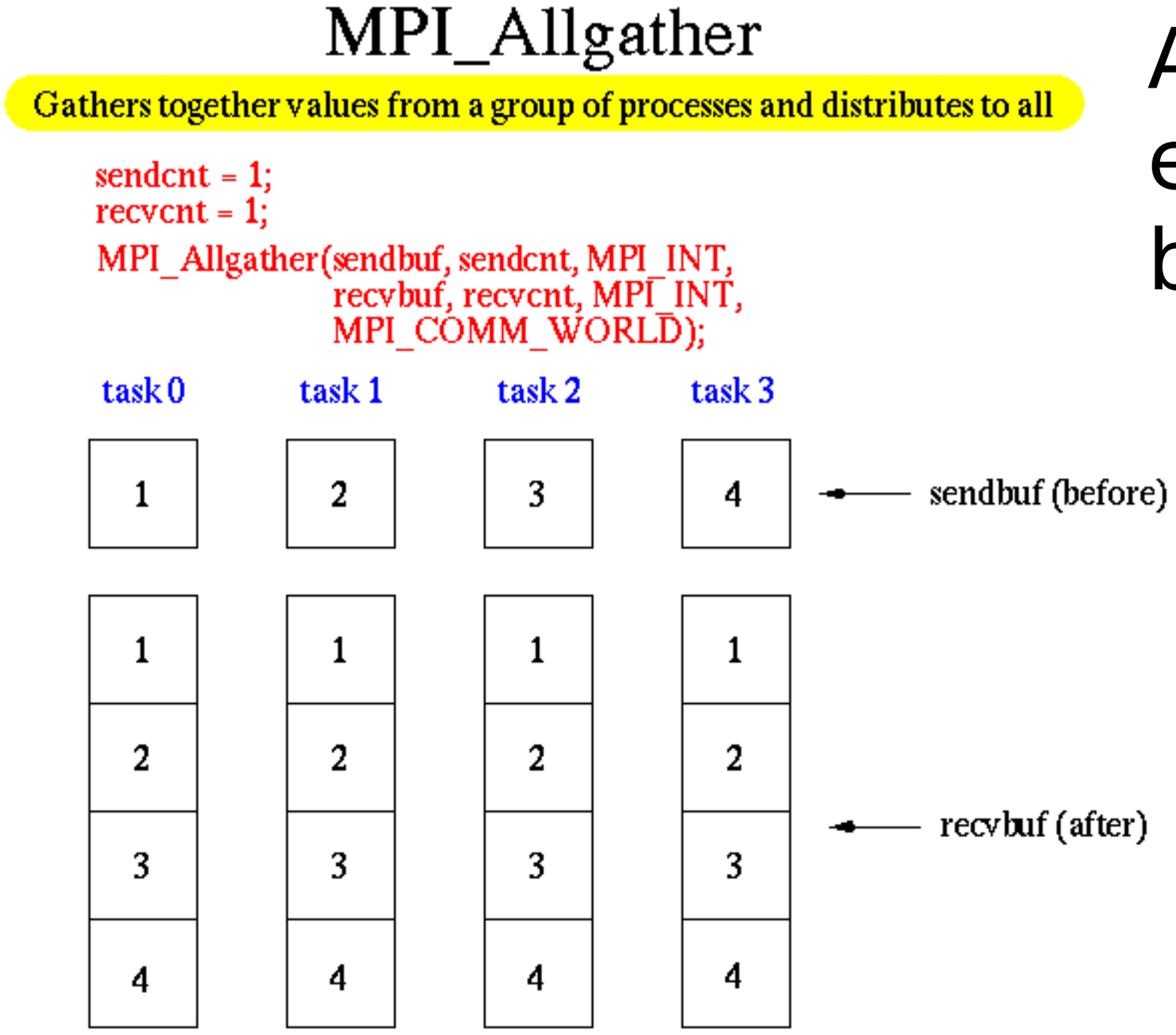
MPI_Gather

Gathers together values from a group of processes

```
sendcnt = 1;
recvcnt = 1;
src  = 1;                messages will be gathered in task 1
MPI_Gather(sendbuf, sendcnt, MPI_INT,
           recvbuf, recvcnt, MPI_INT,
           src, MPI_COMM_WORLD);
```



