Introduction to MPI

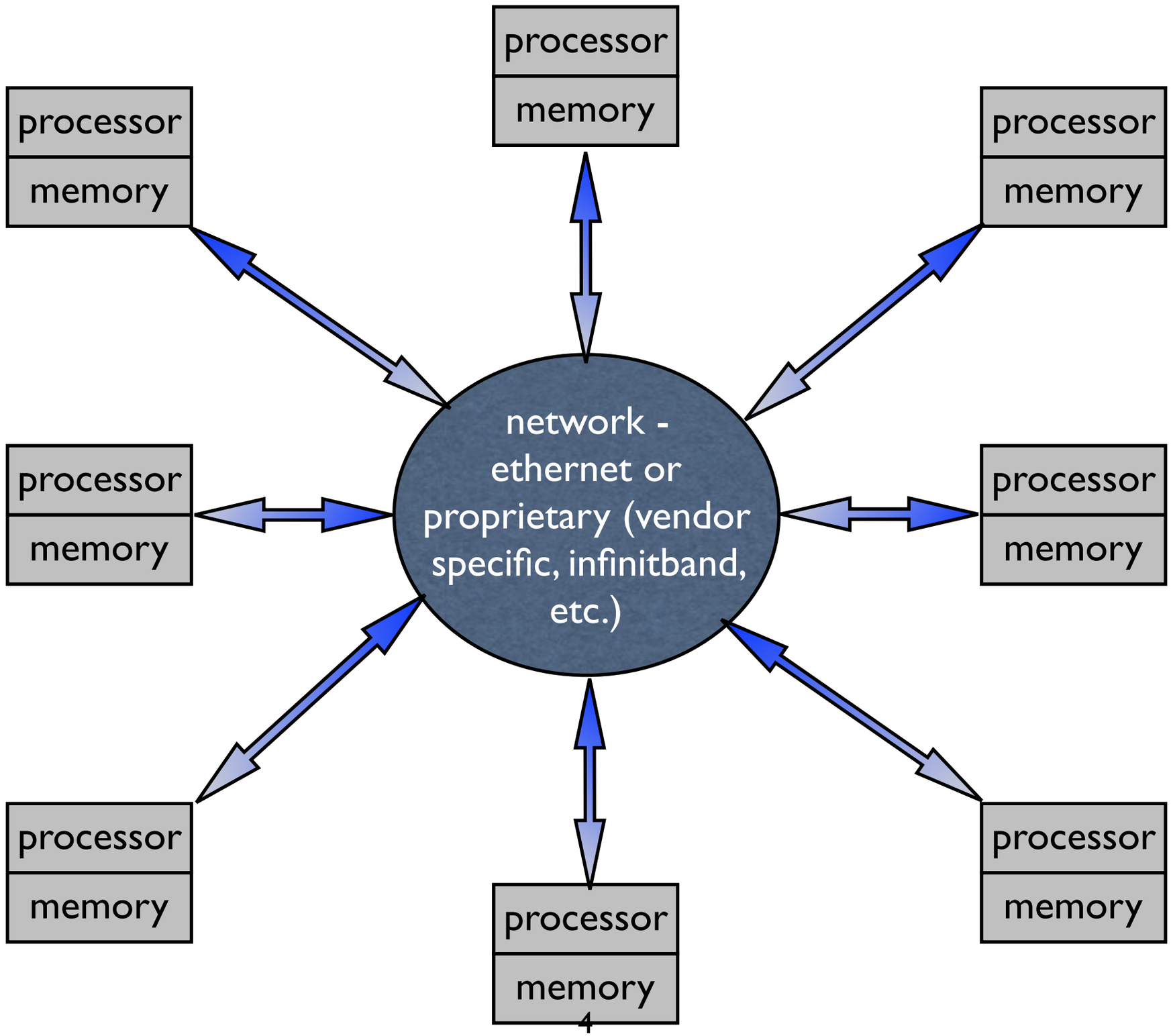
Topics to be covered

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

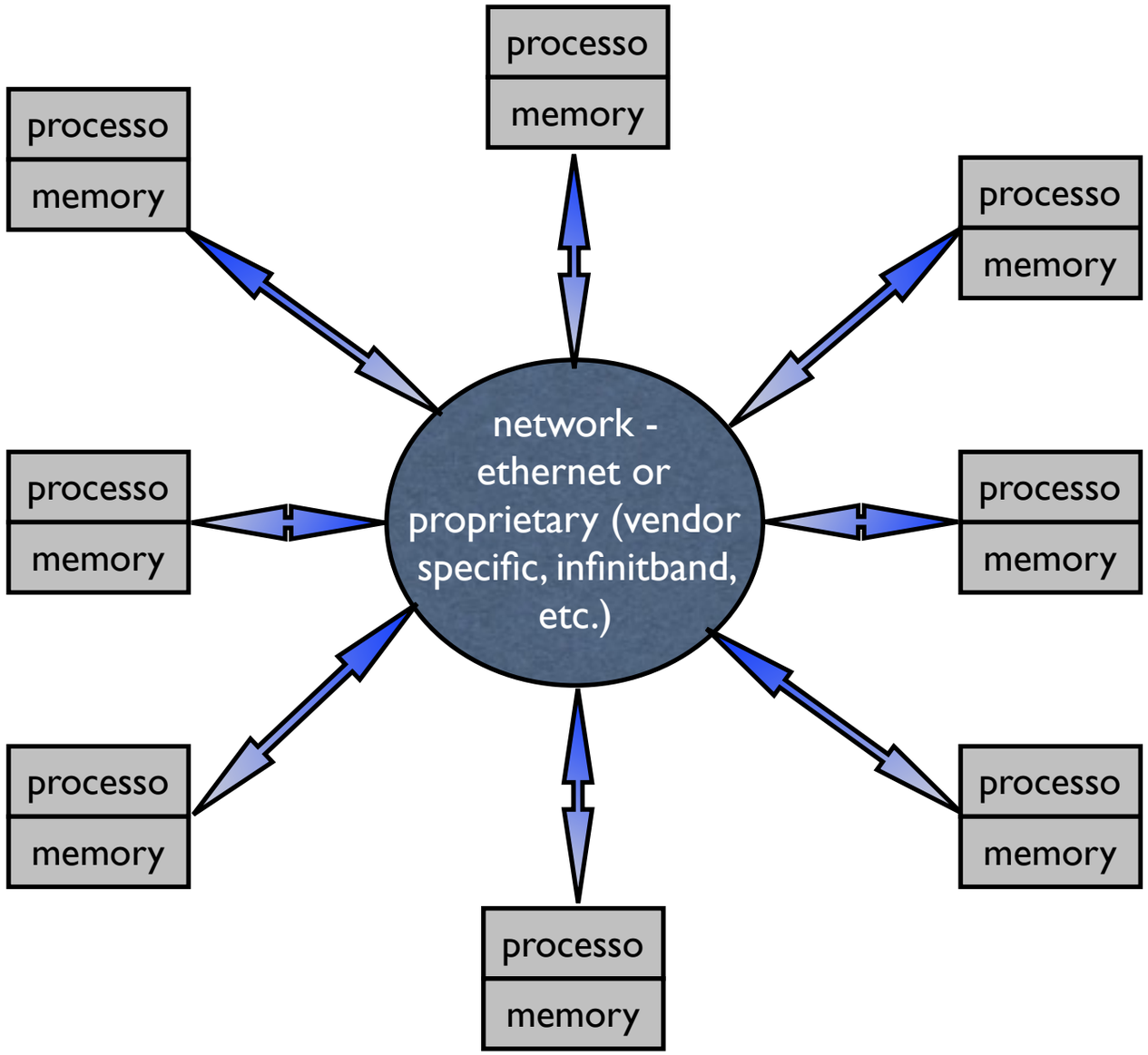
Shared and distributed memory

- **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
- **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

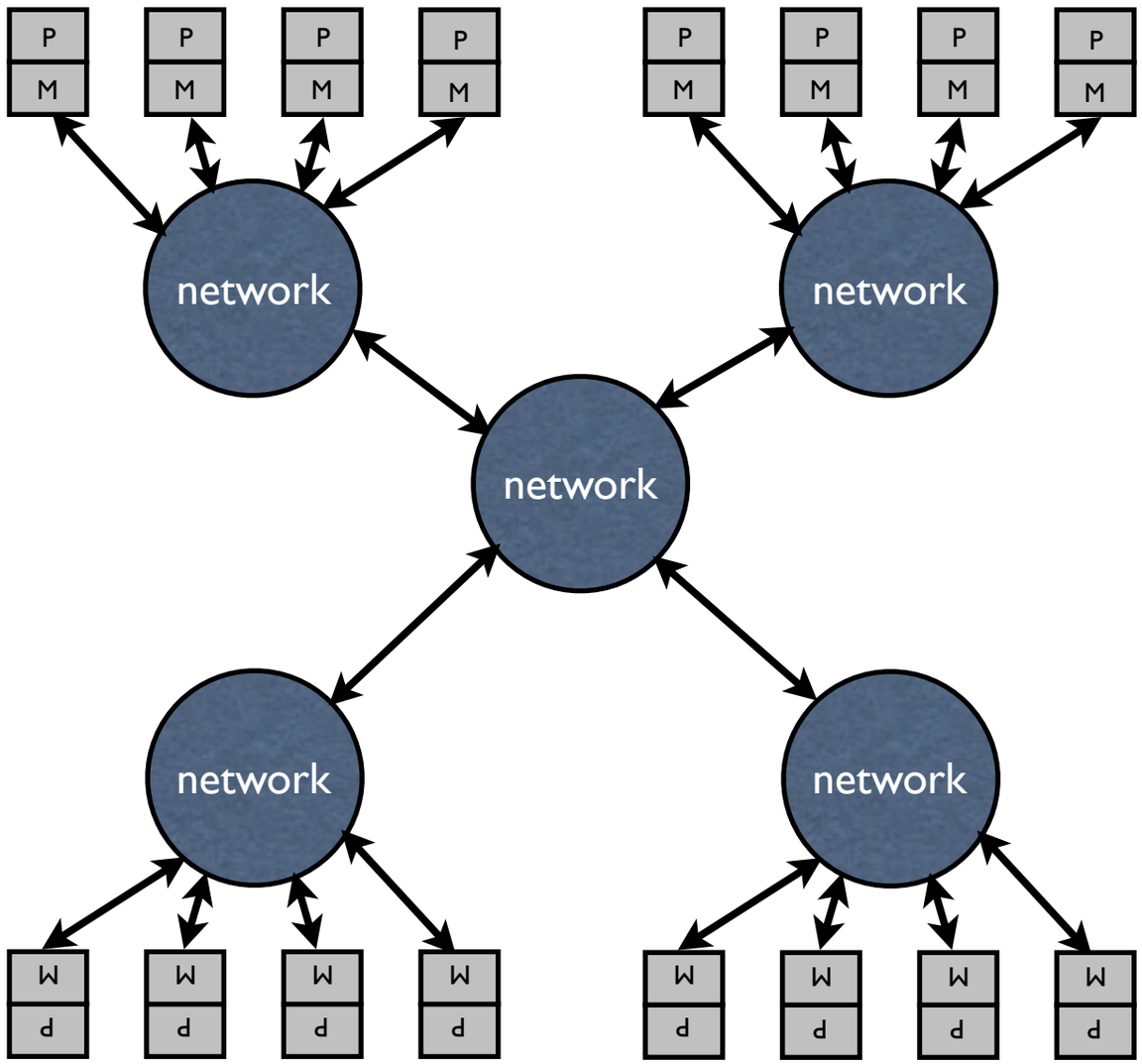


Message Passing Model



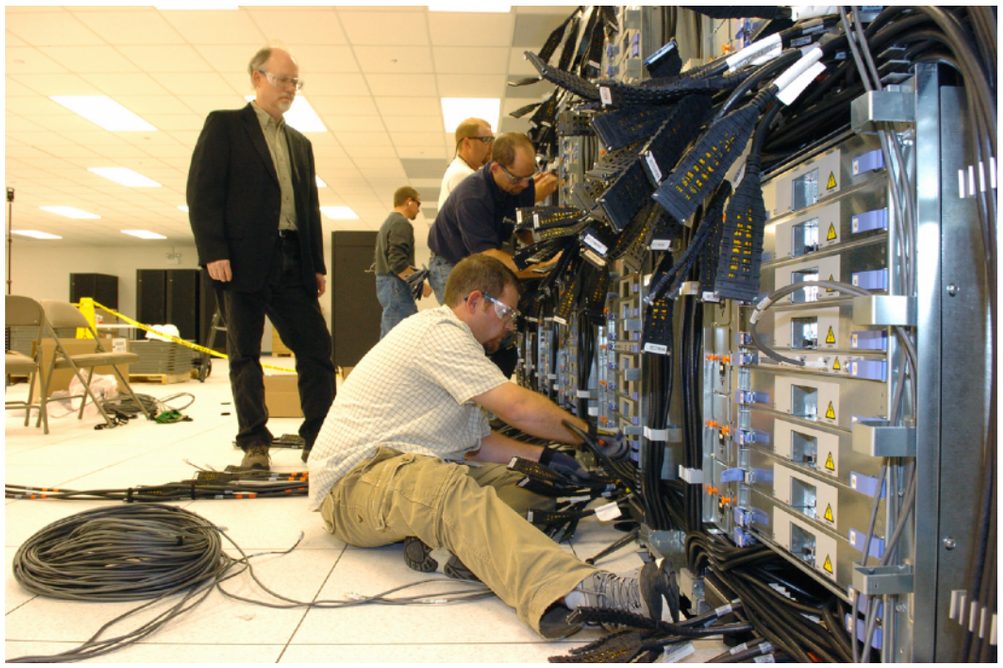
- This drawing implies that all processor are equidistant from one another
- This is often not the case -- the network topology and multicores make some processors closer than others
- programmers have to exploit this manually

