Collective Communication in MPI and Advanced Features

Pacheco’s book. Chapter 3

T. Yang, CS240A. Part of slides from the text book, CS267 K. Yelick from UC Berkeley and B. Gropp, ANL

Outline

- **Collective group communication**
- **Application examples**
  - Pi computation
  - Summation of long vectors
- **More applications**
  - Matrix-vector multiplication
    - performance evaluation
  - Parallel sorting
- **Safety and other MPI issues.**

What MPI Functions are commonly used

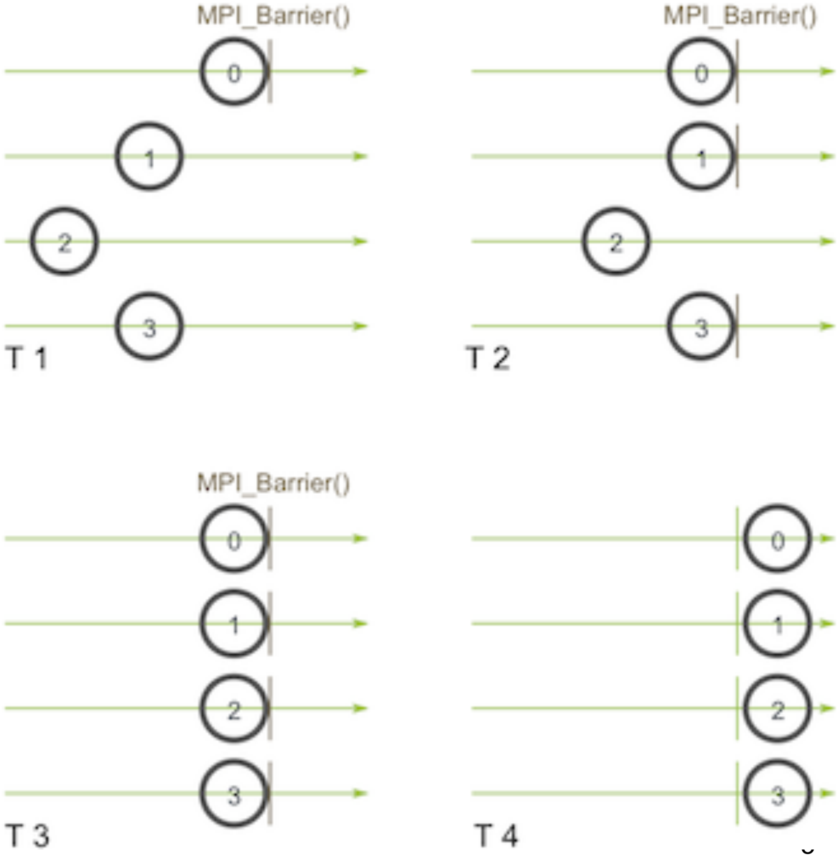
- **For simple applications, these are common:**
  - Startup
    - MPI_Init, MPI_Finalize
  - Information on the processes
    - MPI_Comm_rank, MPI_Comm_size, MPI_Get_processor_name
  - Point-to-point communication
    - MPI_Irecv, MPI_Isend, MPI_Wait, MPI_Send, MPI_Recv
  - Collective communication
    - MPI_Allreduce, MPI_Bcast, MPI_Allgather
- **http://mpitutorial.com/mpi-broadcast-and-collective-communication/**

MPI Collective Communication

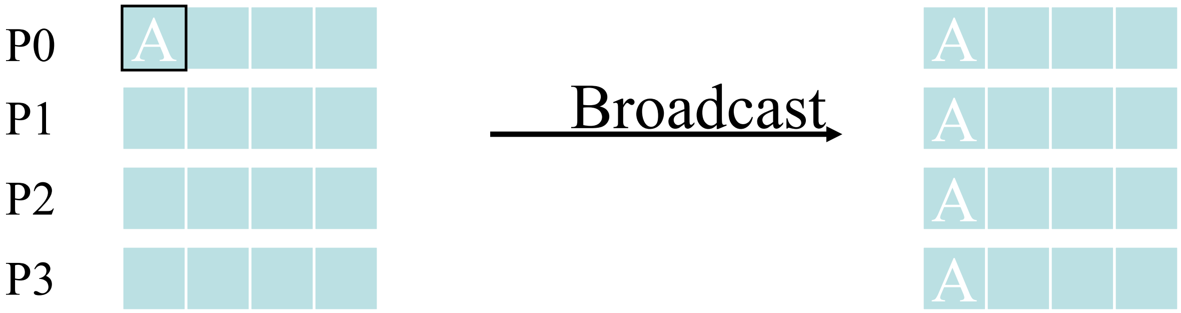
- ***Collective* routines provide a higher-level way to organize a parallel program**
  - Each process executes the same communication operations
  - Communication and computation is coordinated among a group of processes in a communicator
  - Tags are not used
  - No non-blocking collective operations.
- **Three classes of operations:** synchronization, data movement, collective computation.