MPI_Allgather



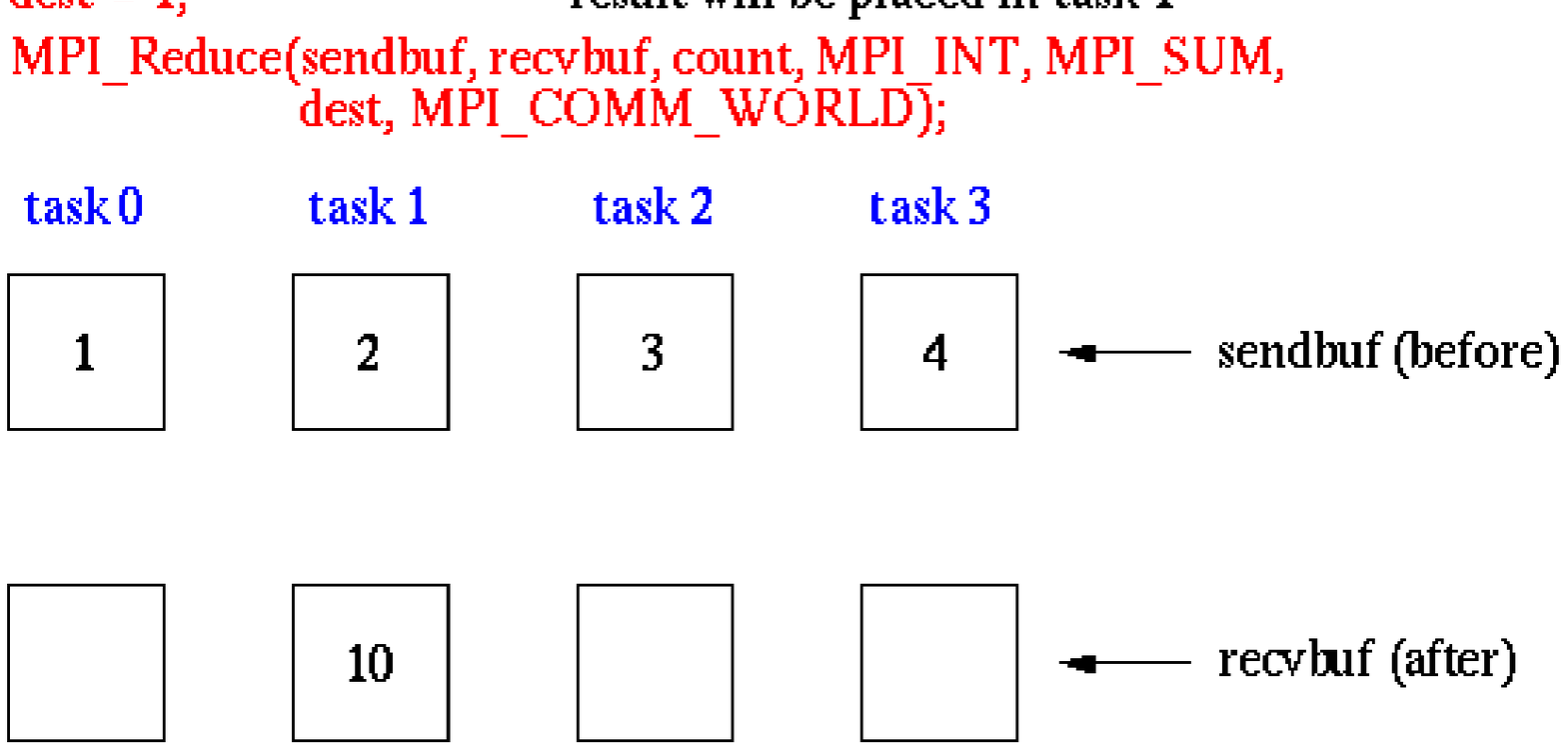
A gather with every process being a target.

MPI_Reduce

MPI_Reduce

Perform and associate reduction operation across all tasks in the group and place the result in one task

```
count = 1;
dest = 1;                    result will be placed in task 1
MPI_Reduce(sendbuf, recvbuf, count, MPI_INT, MPI_SUM,
           dest, MPI_COMM_WORLD);
```



Also see MPI introductory slides.

You can form your own reduction function using MPI_Op_create

MPI_Op_create

```
#include "mpi.h"
   int MPI_Op_create(MPI_User_function *function, int commute, MPI_Op *op )
```

pointer to the user defined Function that is the *Op*

true if commutative, false otherwise

Handle to refer to the function wherever an MPI_Op is needed

More operations

MPI_Allreduce (&sendbuf, &recvbuf, count, datatype, op, comm):

functionally equivalent to an *MPI_Reduce* followed by an *MPI_Bcast*. Faster on most hardware than the combination of these.

MPI_Reduce_scatter(&sendbuf, &recvbuf, recvcount, datatype, op, comm):

Does an element-wise reduce on the vector in *sendbuf* of length *recvcount*. The vector is then split into disjoint segments and spread across the tasks. Equivalent to an *MPI_Reduce* followed by an *MPI_Scatter* operation.

More operations

MPI_Alltoall(&sendbuf, sendcount,
sendtype, &recvbuf, recvcnt,
recvtype, comm):

Each task in the group performs a scatter with the results concatenated on each process in task rank order.

MPI_Scan(&sendbuf, &recvbuf, count,
datatype, op, comm):

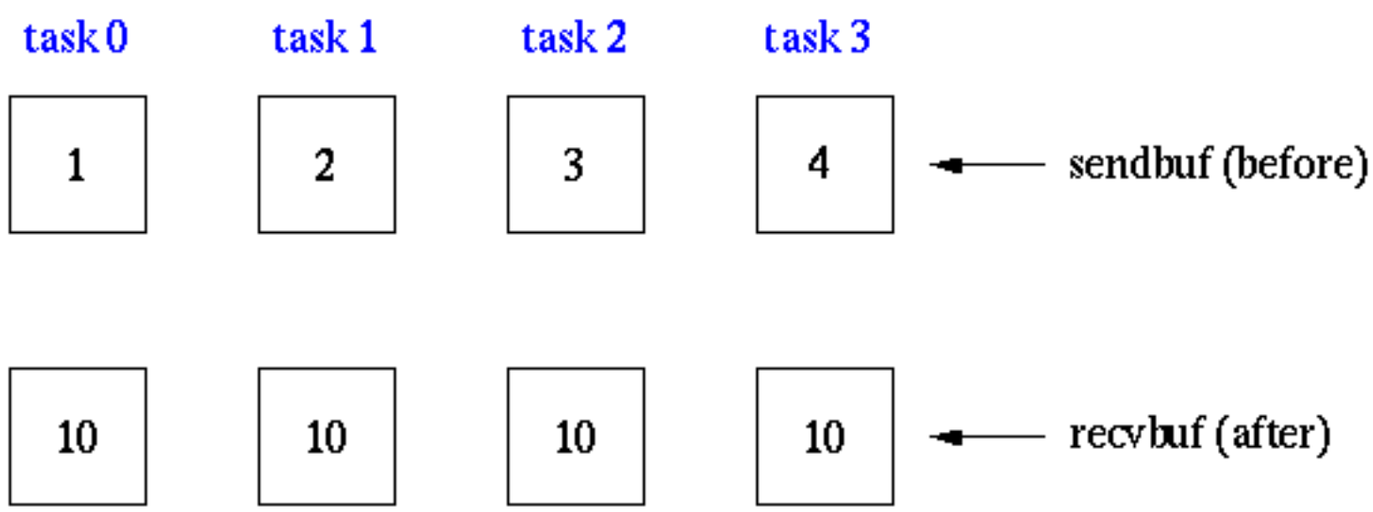
performs the partial sums on each processor that would result from doing an in-order reduction across the processors in rank order.