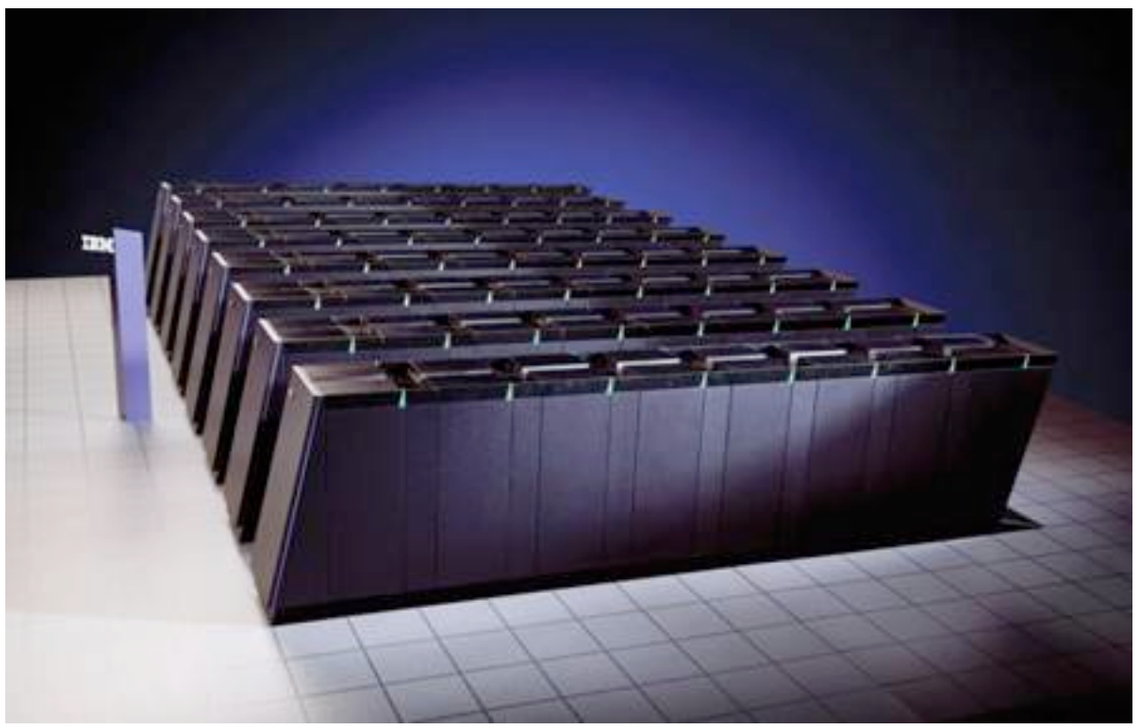
Message Passing Model

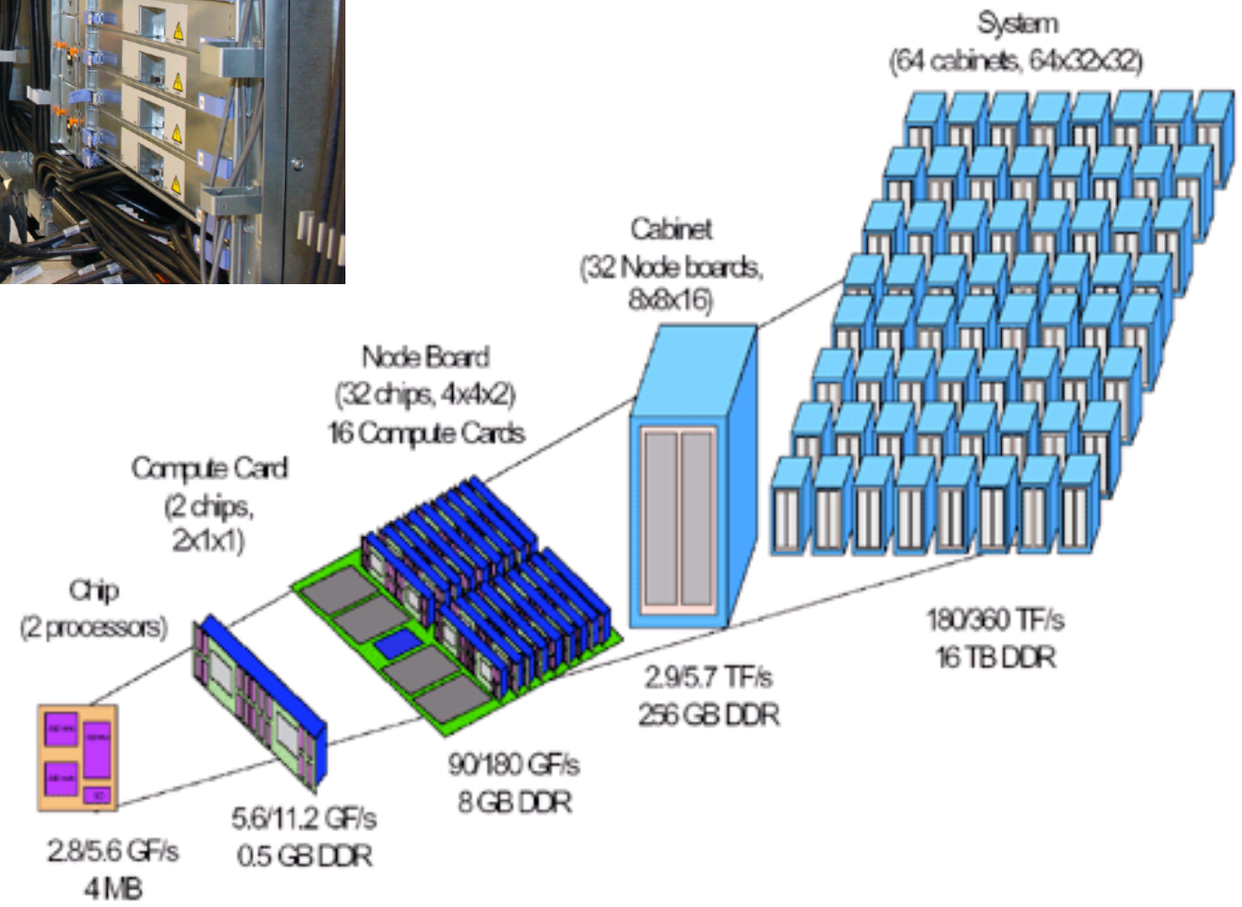


- In reality, processes run on cores, and are closer to other processes on the same processor
- Across processors, some can be reached via a single hop on the network, others require multiple hops
- Not a big issue on small (several hundred processors), but it needs to be considered on large machines.

131,072 cores BG/L







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

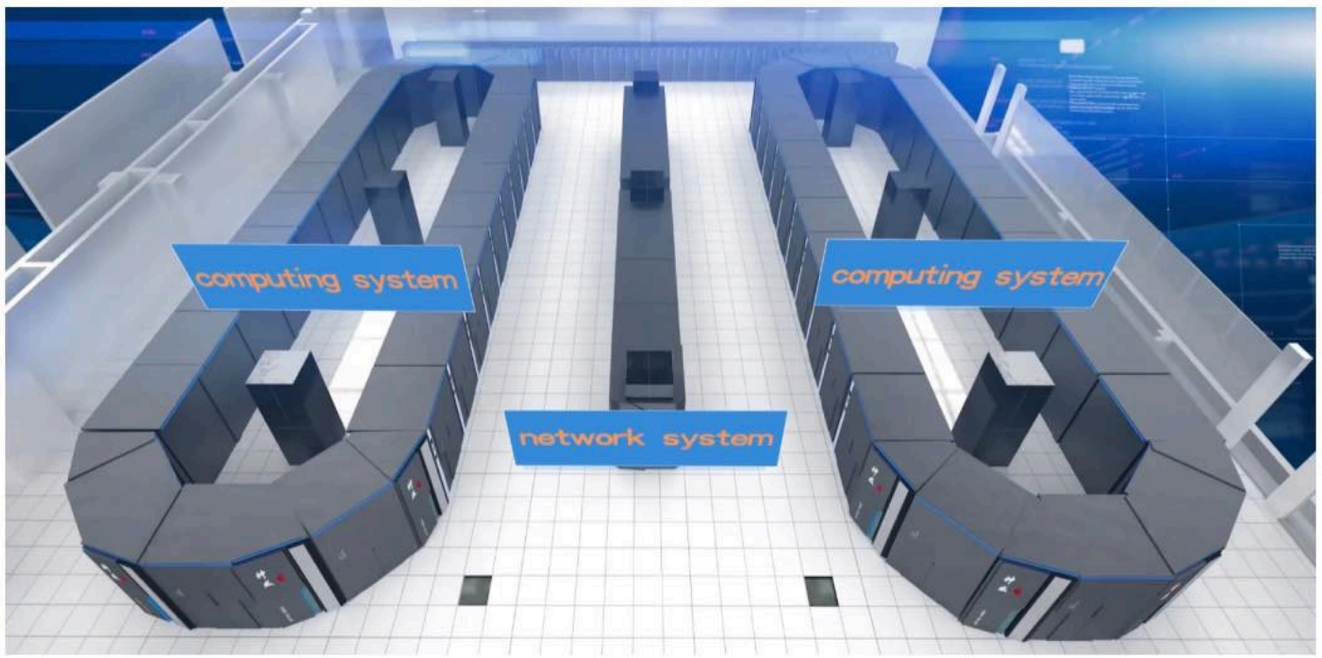
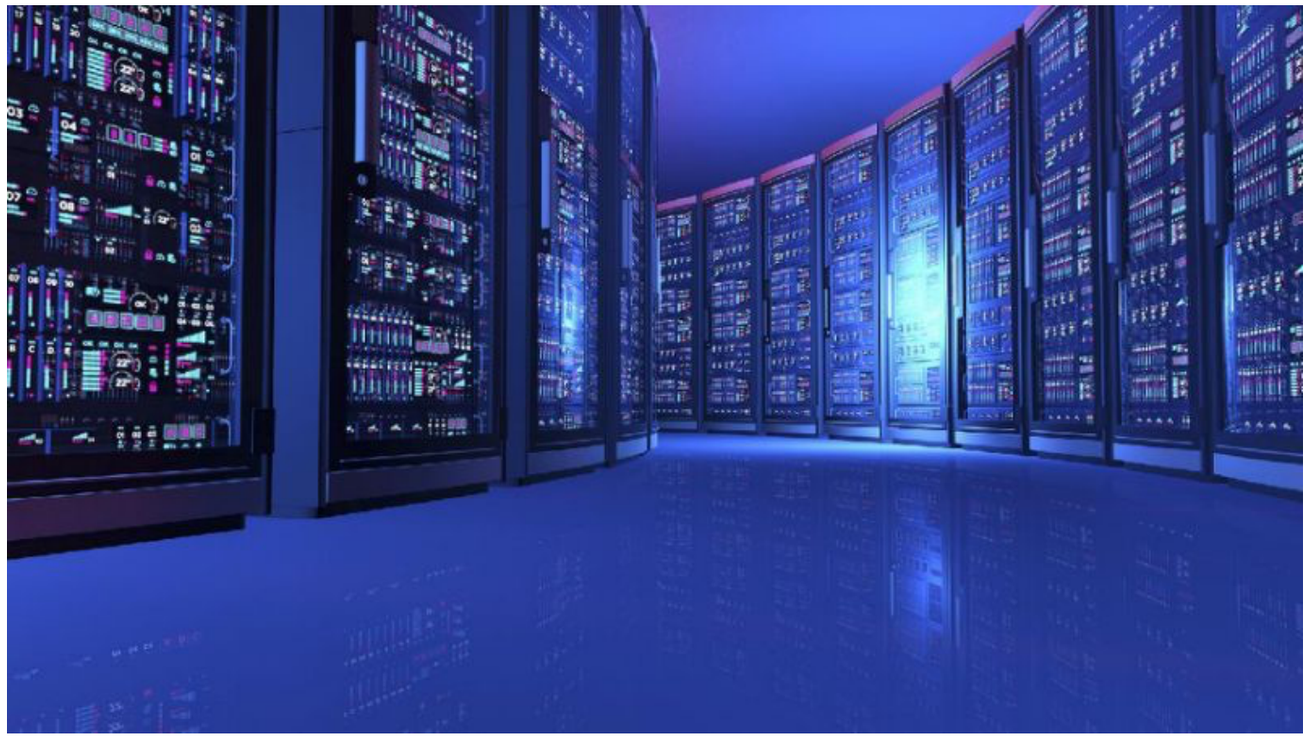


Figure 4: Overview of the Sunway TaihuLight System



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
- 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

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

Process 0

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

n = 99

i = 1

a

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

Process 1

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

n = 99

i = 1

a

0	1	...	n/2-1	n/2
51	52	...	99	100

local index

global index

Work done by processes

- Each process has a unique rank or process id (often called *pid* in programs) that is set when program starts
- Is not changed during the execution of the program (however, see Naik, Moreira, et al. IBM DRMS project if you are really interested in this.)
- Each process has a unique identifier (often called *pid*) that is known to the program
- Typical program pattern is *compute* ⇨ *communicate* ⇨*compute* ... ⇨... ⇨*communicate*