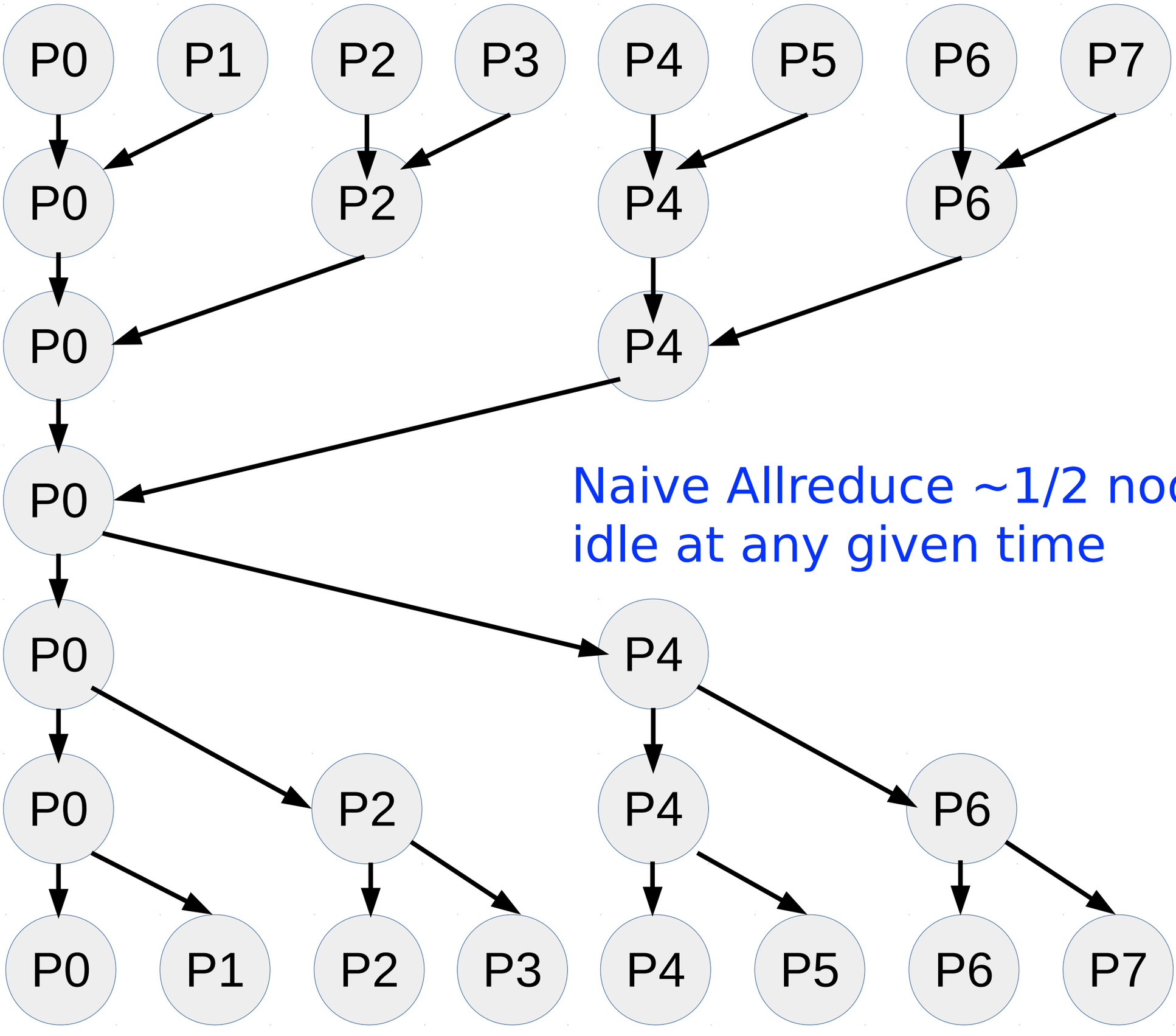
MPI_Allreduce

MPI_Allreduce

Perform and associate reduction operation across all tasks in the group and place the result in all tasks

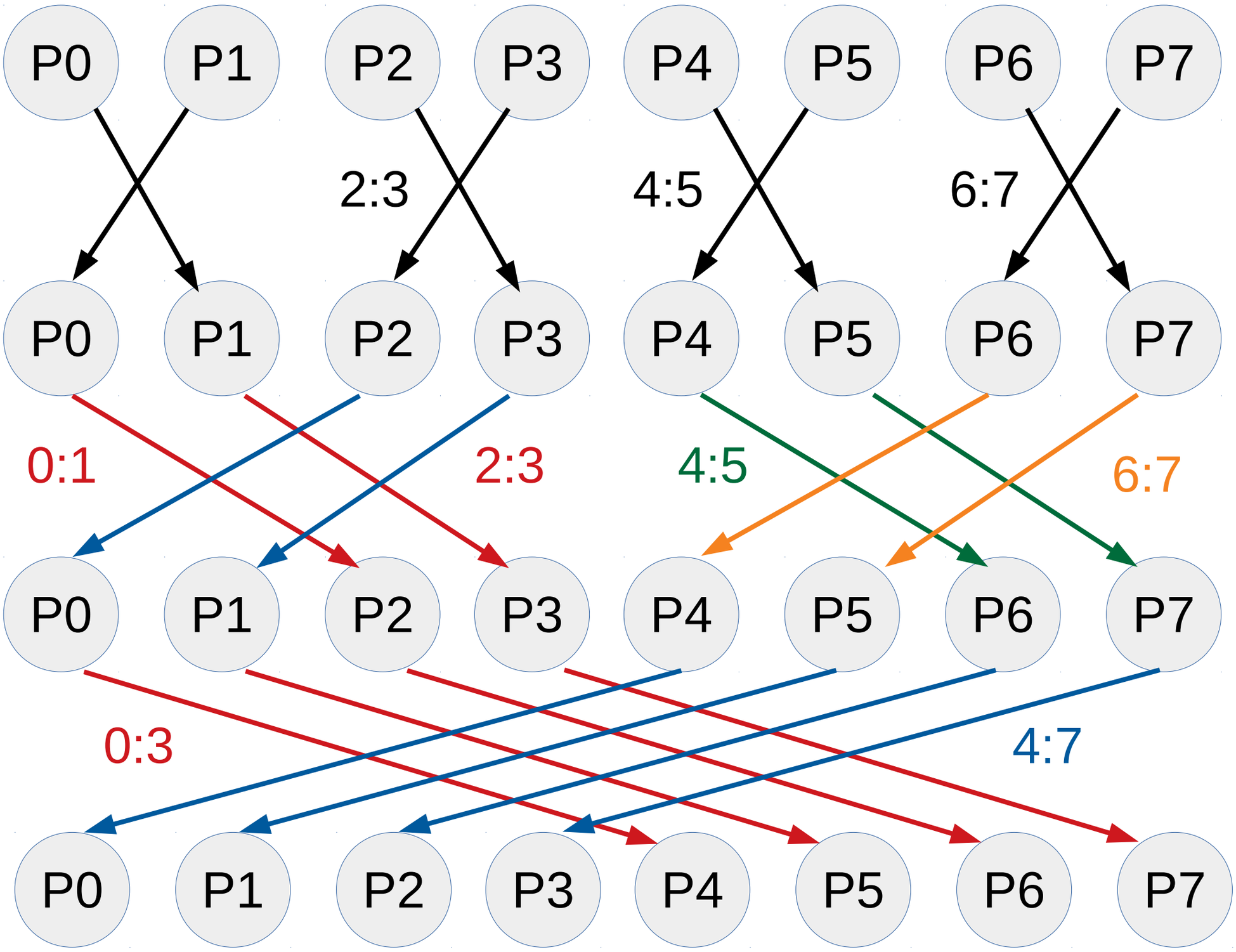
```
count = 1;
MPI_Allreduce(sendbuf, recvbuf, count, MPI_INT, MPI_SUM,
              MPI_COMM_WORLD);
```