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

Sequential program

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

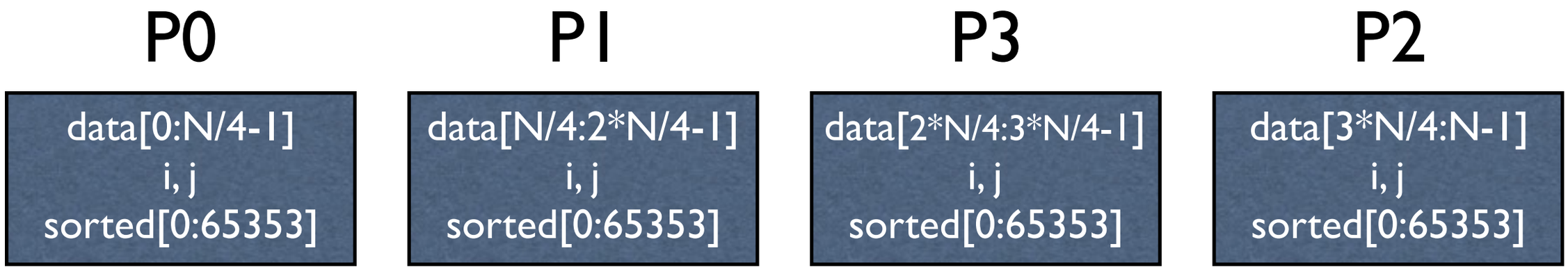
```
for (i=0; i < n; i++) {
   sorted[data[i]]++;
}

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

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

SPMDizing the program



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)

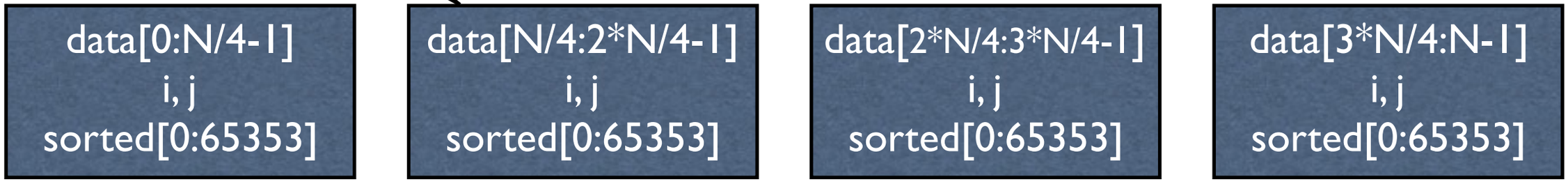
```
for (i=0; i < N/4; i++) {
    sorted[data[i]]++;
}
```

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

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

Data management

global indices shown, local is [**0:n/4-1**]



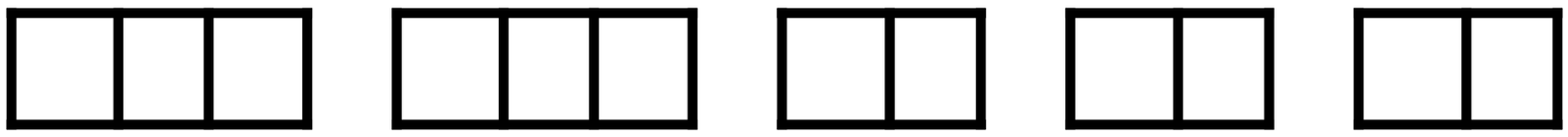
- All declared variables exist within each process
- There is a *global* and *local* logical index space for arrays
  - *globally*, data has *N* elements *0:N-1*
  - *locally*, each process has *N/4* elements numbered $0{:}N/4{-}1$ (if $N \bmod 4 == 0$, otherwise $\lceil N/4 \rceil$ or $\lfloor N/4 \rfloor$ 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

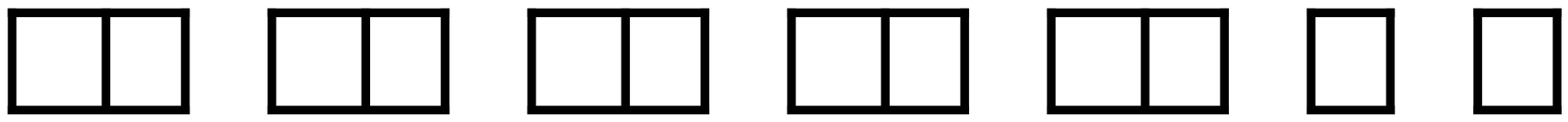
- Two "obvious" ways to compute
- Let *n* be the array size, *P* the number processors

First method

- Let P be the number of processes, n the number of array elements, $0 \leq p \leq P-1$ 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, $5 = 12 \bmod 7$

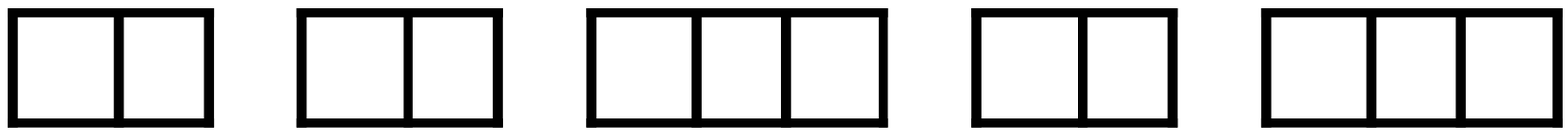


Second method

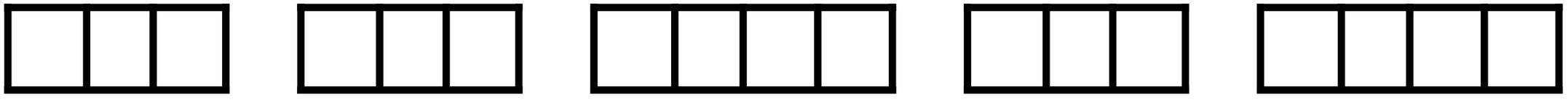
- First element controlled (or owned) by process p is $\lfloor p\ n/P \rfloor$ (first element and first process id p is 0
- Last element controlled by process p is one less that the first element controlled by process $p+1$

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

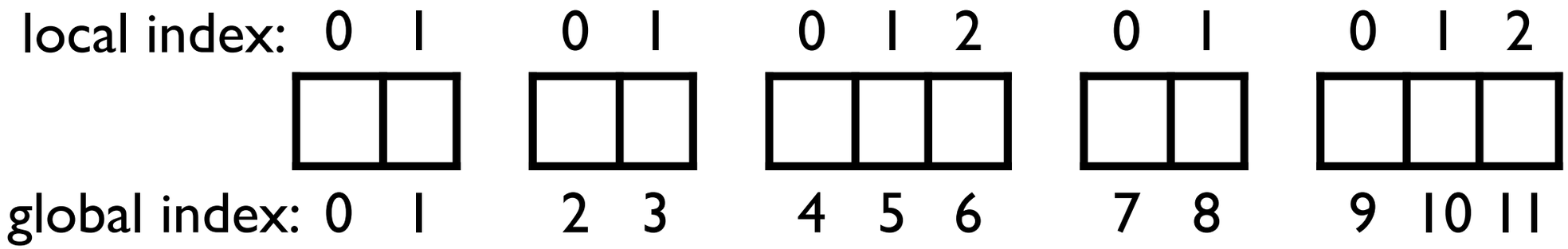
- Process controlling element i is $\lfloor (P(i+1)-1)/n \rfloor$
- Example -- 12 elements over 5 processors, $r = 2 = 12\ mod\ 5$



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

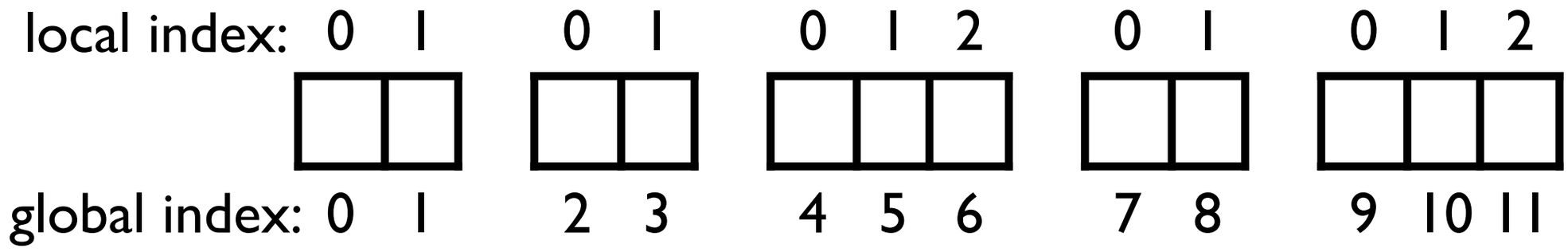


Global *vs* local indices



- 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



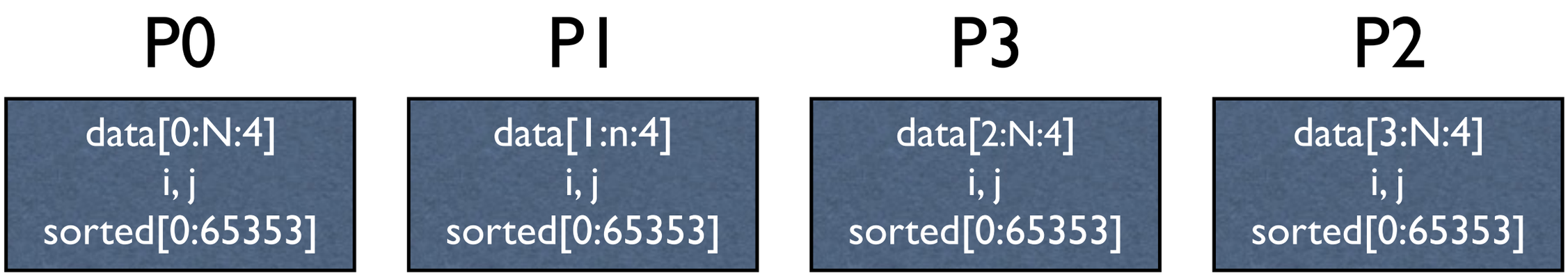
- Macros or functions can be used to compute these.
- Block lower bound: $LB(p, P, n) = (p*n/P)$
- Block upper bound: $UB(p, P, n) = LB(p+1, P, n)-1$
- Block size: $LB(p+1, P, n) - LB(p, P, n)$
- Block owner: $Owner(i, P, n) = (P*(i+1)-1)/n$

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

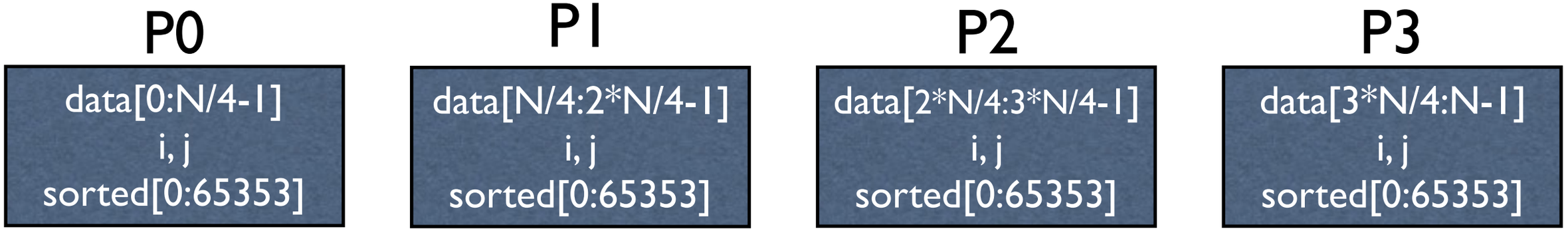


- Let *A* be an array with *N* elements.
- Let the array be *cyclically distributed* over *P* processes
- Process *p* gets elements *p*, *p*+*P*, *p*+2**P*, *p*+3**P*, ...
- In the above
  - process 0 gets elements 0, 4, 8, 12, ... of data
  - process 1 gets elements 1, 5, 9, 13, ... of data
  - process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

Converting the program to MPI: *System initialization*

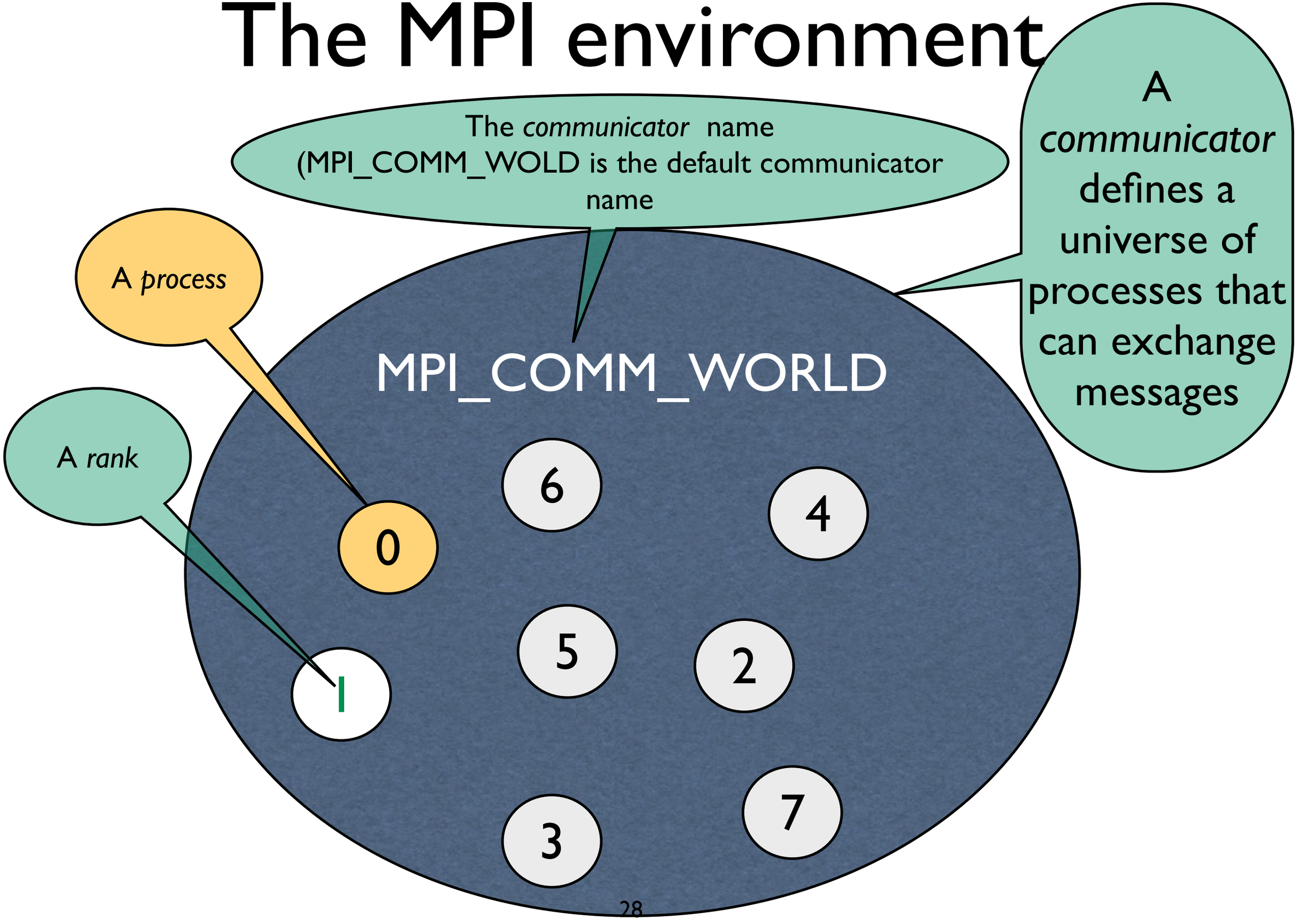



```
#include <mpi.h> /* MPI library prototypes, etc. */
#include <stdio.h>
// all processors execute this (replicated execution)
int main(int argc, char * argv[ ]) {
    int pid; /* MPI process ID)
    int numP; /* number of MPI processes */
    int N;
    extractArgv(&N, argv); // get N from the arg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

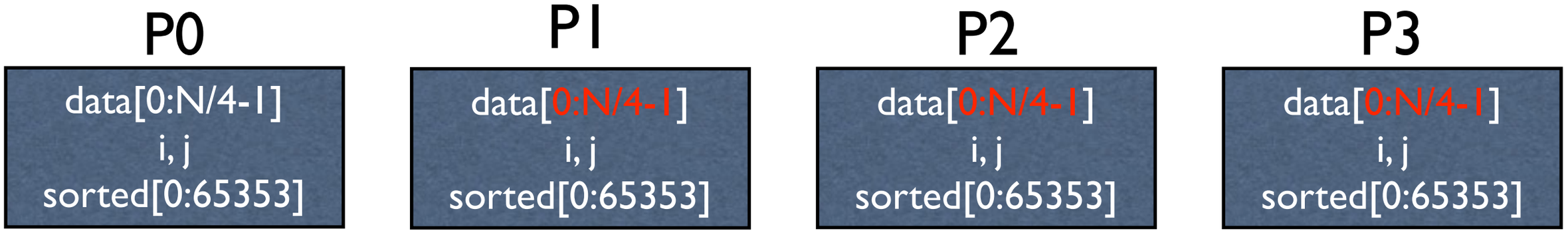
MPI_INIT

- 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



Converting the program to MPI

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    int numP; /* number of MPI processes */
    int N;
    extractArgv(&N, argv);
    int sorted[65536]; int data[N/4];
    MPI_INIT(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &numP);
    for (i=0; i < 65535; i++) {
        sorted[i] = 0;
}}
```

cheat! should malloc

Communicator name

get number of processors

Converting the program to MPI

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

```
#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);
    int sorted[65536]; int data[*N/4]; 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;
}}
```

Communicator name

arg to get *rank* (i.e. *pid*) of this

Converting the program to MPI

P0	P1	P2	P3
data[0:N/4-1] i, j sorted[0:65353]	data[N/4:2*N/4-1] 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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#include <stdio.h>
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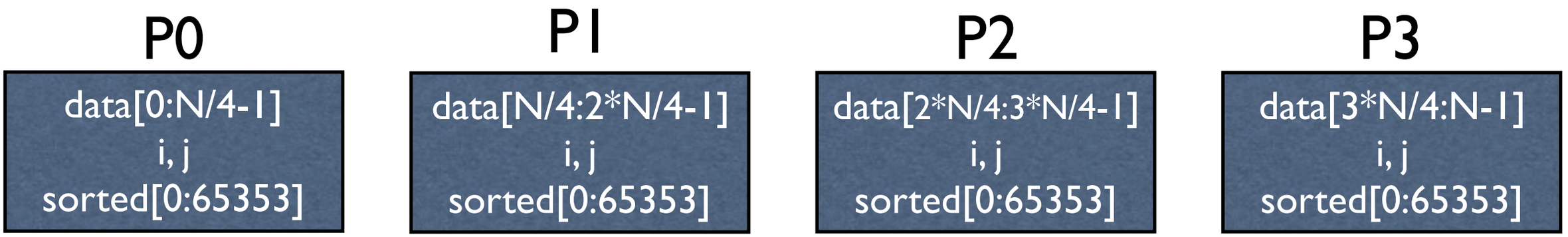
    int numP; /* number of MPI processes */
    int N;
    extractArgv(&N, argv);
    int sorted[65536]; int data[*N/4]; MPI_INIT(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &numP);
    MPI_Comm_rank(MPI_COMM_WORLD, &pid);
    for (i=0; i < 65535; i++) {
        sorted[i] = 0;
    }
    MPI_Finalize( );
}
```

The *last* MPI function called

MPI_Finalize frees system resources associated with MPI

Time to do something useful

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    int N;
    extractArgv(&N, argv);
    int sorted[65536]; int data[*N/4];
    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;
    }
    sort(data, sort, pid, numP);
    MPI_Finalize( );
}
```
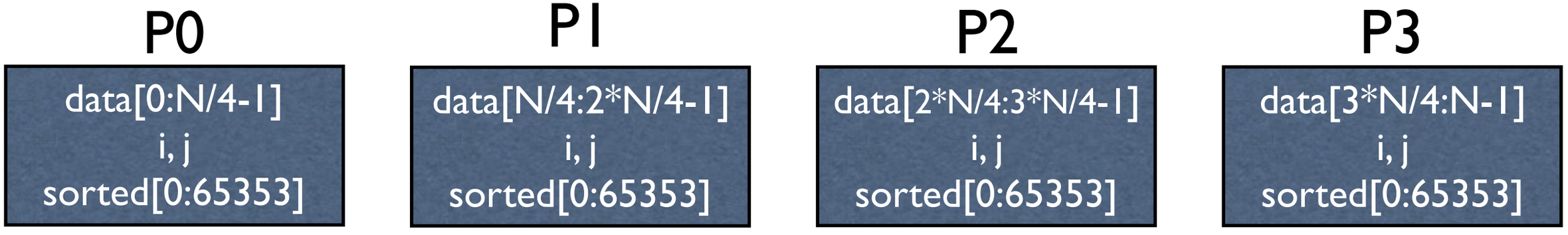

The serial code