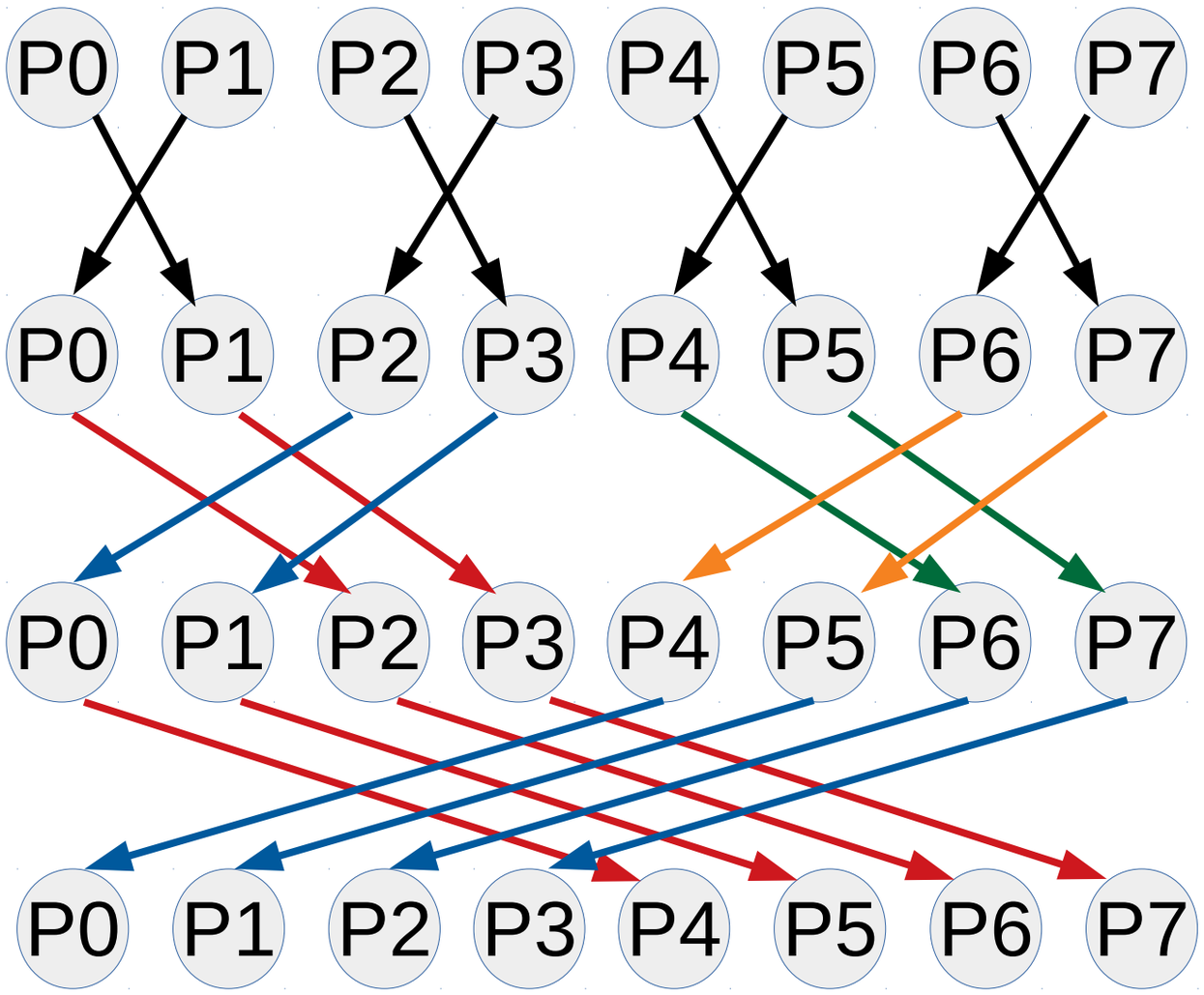


$2*log_2(|P|)$ steps

Naive Allreduce ~1/2 nodes are idle at any given time


P0
P1
P2
P3
P4
P5
P6
P7
2:3
4:5
6:7
P0
P1
P2
P3
P4
P5
P6
P7
0:1
2:3
4:5
6:7
P0
P1
P2
P3
P4
P5
P6
P7
0:3
4:7
P0
P1
P2
P3
P4
P5
P6
P7

$log_2(|P|)$ steps



All processors all busy each step.