```
void sort (sort[ ], data[ ], int pid, int numP) {
    for (i=0; i < N; i++) {
        sorted[data[i]]++;
    }
    // sorted results available here ...
}
```

If above is done in parallel, need to get results from all processes before printing them

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

MPI_Reduce(...)

- Does a reduction like the reduce clause in OpenMP, only it uses messages.

address of the first element to be reduced

address of the first result element

number reduction elements/ results

type of data being reduced

MPI_Reduce(*void* *opnd, *void* *result, *int* count, *MPI_Datatype* type,
MPI_Operator op, int root, MPI_Comm comm);

reduction operation

rank of the process getting the result

the 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_Op

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

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

MPI_Reduce(...)

- Does a reduction like the reduce clause in OpenMP, only it uses messages.

use *result as in and out buffer on root

address of the first result element

number reduction elements/ results

type of data being reduced

MPI_Reduce(MPI_IN_PLACE, *void* *opnd, *int* count, *MPI_Datatype* type, MPI_Operator op, int root, MPI_Comm comm);

reduction operation

rank of process getting the result

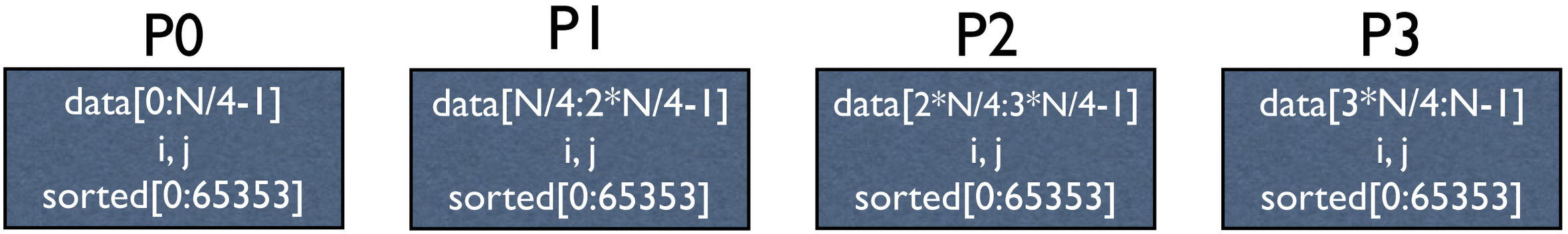
the communicator

Example of reduction

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

```
MPI_Reduce(MPI_IN_PLACE, sorted, 8, 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);
}
```

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

Notes on Reduce

- There is a result for each element of the source array across all processors
- The result ends up on only *one* processor (allreduce sends the result to all processors)

Determining program performance

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

```
int main(int argc, char * argv[ ]) {
    ...
    double elapsed;
    int pid; /* MPI process ID)
    int numP; /* number of MPI processes */
    int N;
    extractArgv(&N, argv);
    for (i=0; i < 65535; i++) {
        sorted[i] = 0;
    }
    MPI_Barrier( );
    elapsed = -MPI_Wtime( );
    sort(data, sort, pid, numP);
    elapsed += MPI_Wtime( );
    if (pid == 0) printSort(final);
    MPI_Finalize( );
}
```

Determining program performance

```
int main(int argc, char * argv[ ]) {
    ...
    double elapsed;
    int pid; /* MPI process ID)
    int numP; /* number of MPI processes */
    int N;
    extractArgv(&N, argv); for (i=0; i < 65535; i++) {
        sorted[i] = 0;
    }
    MPI_Barrier( );
    elapsed = -MPI_Wtime( );
    sort(data, sort, pid, numP);
    elapsed += MPI_Wtime( );
    if (pid == 0) printSort(final, elapsed);
    MPI_Finalize( );
}
```

Holds the elapsed time

wait for all processors to finish initialization

negative of start time

plus finish time gives elapsed time

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

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}

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

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

3 is prime

mark all multiples of 3 > 9

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

5 is prime

mark all multiples of 5 > 25

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

7 is prime

mark all multiples of 7 > 49

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

11 is prime

mark all multiples of 11 > 121

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~~, 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.

1 is not prime by definition

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

What is (are) the fundamental operation(s)?

- Marking of the multiples of the last prime found
  - if *v* a multiple of *k* then *v mod k == 0*

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

- *min*-reduction to find the next prime (i.e. smallest unmarked value) across all processes
- *broadcast* the value to all tasks

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/ partitioning data

- 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/ partitioning data

- 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

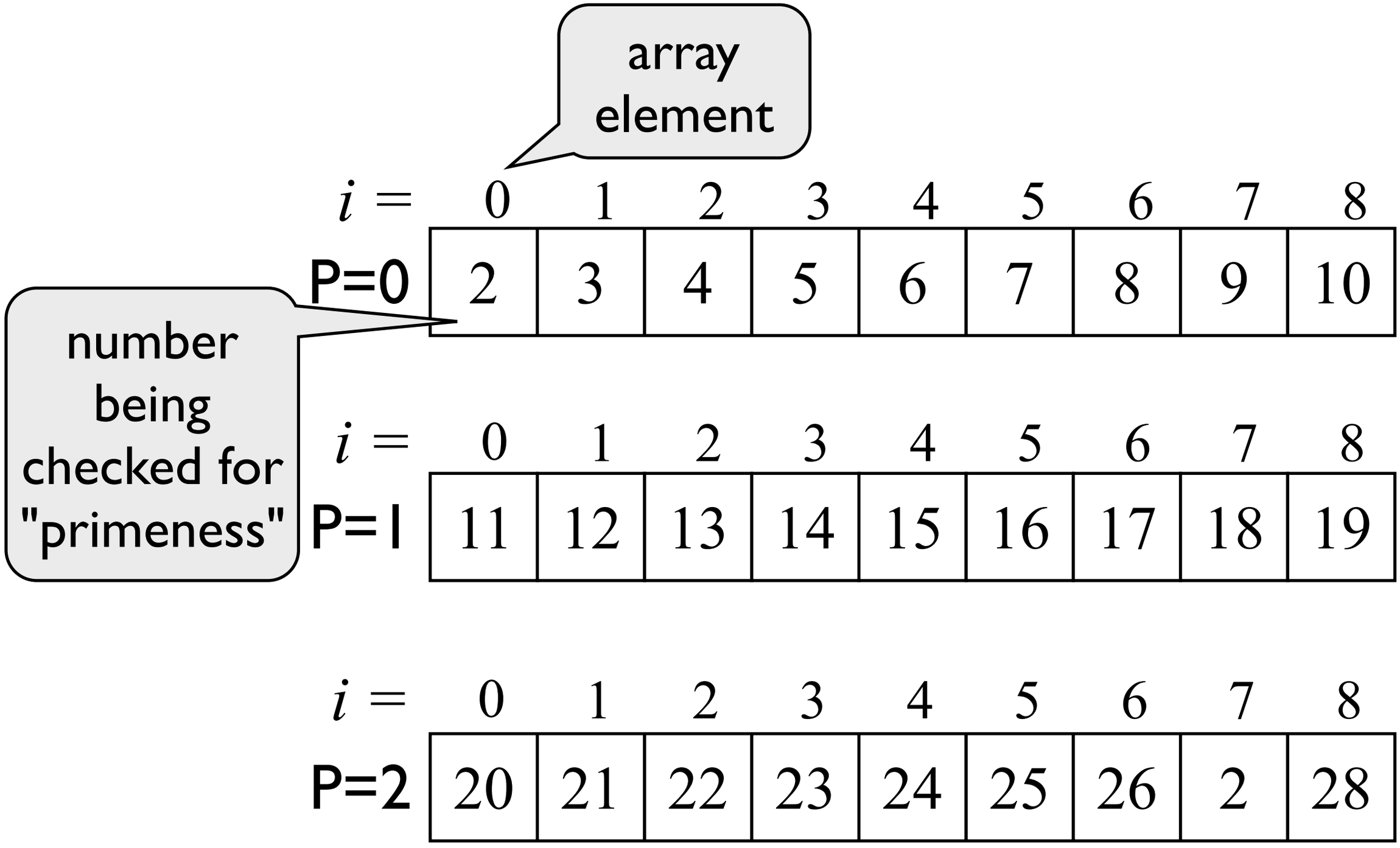
```
for all e in the block
        if e mod k = 0, mark e
```

- 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
   - 3.1. On each process, mark all multiples of k
   - 3.2. On process *0*, find smallest unmarked number u, set $k=u$
   - 3.3. 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



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);
   }
```

standard stuff

bounds macros, etc.

setup, check args, etc.

Algorithm, 2/4

Get min and max possible prime on p in global space

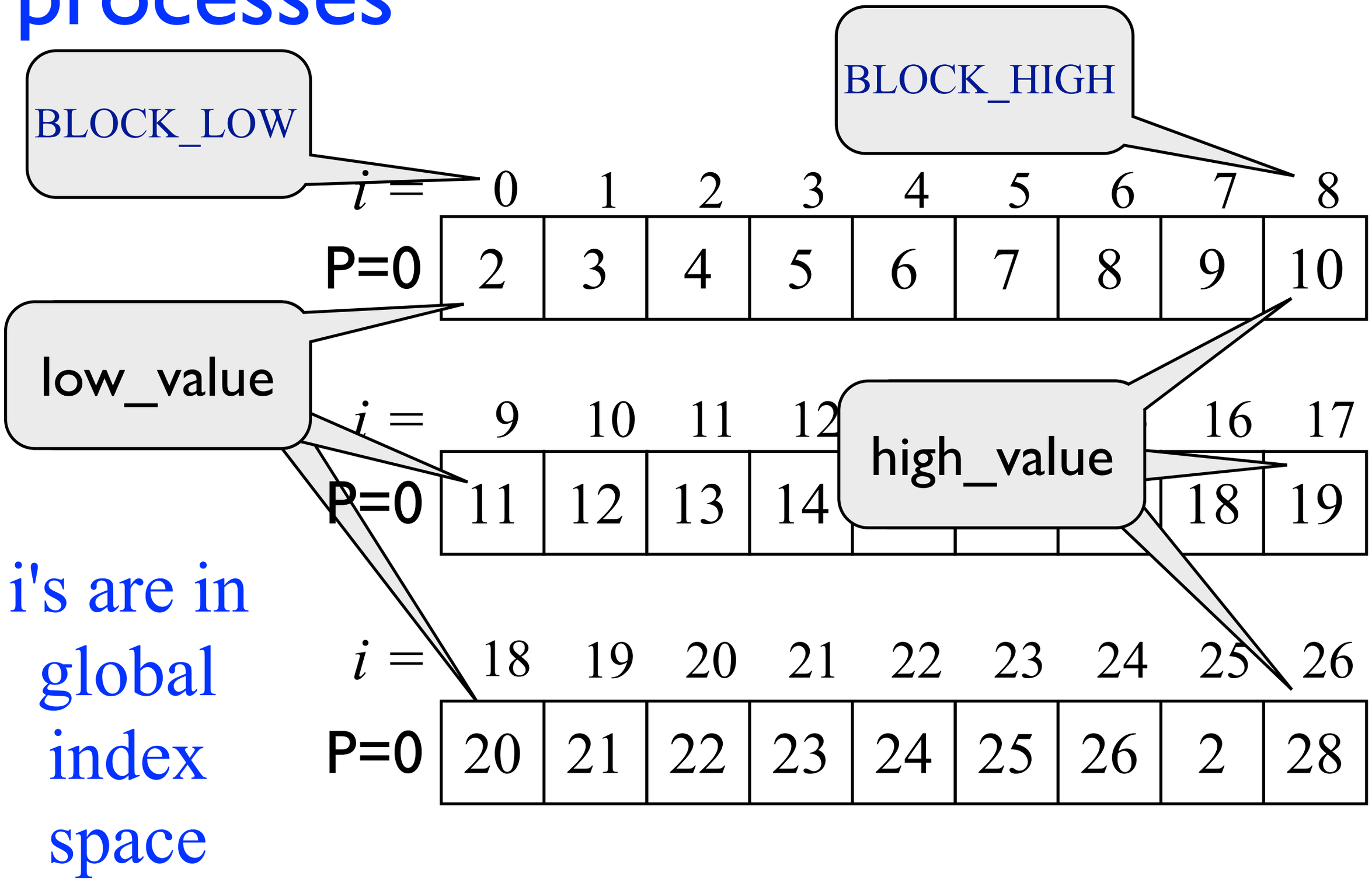
```
n = atoi(argv[1]);
low_value = 2 + BLOCK_LOW(id,p,n-1);
high_value = 2 + BLOCK_HIGH(id,p,n-1);
size = BLOCK_SIZE(id,p,n-1);
proc0_size = (n-1)/p;
if ((2 + proc0_size) < (int) sqrt((double) n)) {
   if (!id) printf ("Too many processes\n");
   MPI_Finalize();
   exit (1);
}
```

Figure out if too many processes for $\sqrt{\Phi}$ candidates on $p=0$

allocate array to use to mark primes

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

values for P=0, similar for other processes



i's are in global index space

Algorithm 3/4

```
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

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 |

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;
}
```

Mark all prime elements starting with *first*

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

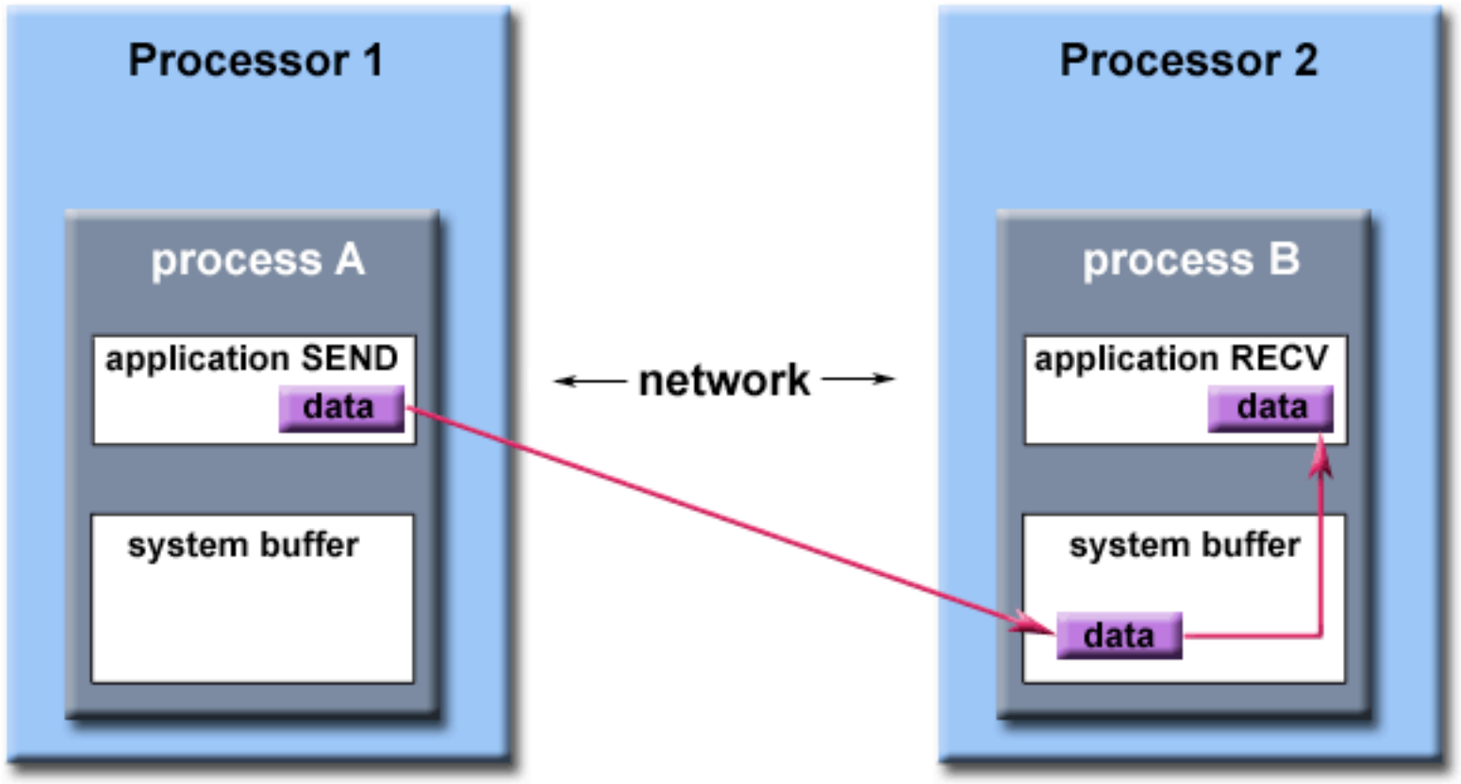
point-to-point communication

- 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

  Can help performance by allowing 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

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

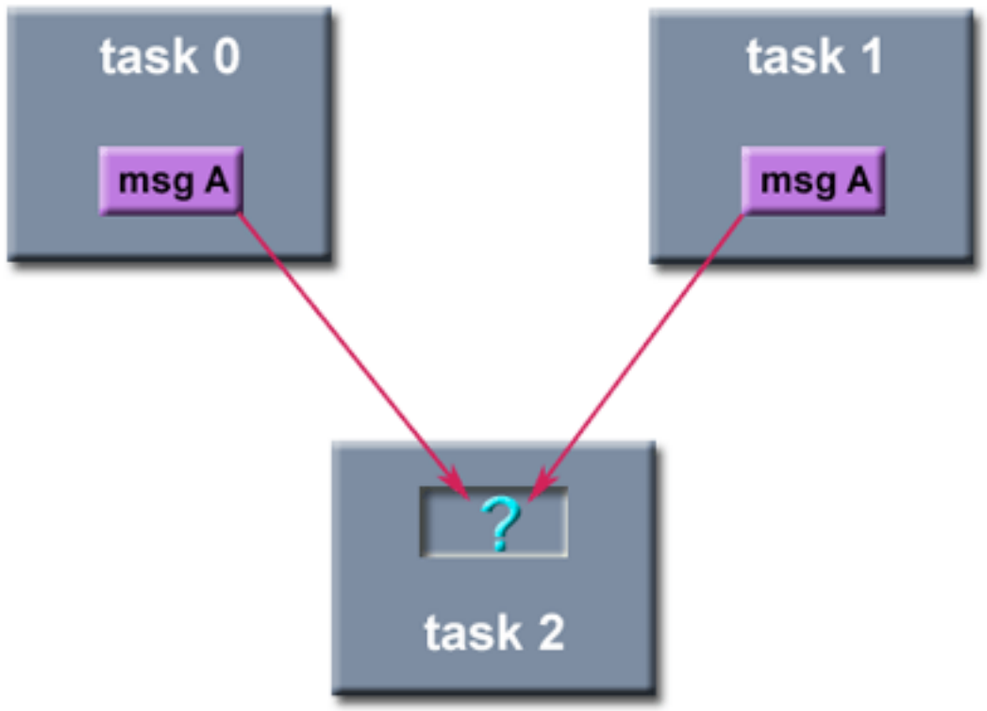
Synchronous and buffered sends and receives

- 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

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.

Example of blocking send/recv

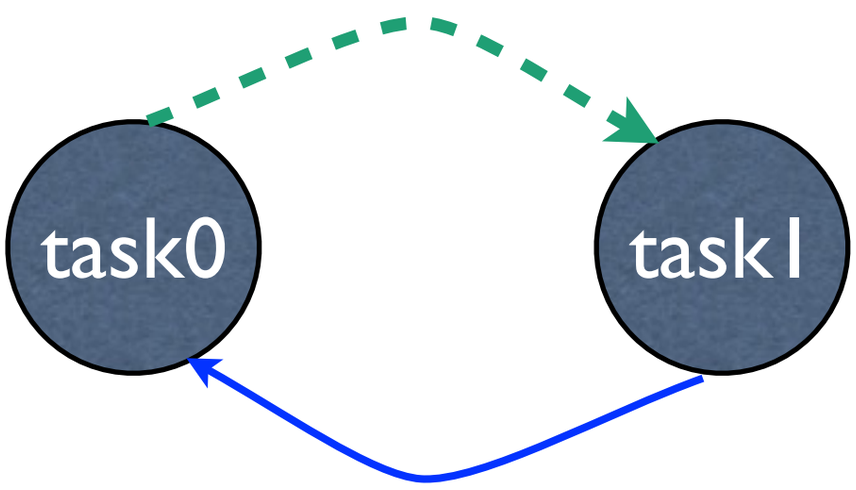
```
#include "mpi.h"
#include <stdio.h>

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).
- 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

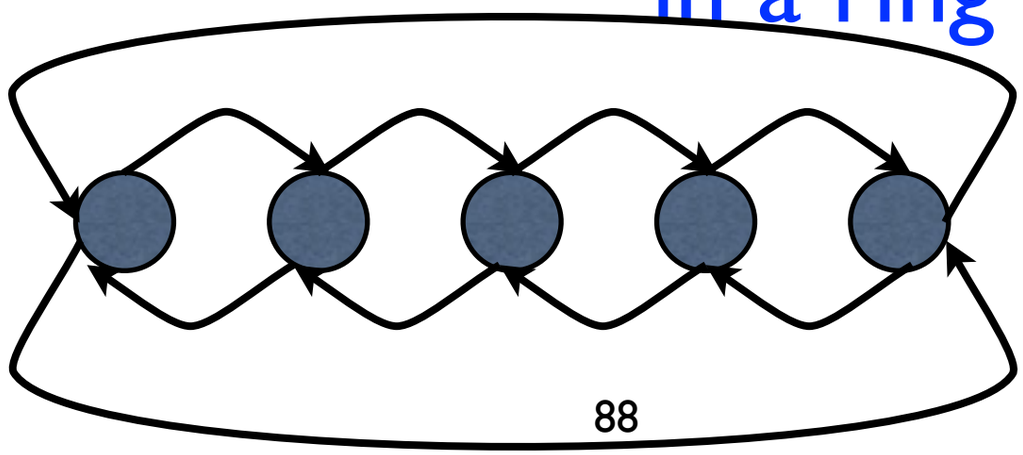
Non-blocking example

```
#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.

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*.

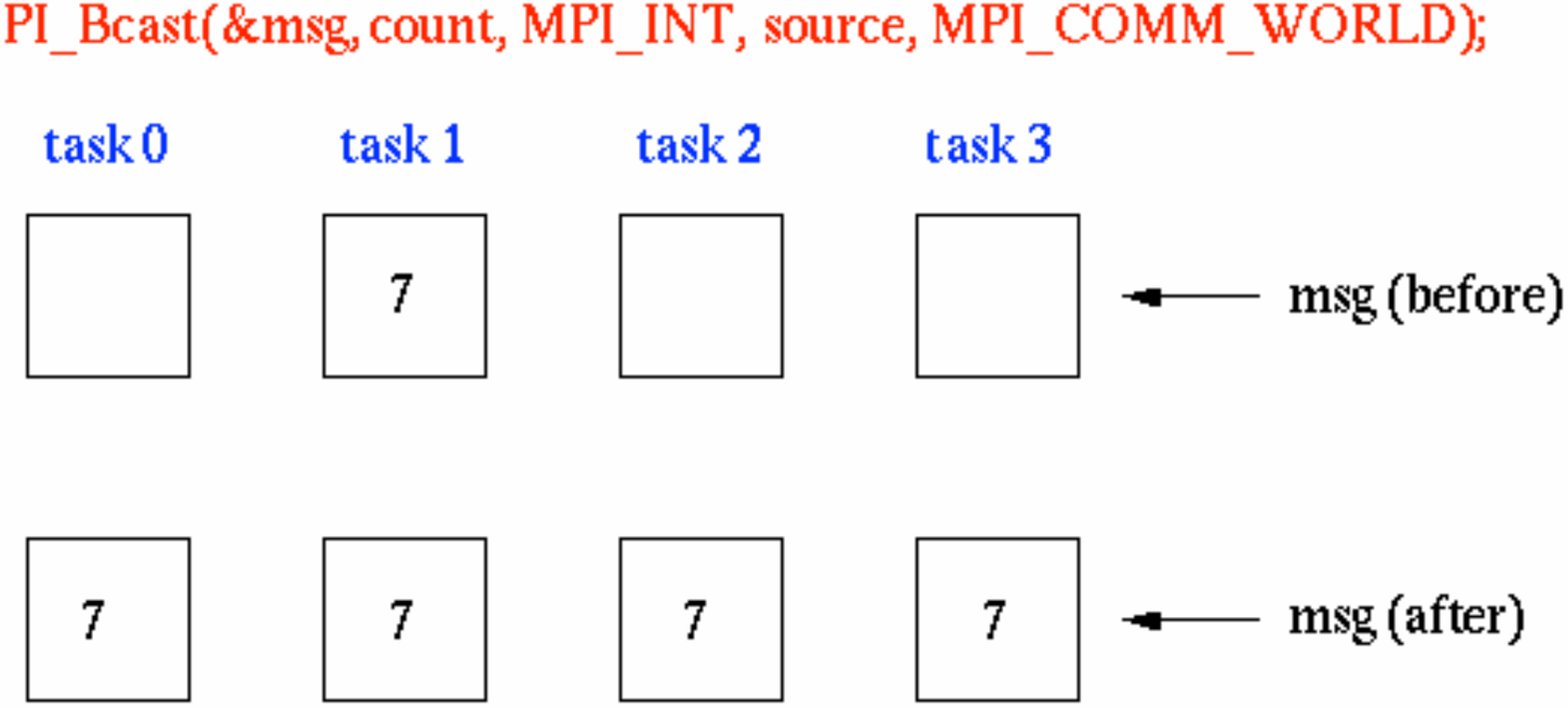
MPI_Reduce (&sendbuf,&recvbuf,count,datatype,op,root,comm): performs a reduction using operation *op* and places the result into *recvbuf* on the *root* process.

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);
```

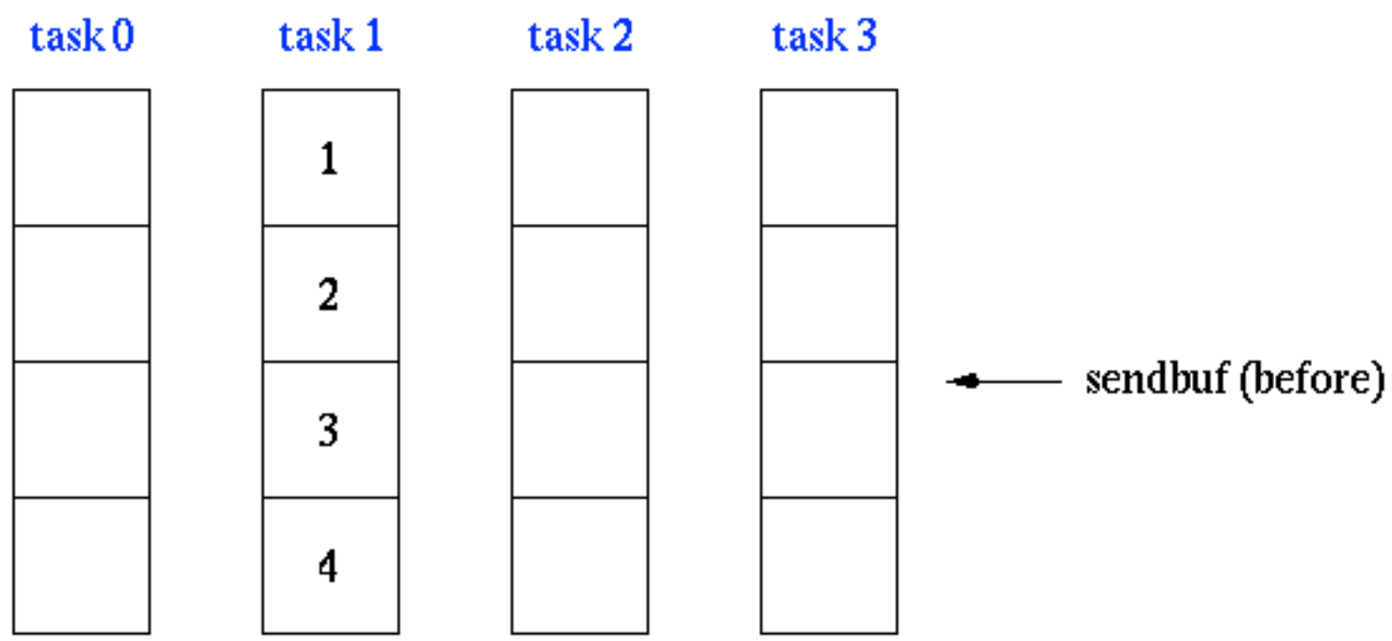


MPI Scatter

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);
```



Equivalent to

MPI_Send(sendbuf+i*sendcount*extent(sendtype), sendcount, sendtype, i, ...)

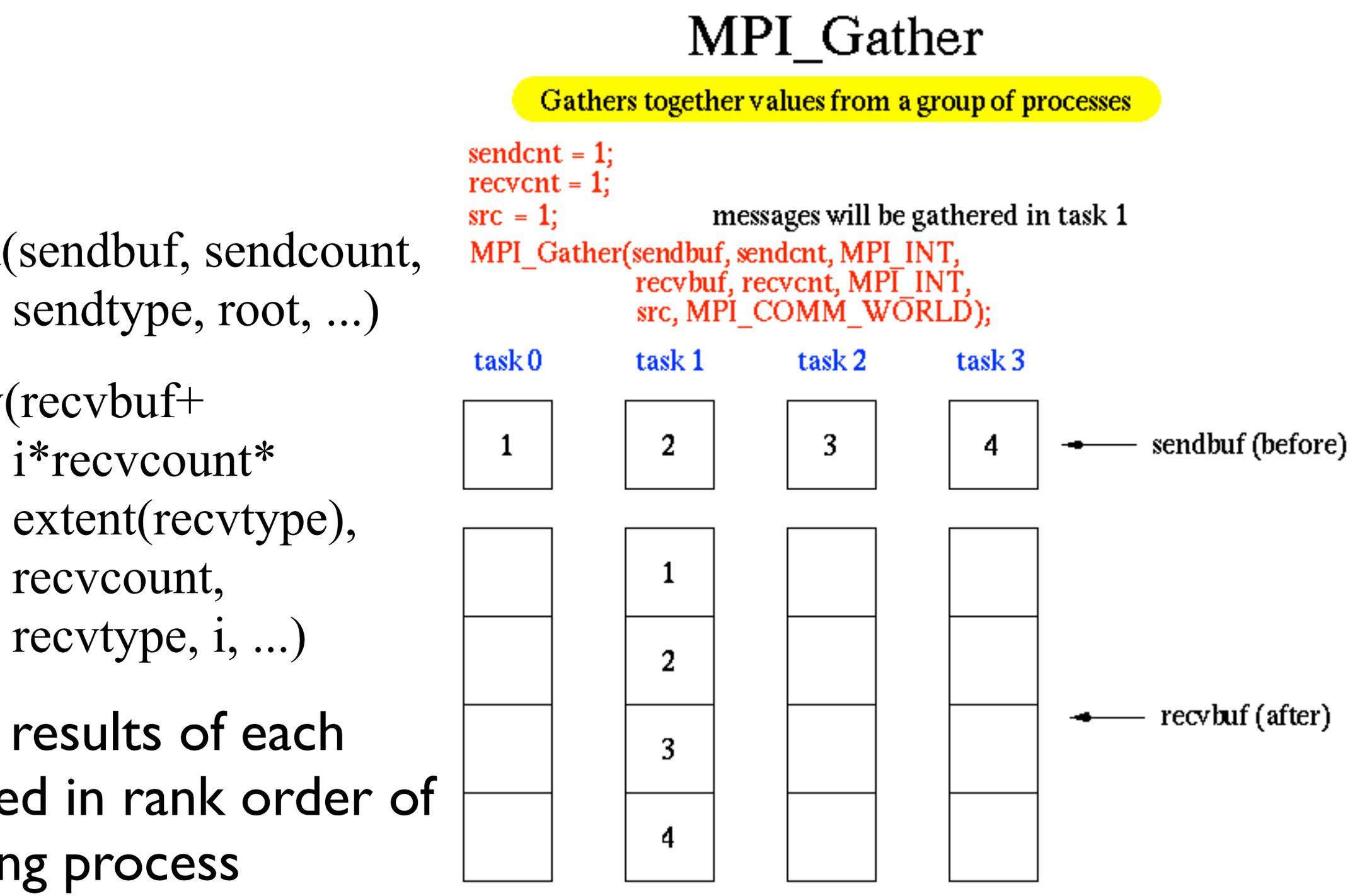
MPI_Recv(recvbuf, recvcount, recvtype, i, sendcount, sendtype, i, ...)