Note that the bandwidth requirements of the network change

Algorithm from *Optimization of Collective Reduction Operations*, Rolf Rabenseifner, International Conference on Computational Science, 2004

MPI_Reduce_scatter

MPI_Reduce_scatter

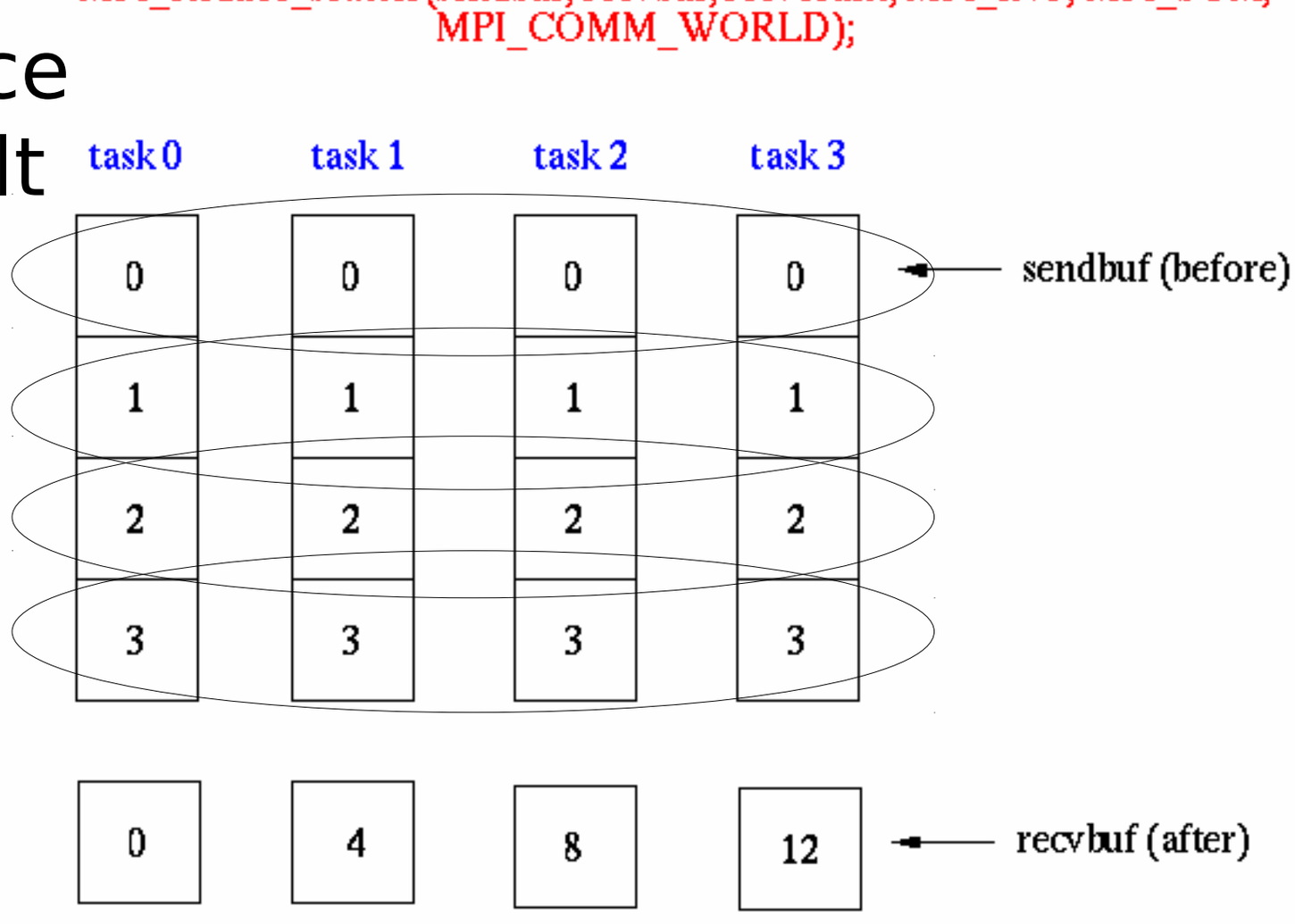
Perform reduction operation on vector elements across all tasks in the group, then distribute segments of result vector to tasks

```
recvcount = 1;
MPI_Reduce_scatter(sendbuf, recvbuf, recvcount, MPI_INT, MPI_SUM,
                   MPI_COMM_WORLD);
```