MPI_Gather

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



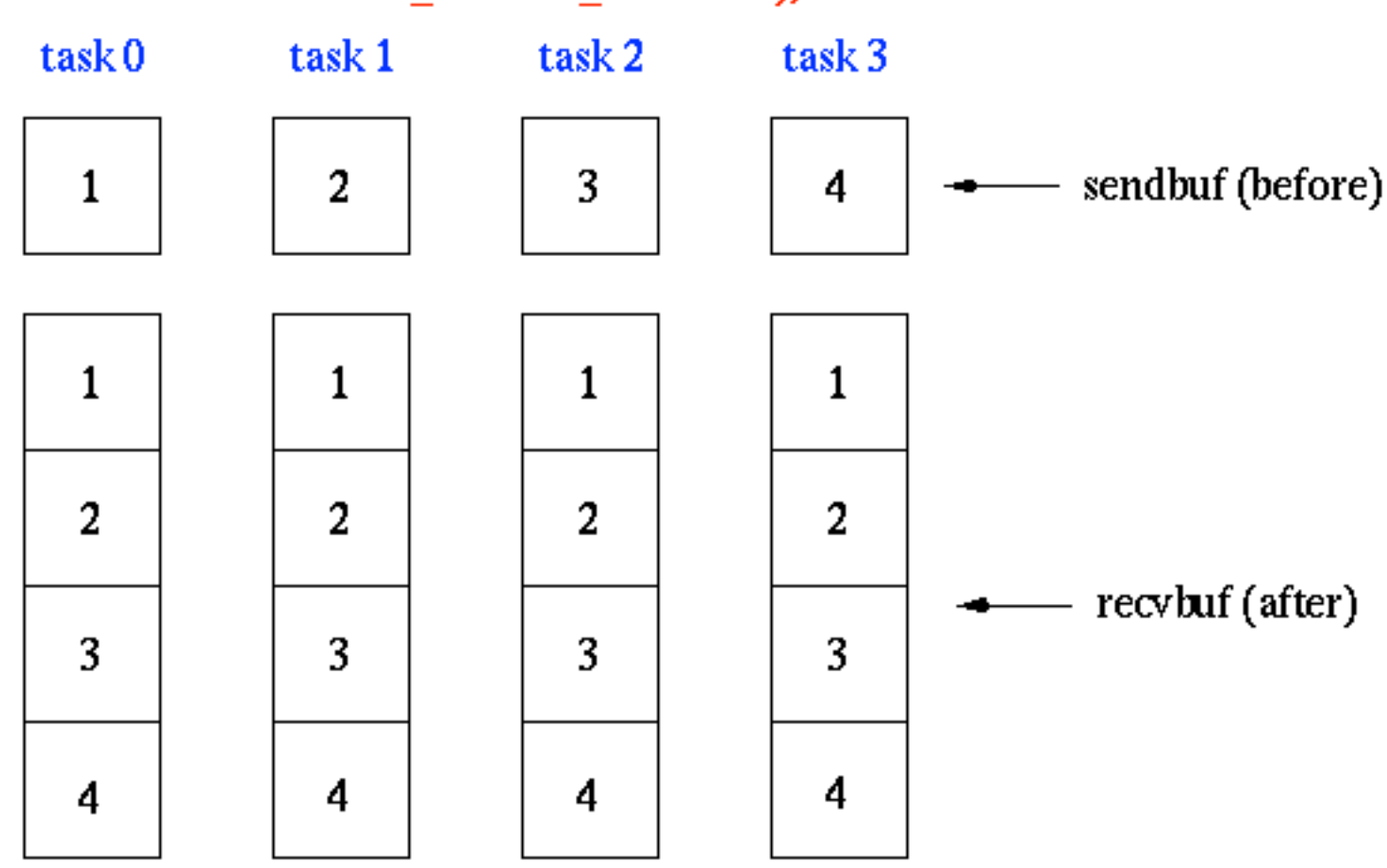
MPI_Allgather

A gather with every process being a target.

MPI_Allgather

Gathers together values from a group of processes and distributes to all

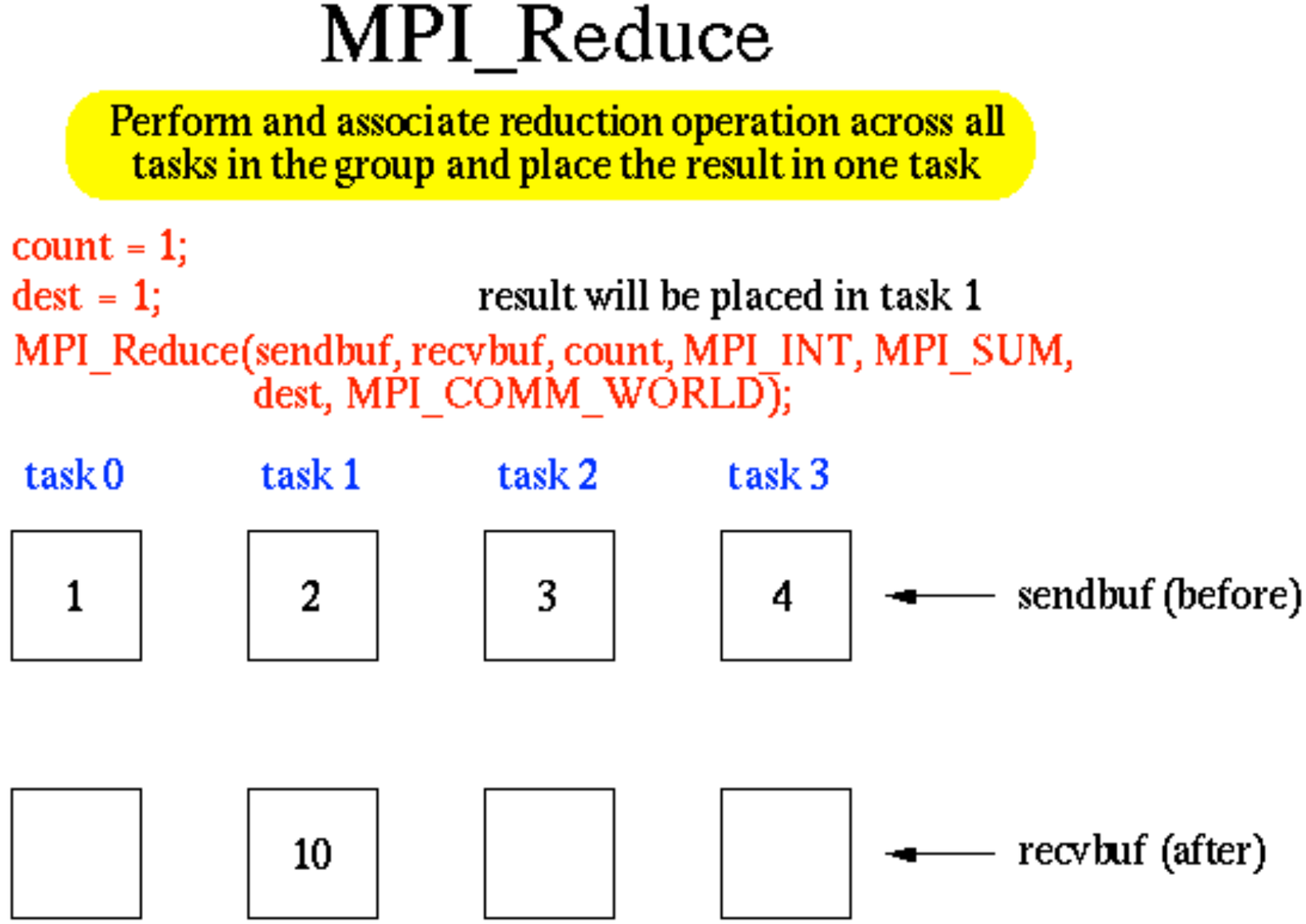
```
sendcnt = 1;
recvcnt = 1;
MPI_Allgather(sendbuf, sendcnt, MPI_INT,
              recvbuf, recvcnt, MPI_INT,
              MPI_COMM_WORLD);
```



MPI_Reduce

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

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.

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.

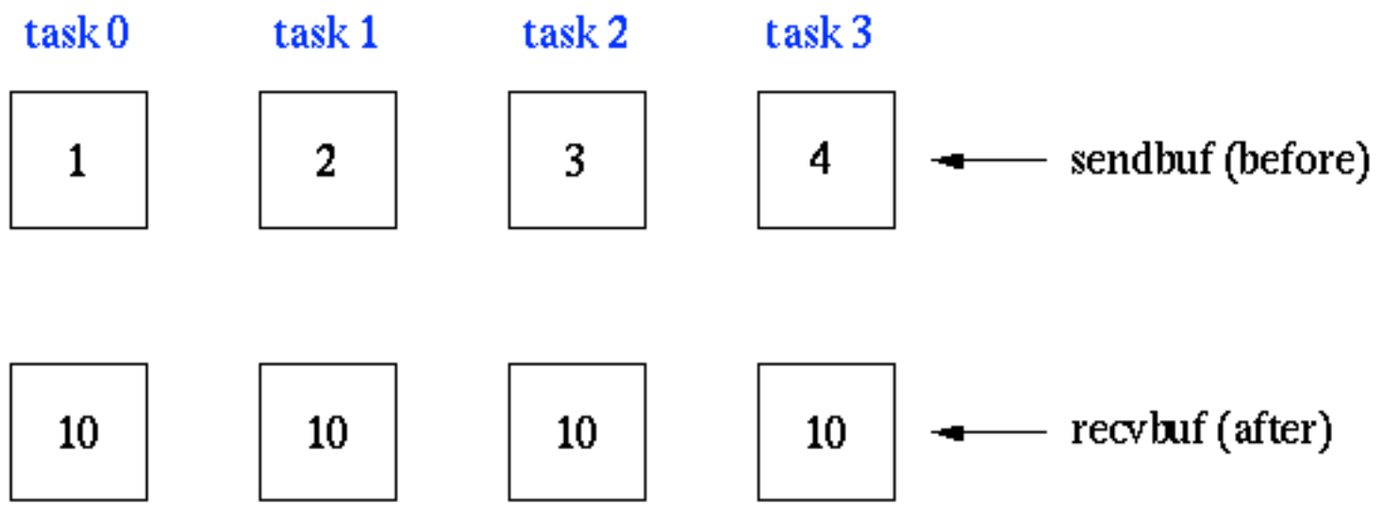
MPI_Scan(&sendbuf, &recvbuf, count, datatype, op, comm): performs the partial sums on each processor that would result from doing an in-order reduction across the processors in rank order.

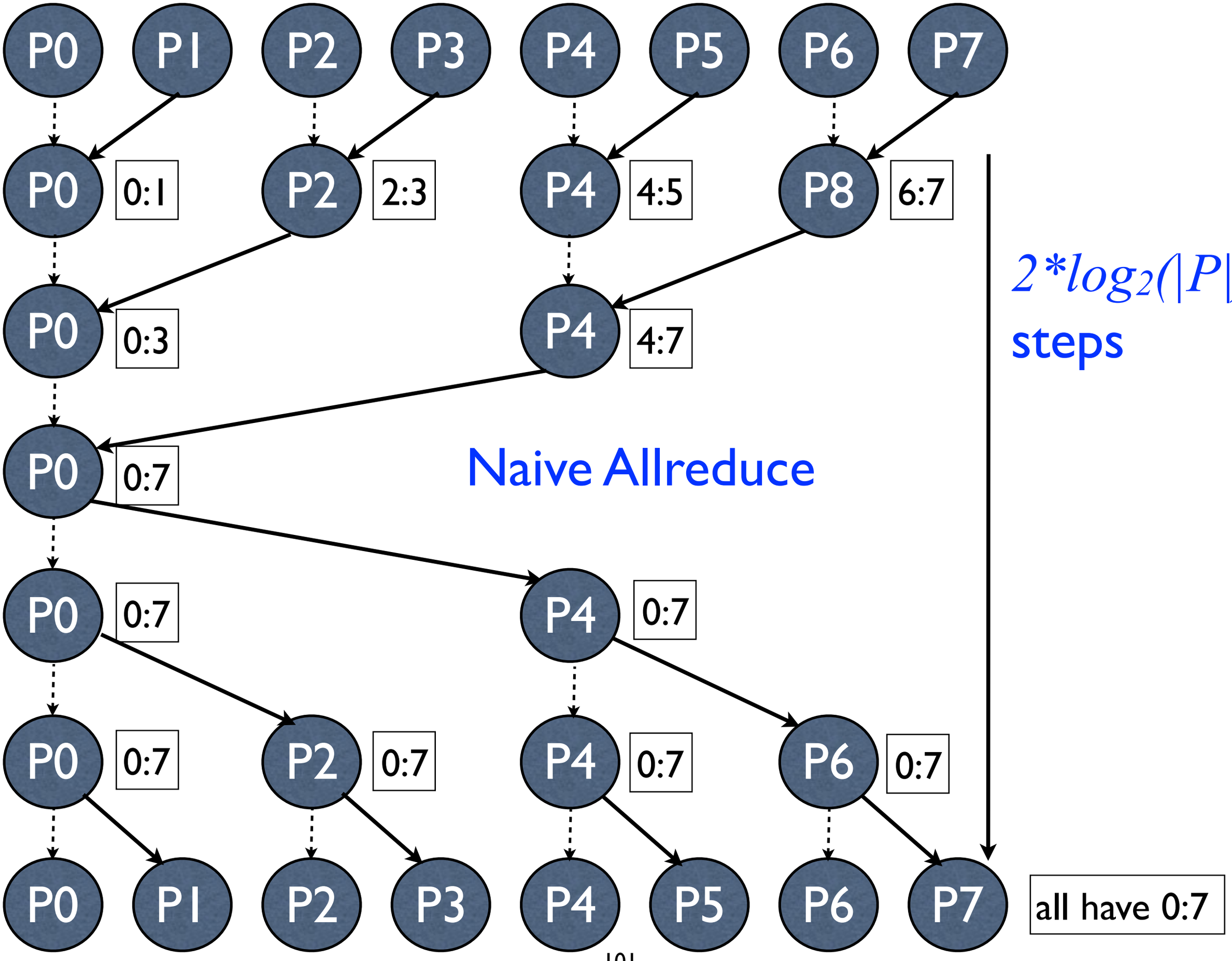
MPI_Allreduce

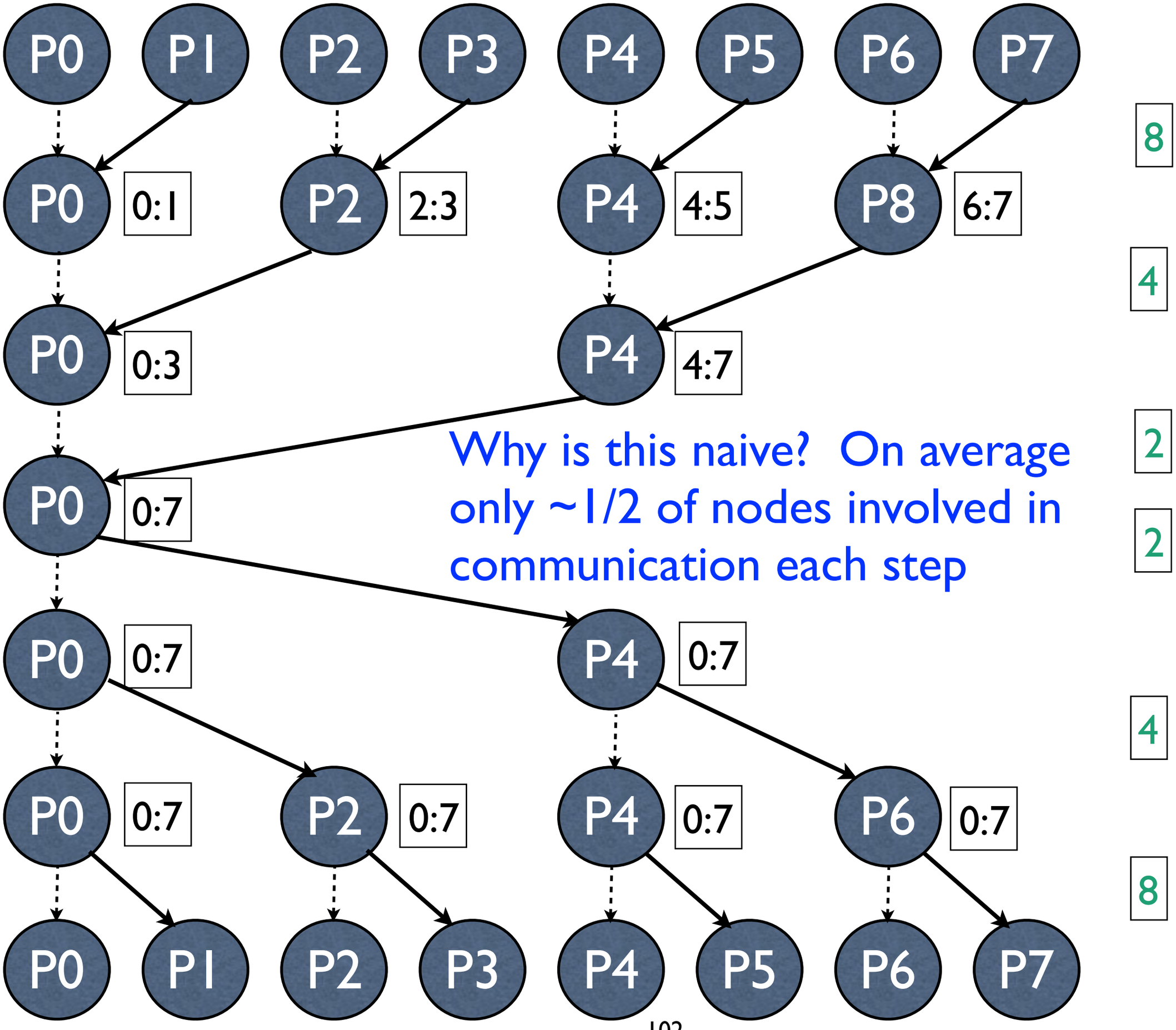
MPI_Allreduce

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);
```




P0
P1
P2
P3
P4
P5
P6
P7
P0
0:1
P2
2:3
P4
4:5
P8
6:7
P0
0:3
P4
4:7
P0
0:7
Naive Allreduce
2*log2(|P|)
steps
P0
0:7
P4
0:7
P0
0:7
P2
0:7
P4
0:7
P6
0:7
P0
P1
P2
P3
P4
P5
P6
P7
all have 0:7


P0
P1
P2
P3
P4
P5
P6
P7
P0
0:1
P2
2:3
P4
4:5
P8
6:7
P0
0:3
P4
4:7
P0
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P4
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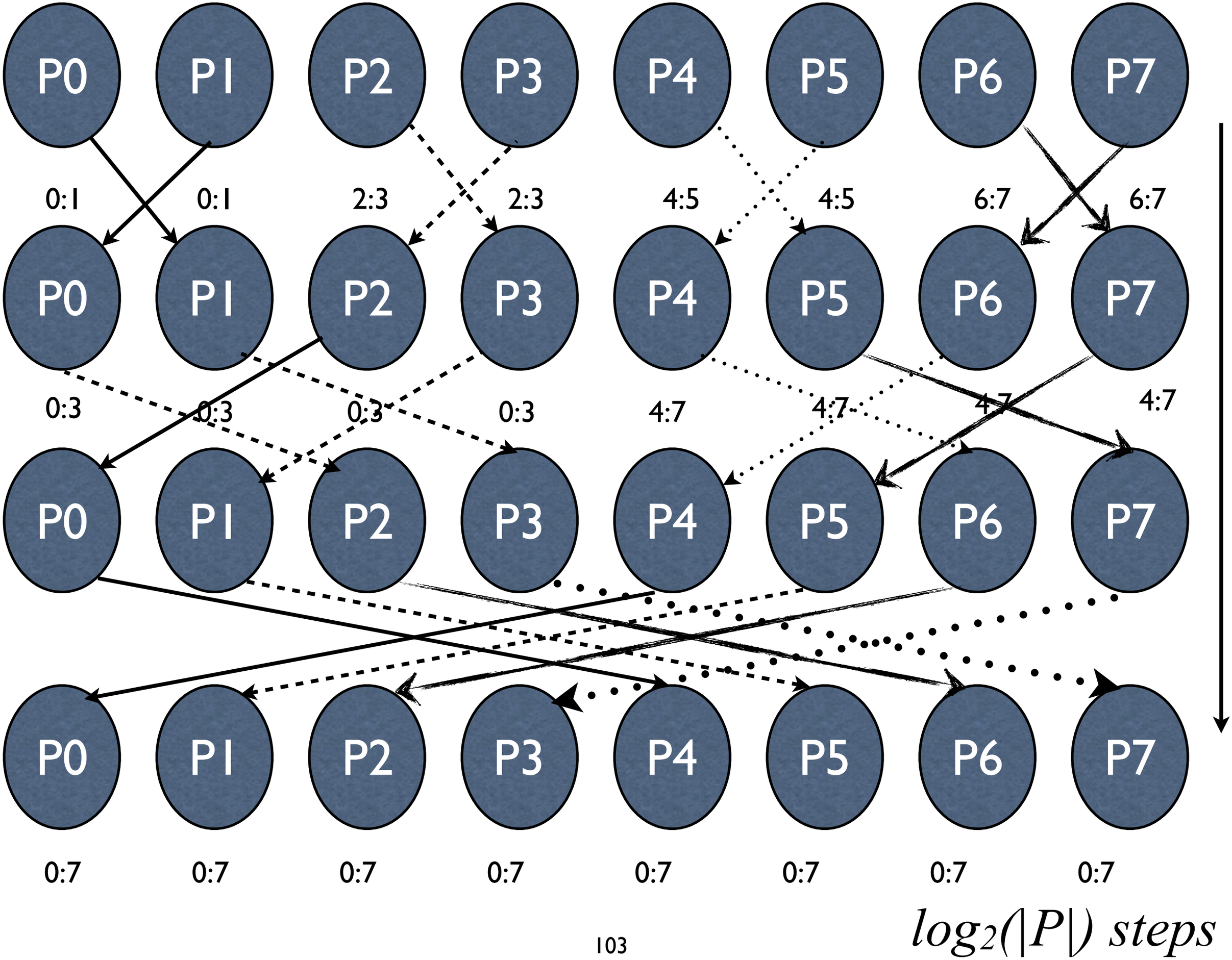
P0
0:7
P2
0:7
P4
0:7
P6
0:7
P0
P1
P2
P3
P4
P5
P6
P7
8
4
2
2
4
8
Why is this naive? On average only ~1/2 of nodes involved in communication each step
all have 0:7


P0
P1
P2
P3
P4
P5
P6
P7
0:1
0:1
2:3
2:3
4:5
4:5
6:7
6:7
0:3
0:3
0:3
0:3
4:7
4:7
4:7
4:7
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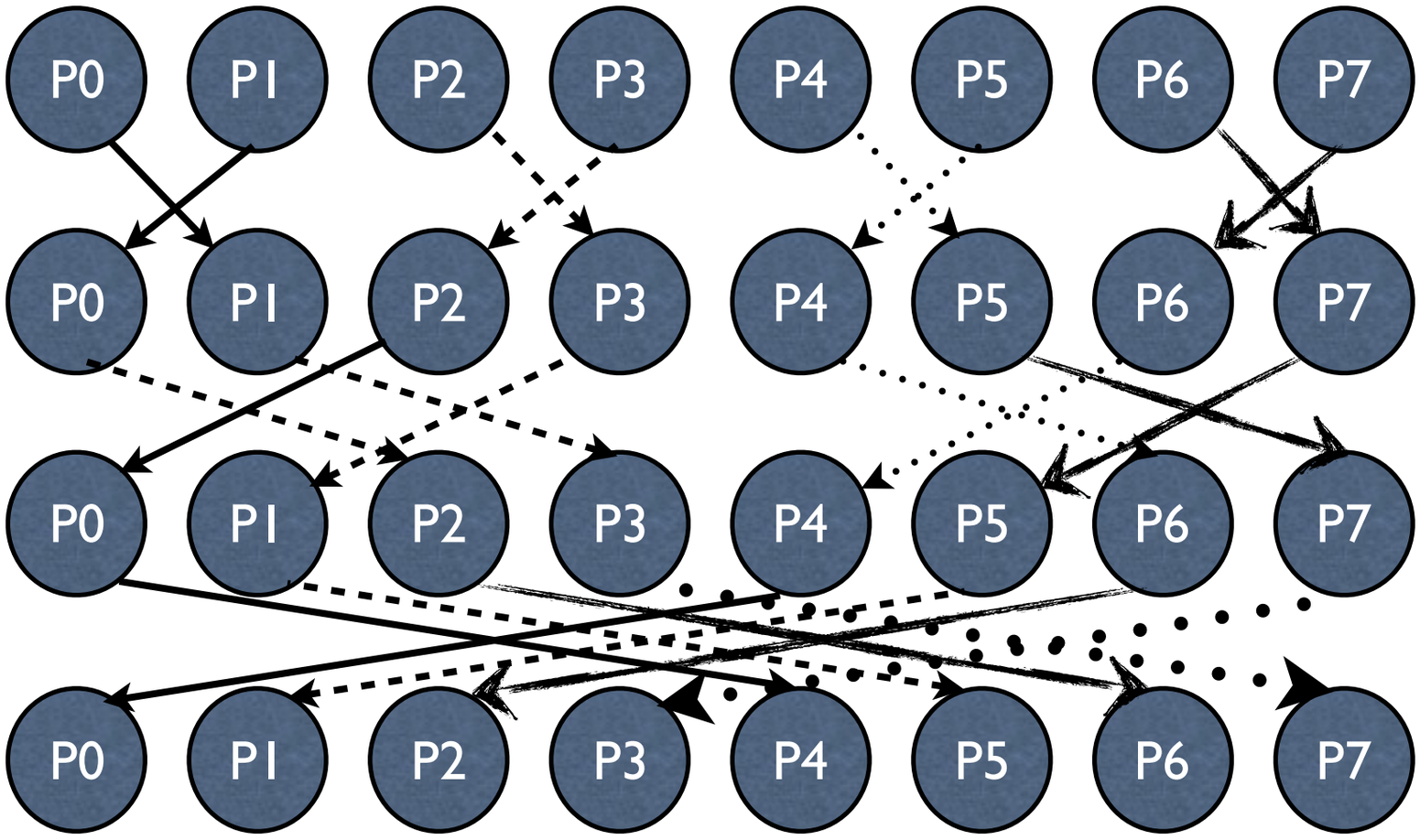
0:7
0:7
0:7
$log_2(|P|)$ steps



All processors all busy each step.

Note that the bandwidth requirements of the network change

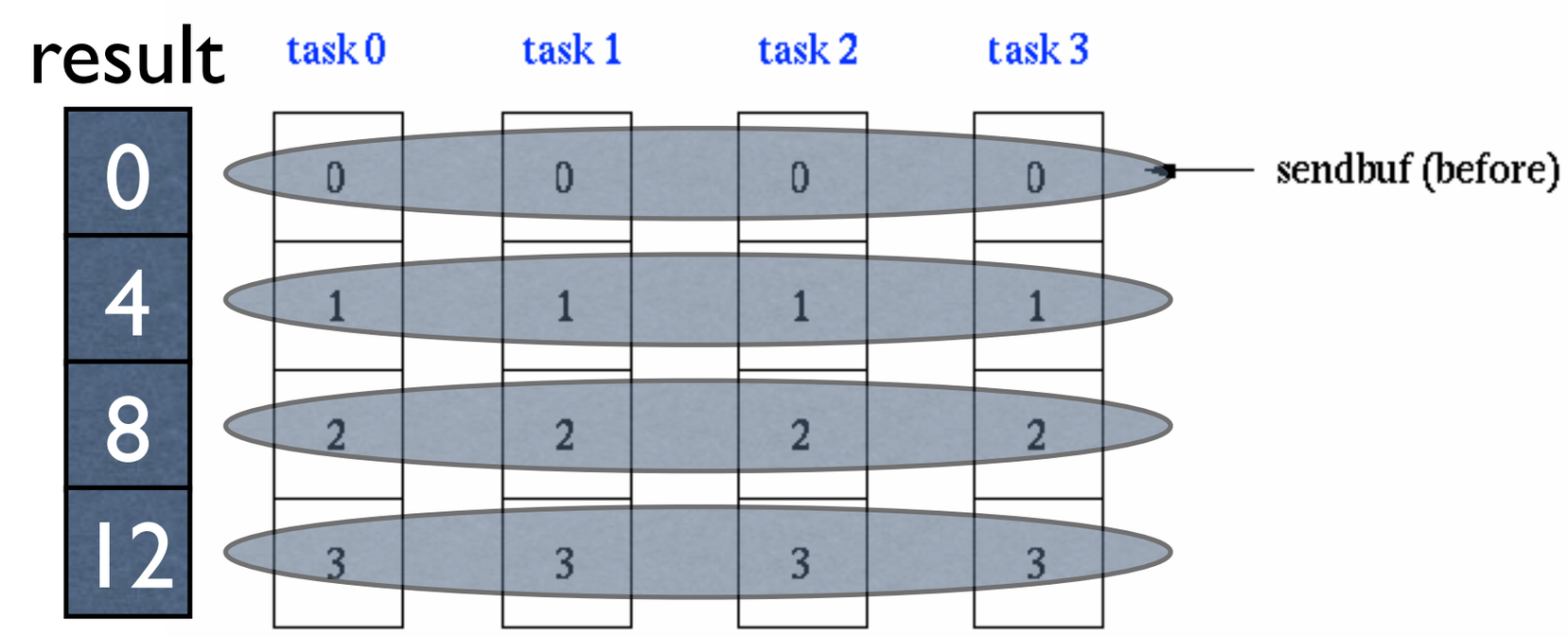
Algorithm from *Optimization of Collective Reduction Operations*, Rolf Rabenseifner, International Conference on Computational Science, 2004