reduce

result

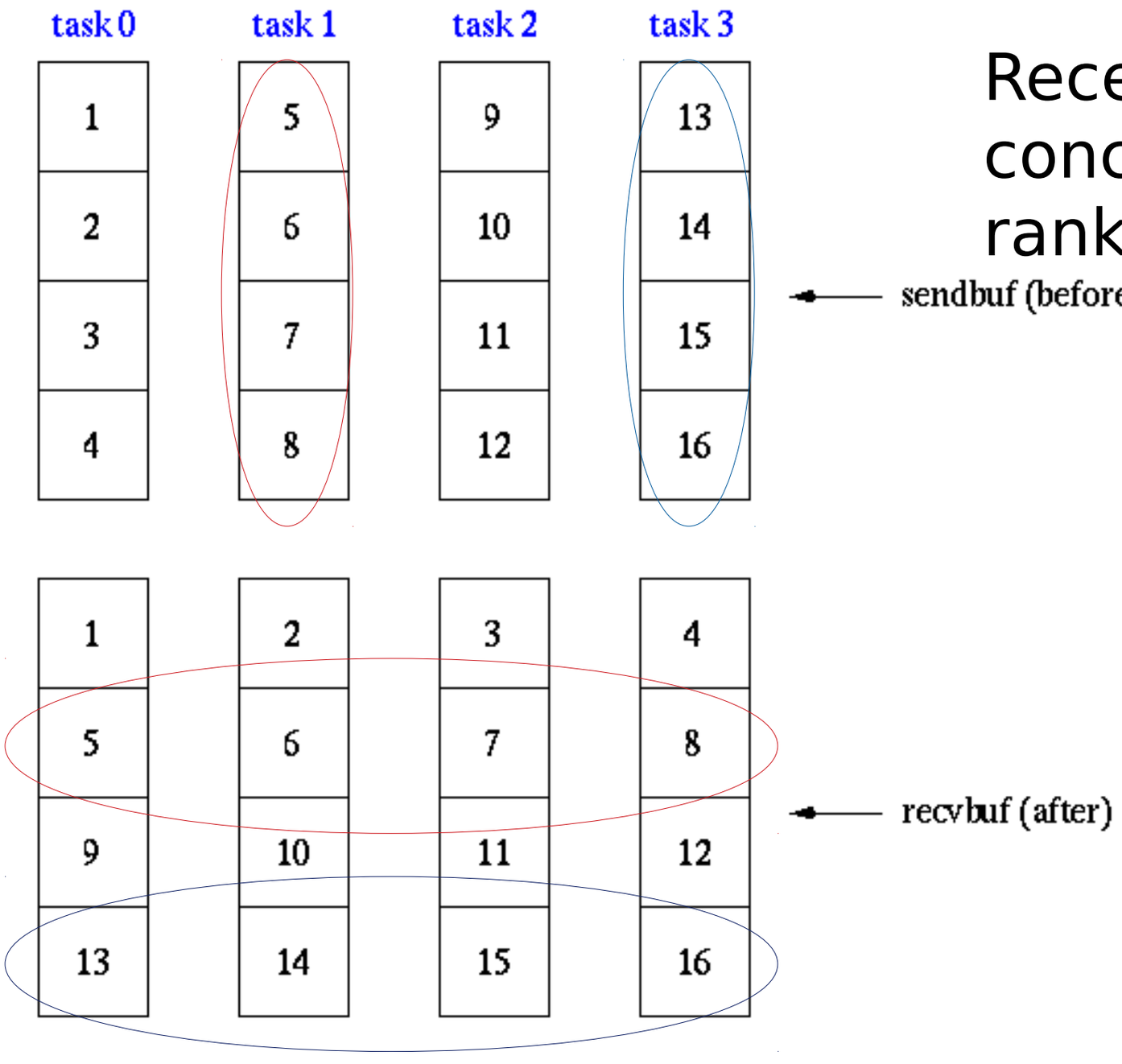
0
4
8
12



MPI_Alltoall

Sends data from all to all processes. Each process performs a scatter operation.

```
sendcnt = 1;
recvcnt = 1;
MPI_Alltoall(sendbuf, sendcnt, MPI_INT,
             recvbuf, recvcnt, MPI_INT,
             MPI_COMM_WORLD);
```



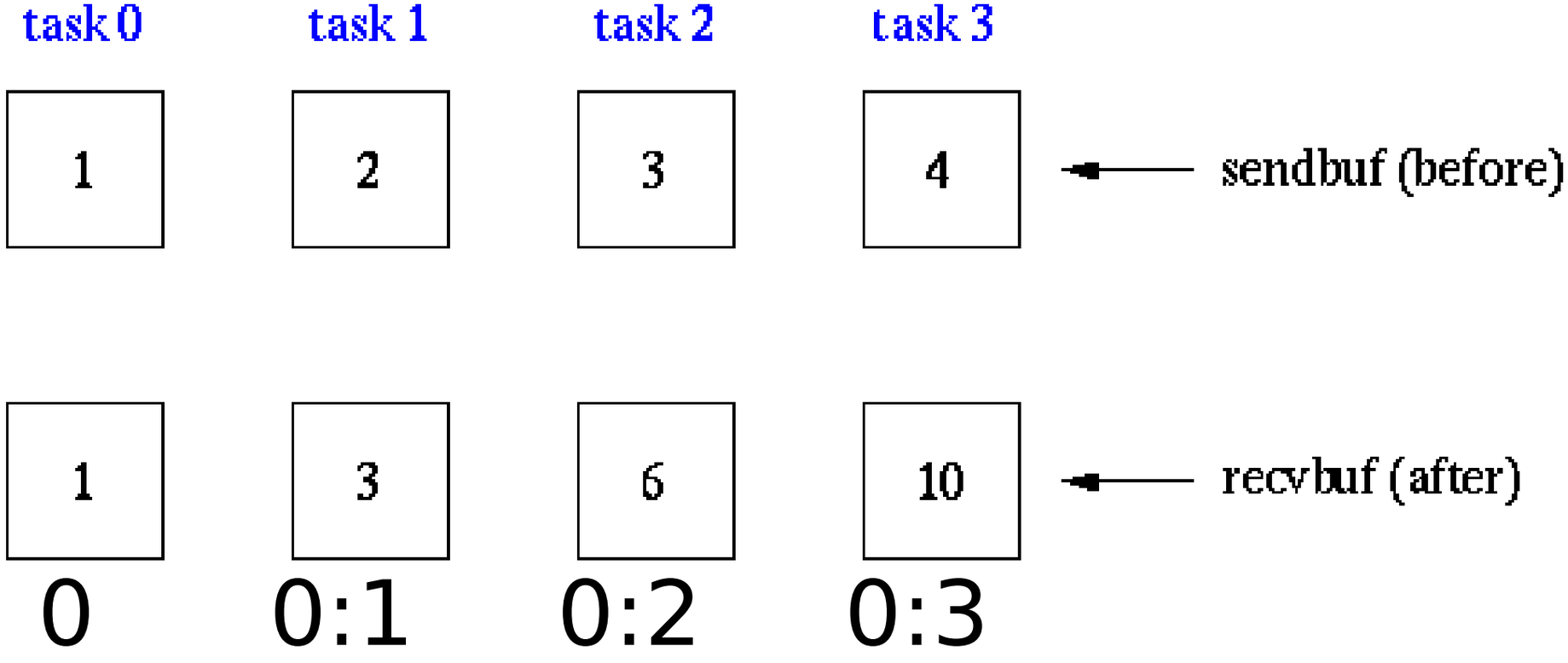
Each process performs a scatter of its elements to all other processes.

Received data is concatenated in sender rank order

MPI_Scan

Computes the scan (partial reductions) of data on a collection of processes

```
count = 1;
MPI_Scan(sendbuf, recvbuf, count, MPI_INT, MPI_SUM,
                  MPI_COMM_WORLD);
```



Group and communicator

- Remember that
  - A *communicator* is a group of processes that can communicate with each other
  - A *group* is an ordered set of processes
- Programmers can view groups and communicators as being the same thing
- group routines are used in collecting processes to form communicator.