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

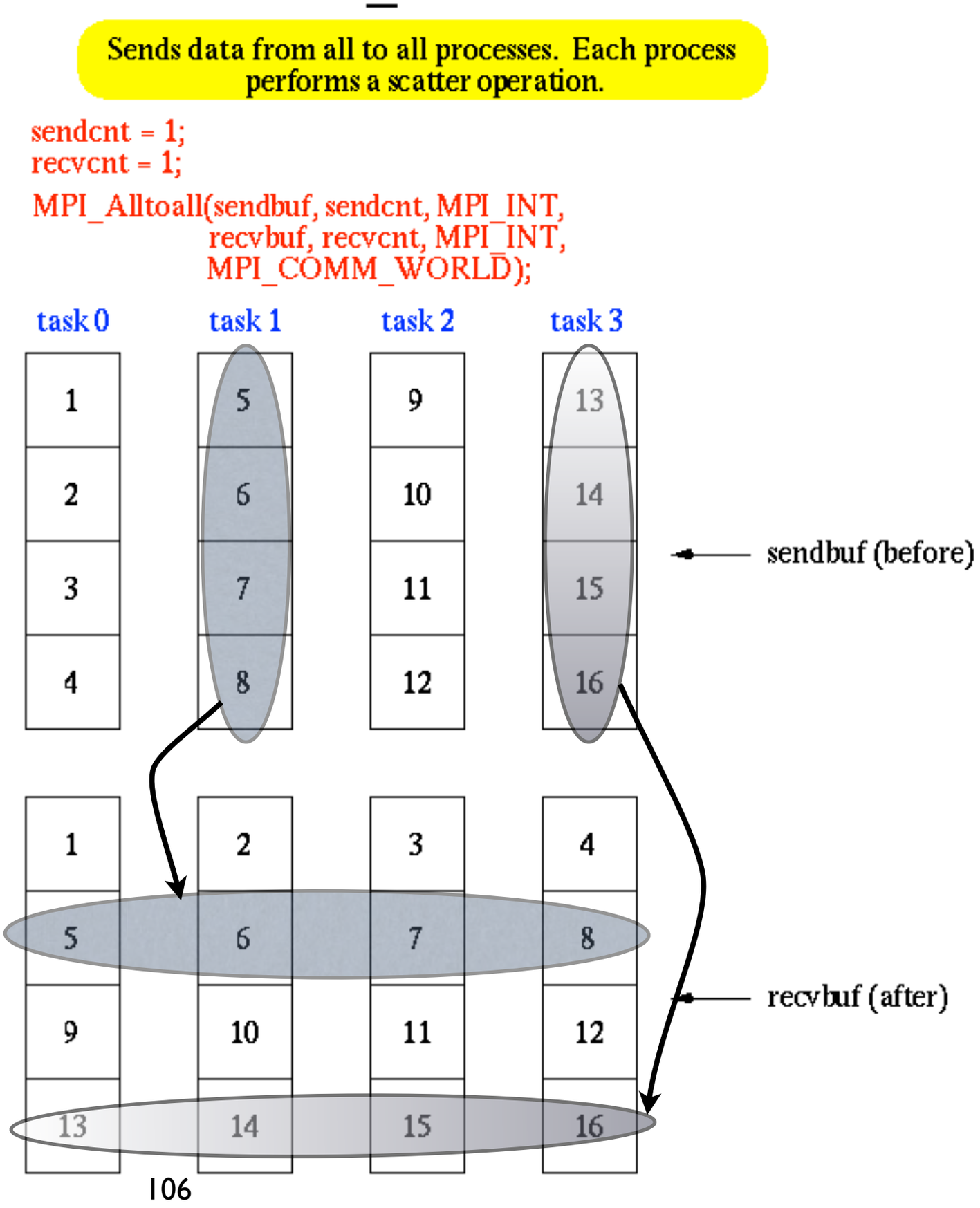
```
recvcount = 1;
MPI_Reduce_scatter(sendbuf, recvbuf, recvcount, MPI_INT, MPI_SUM,
                   MPI_COMM_WORLD);
```



MPI_Alltoall

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

Received data is concatenated in sender rank order

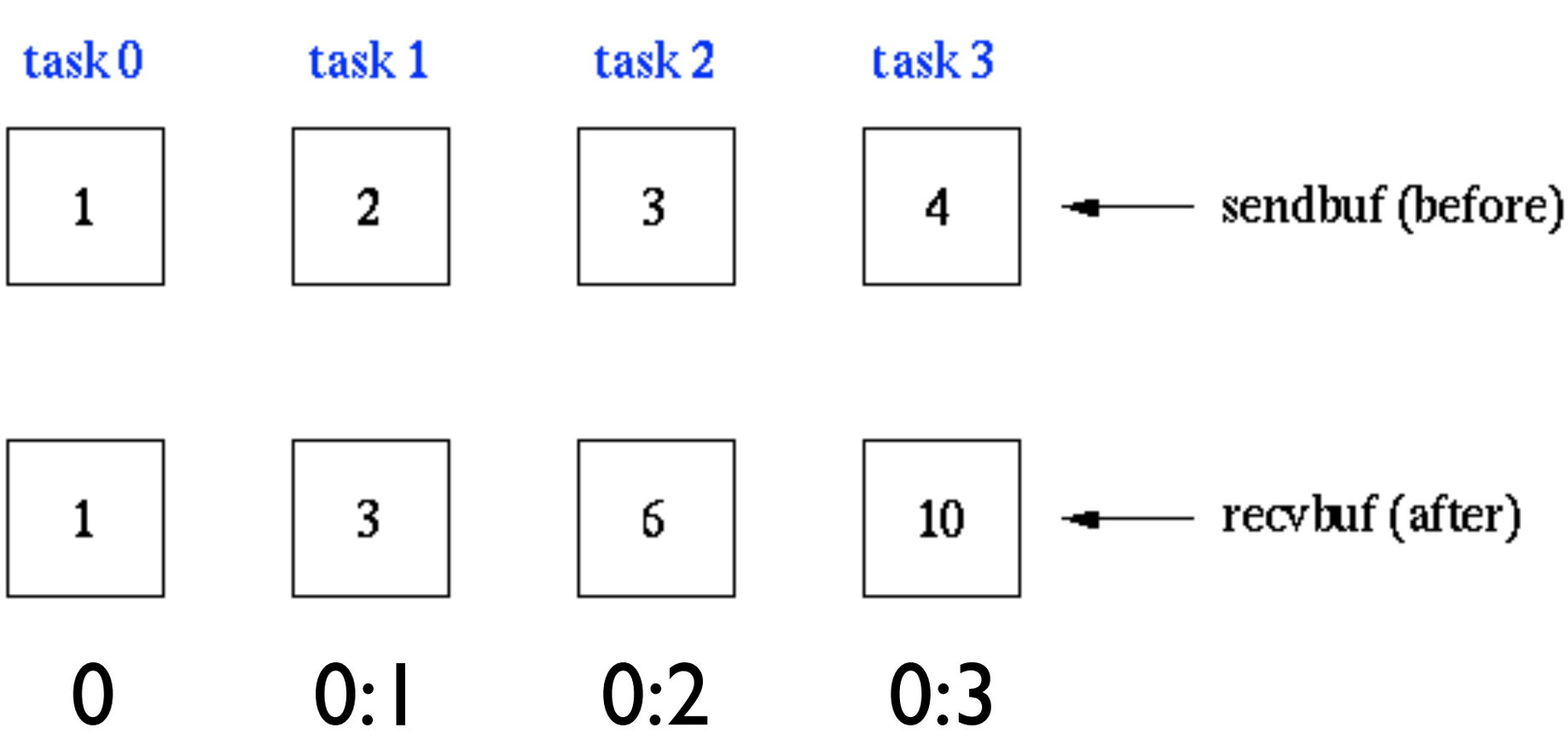


MPI_Scan

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.

Tasks these 40+ routines can perform

Extract handle of a global group a communicator using MPI_Comm_group

Form new group as a subset of another group using MPI_Group_incl

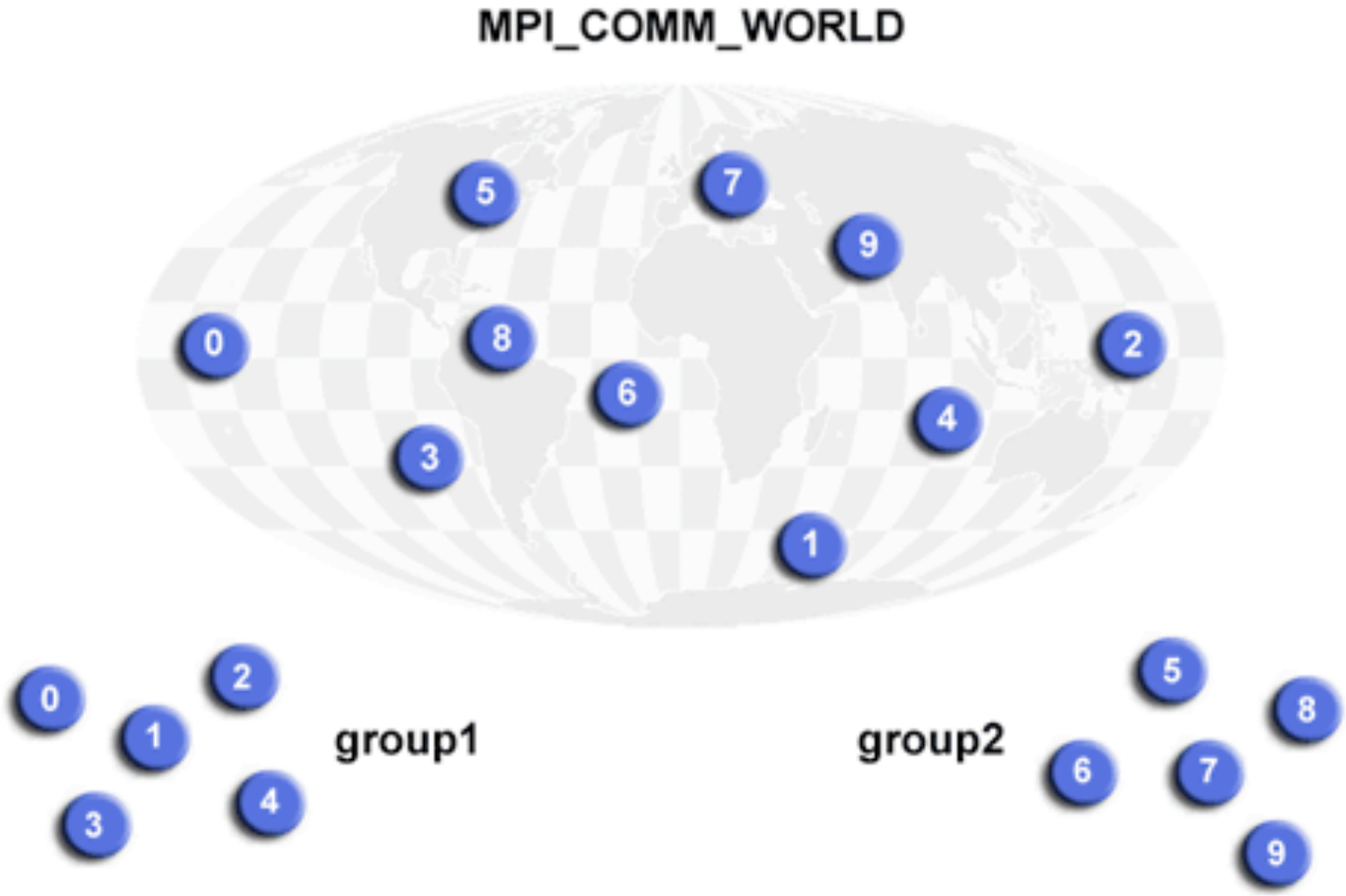
Create new communicator for a group using MPI_Comm_create

Determine a processor's rank in a communicator using MPI_Comm_rank

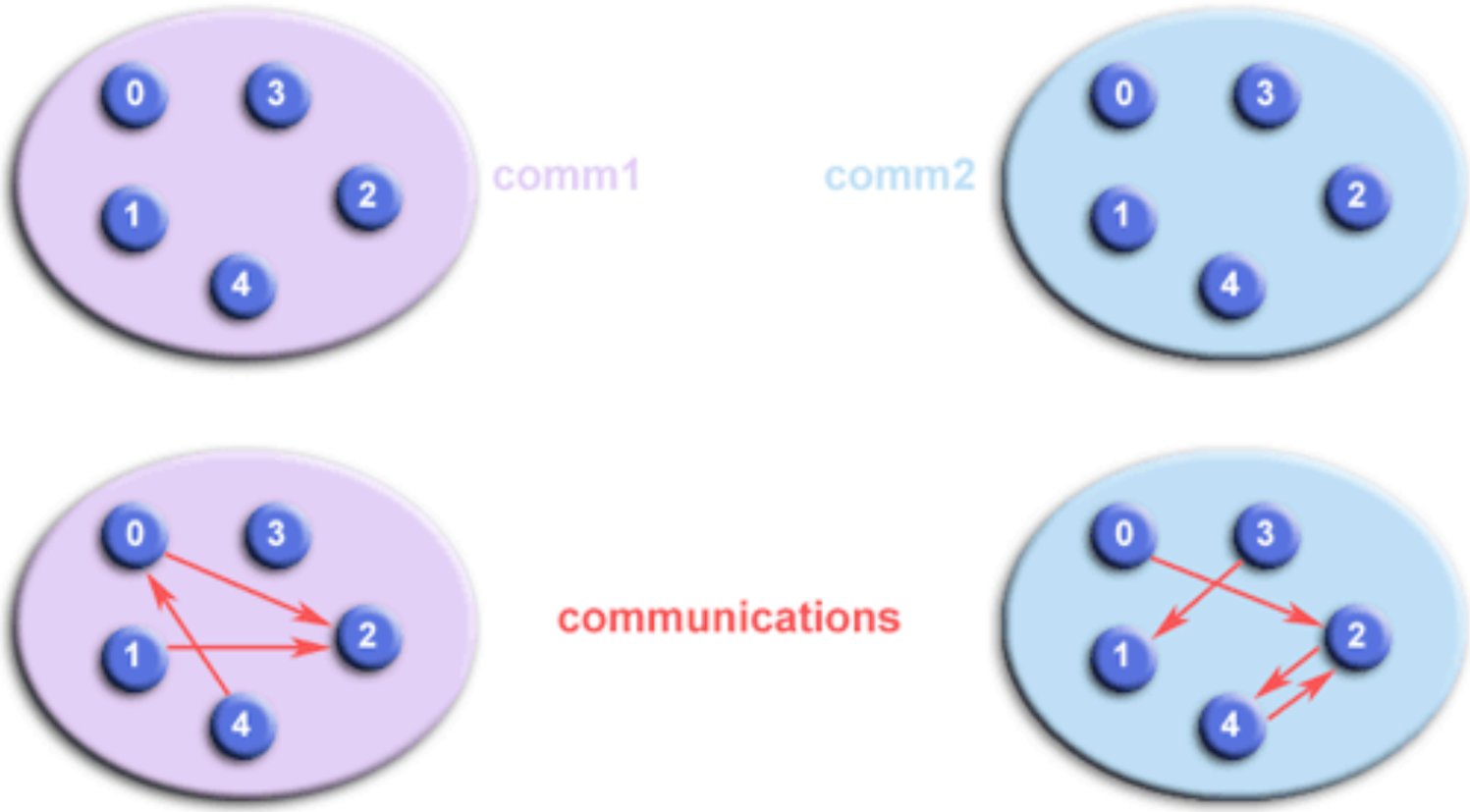
Communicate among the processors of a group

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, &rank);
MPI_Comm_size(MPI_COMM_WORLD, &numtas

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 these statements.

Based on its number, 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 group

Get the processes rank within the new group