Why groups and communicators?

- Allow programmer to organize tasks by functions
- Enable collective communication operations
- Allow user-defined *virtual topologies* to be formed
- Enable manageable communication by enabling synchronization

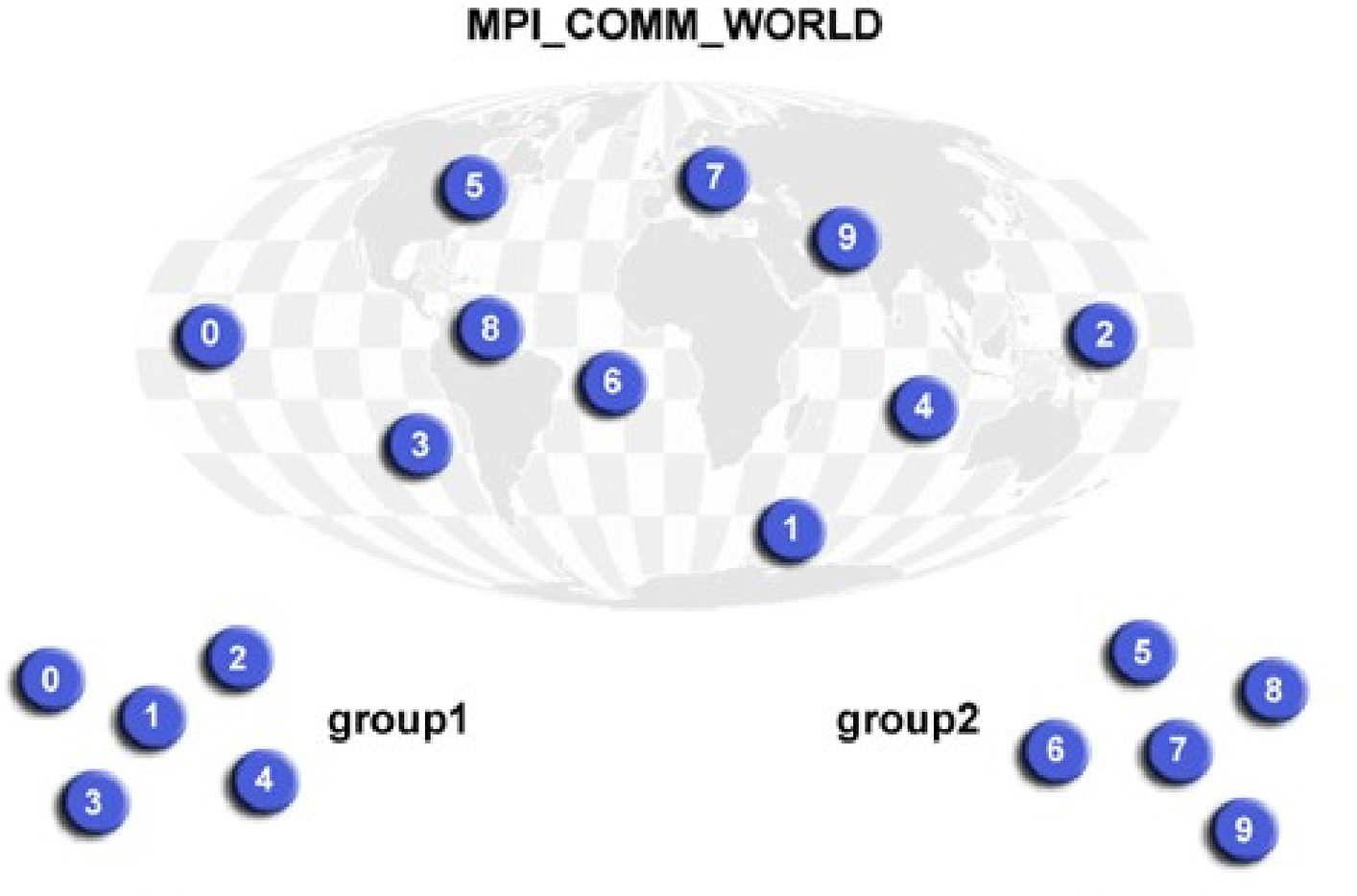
Properties

- Groups/communicators are dynamic, i.e. they can be created and destroyed
- Processes can be in many groups, and will have a unique, possibly different, rank in each group
- MPI provides 40+ routines for managing groups and communicators! Mercifully, we will not cover them all.

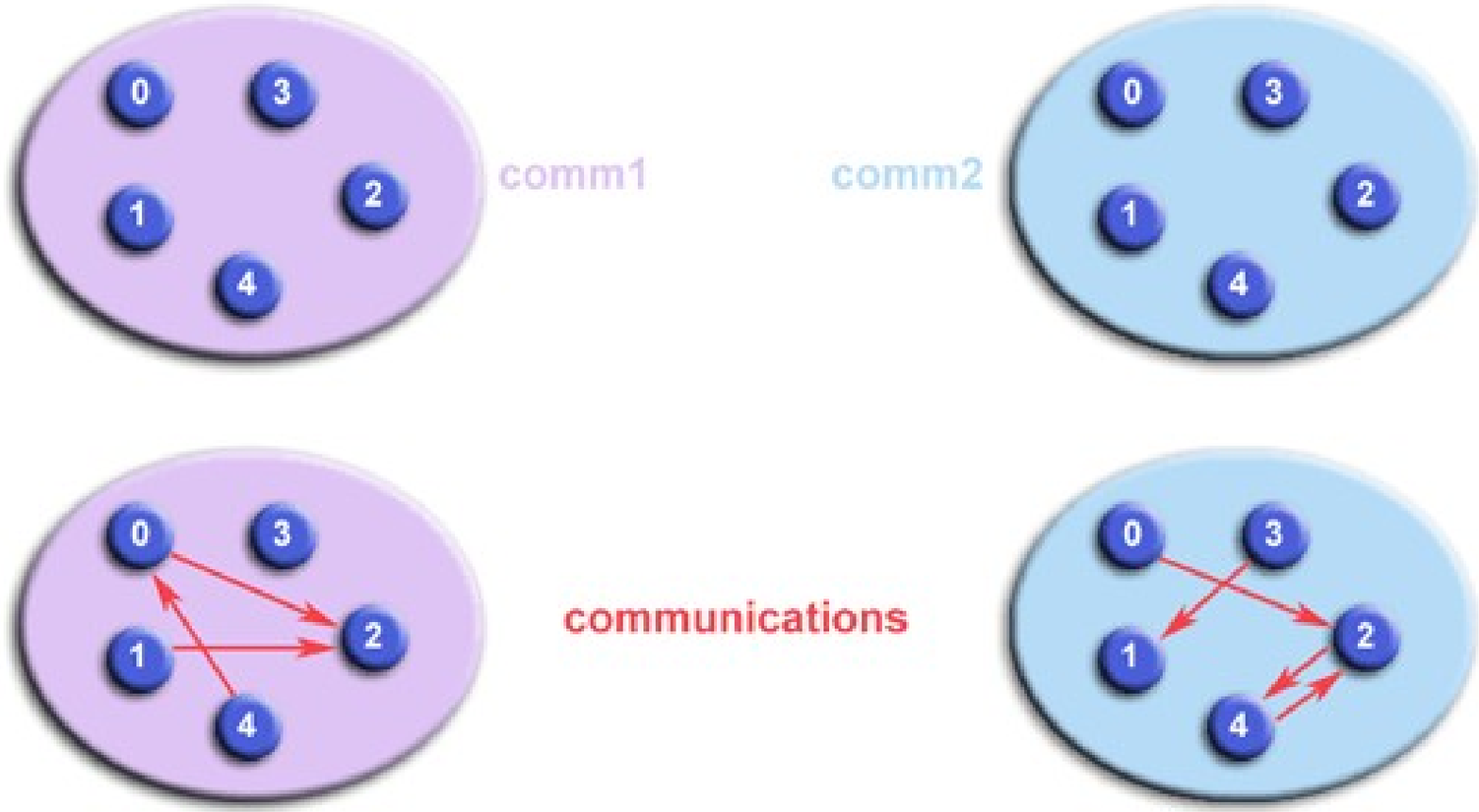
functions of these 40+ routines

- Extract handle of a global group and communicator using MPI_Comm_group
- Form new group as a subset of another group using MPI_Group_incl
- Create new communicator for a group using MPI_Comm_create
- Determine a processor's rank in a communicator using MPI_Comm_rank
- Communicate among the processors of a group
- When finished, free communicators and groups using MPI_Comm_free and MPI_Group_free

Relationships among communicators and groups.



Both collective and point-to-point communication is within a group.



```
#include "mpi.h"
#include <stdio.h>
#define NPROCS 8

int main(argc,argv)
int argc;
char *argv[];  {
int        rank, new_rank, sendbuf, recvbuf, numtasks,
           ranks1[4]={0,1,2,3}, ranks2[4]={4,5,6,7};
MPI_Group  orig_group, new_group;
MPI_Comm   new_comm;

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

if (numtasks != NPROCS) {
  printf("Must specify MP_PROCS= %d. Terminating.\n",NPROCS);
  MPI_Finalize();
  exit(0);
  }
```

Handle for MPI_COMM_WORLD group

Handle for a new group

Handle for a new communicator

Get the number of tasks and the rank of MPI_COMM_WORLD for this process

sanity check code

```
#include "mpi.h"
#include <stdio.h>
#define NPROCS 8

int main(argc,argv)
int argc;
char *argv[];  {
int        rank, new_rank, sendbuf, recvbuf, numtasks,
           ranks1[4]={0,1,2,3}, ranks2[4]={4,5,6,7};
MPI_Group  orig_group, new_group;
MPI_Comm   new_comm;

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

if (numtasks != NPROCS) {
  printf("Must specify MP_PROCS= %d. Terminating.\n",NPROCS);
  MPI_Finalize();
  exit(0);
  }
```

Variables to hold information about the new Group this will be in. Note that since this is an SPMD program, if we do this statically we need information for all groups the process can be in, not just the one that it is in.

Hold the ranks of processors in (in MPI_COMM_WORLD) of processes in each of the two new groups.

```
sendbuf = rank;

/* Extract the original group handle */
MPI_Comm_group(MPI_COMM_WORLD, &orig_group);

/* Divide tasks into two distinct groups based upon rank */
if (rank < NPROCS/2) {
  MPI_Group_incl(orig_group, NPROCS/2, ranks1, &new_group);
  }
else {
  MPI_Group_incl(orig_group, NPROCS/2, ranks2, &new_group);
  }

/* Create new new communicator and then perform collective communications */
MPI_Comm_create(MPI_COMM_WORLD, new_group, &new_comm);
MPI_Allreduce(&sendbuf, &recvbuf, 1, MPI_INT, MPI_SUM, new_comm);

MPI_Group_rank (new_group, &new_rank);
printf("rank= %d newrank= %d recvbuf= %d\n",rank,new_rank,recvbuf);

MPI_Finalize();
}
```

get handle for MPI_COMM_WORLD

Each process executes one of the if branches. Based on its number, each process becomes a member of one of the new groups.

```
sendbuf = rank;

/* Extract the original group handle */
MPI_Comm_group(MPI_COMM_WORLD, &orig_group);

/* Divide tasks into two distinct groups based upon rank */
if (rank < NPROCS/2) {
  MPI_Group_incl(orig_group, NPROCS/2, ranks1, &new_group);
  }
else {
  MPI_Group_incl(orig_group, NPROCS/2, ranks2, &new_group);
  }

/* Create new new communicator and then perform collective communications */
MPI_Comm_create(MPI_COMM_WORLD, new_group, &new_comm);
MPI_Allreduce(&sendbuf, &recvbuf, 1, MPI_INT, MPI_SUM, new_comm);

MPI_Group_rank (new_group, &new_rank);
printf("rank= %d newrank= %d recvbuf= %d\n",rank,new_rank,recvbuf);

MPI_Finalize();
}
```

Create a communicator From the group formed above

Perform collective communication within the communicator comm

Get the processes rank within the new group