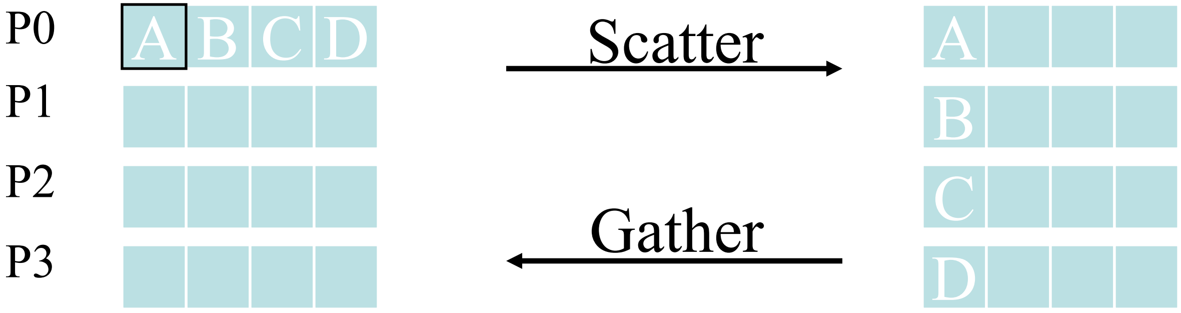
Synchronization

- `MPI_Barrier( comm )`
- Blocks until all processes in the group of the communicator `comm` call it.
- Not used often. Sometime used in measuring performance and load balancing

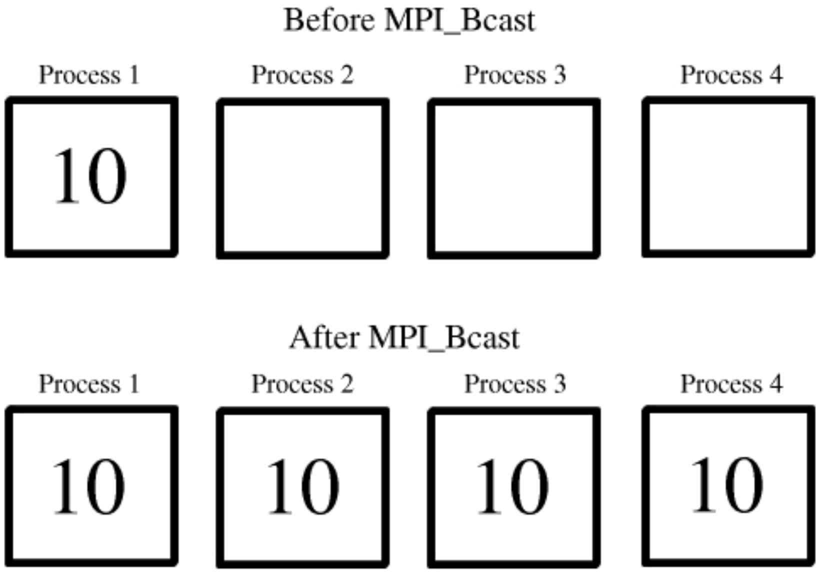


Collective Data Movement: Broadcast, Scatter, and Gather





Broadcast



Before MPI_Bcast

Process 1	Process 2	Process 3	Process 4
10			

After MPI_Bcast

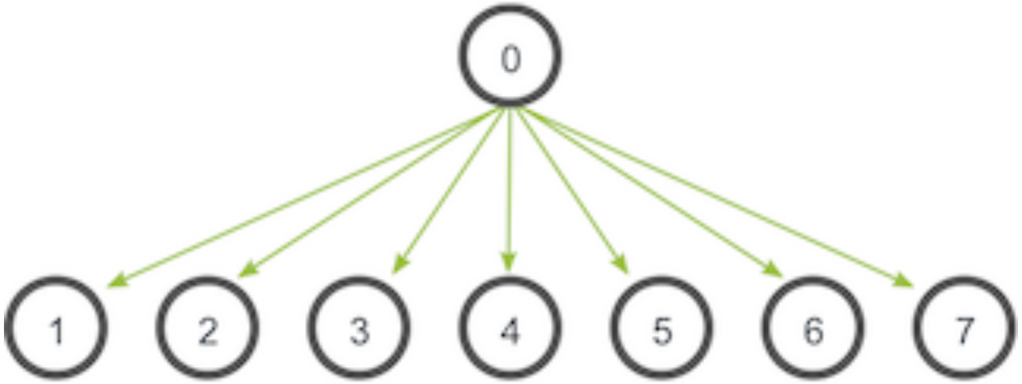
Process 1	Process 2	Process 3	Process 4
10	10	10	10

- **Data belonging to a single process is sent to all of the processes in the communicator.**

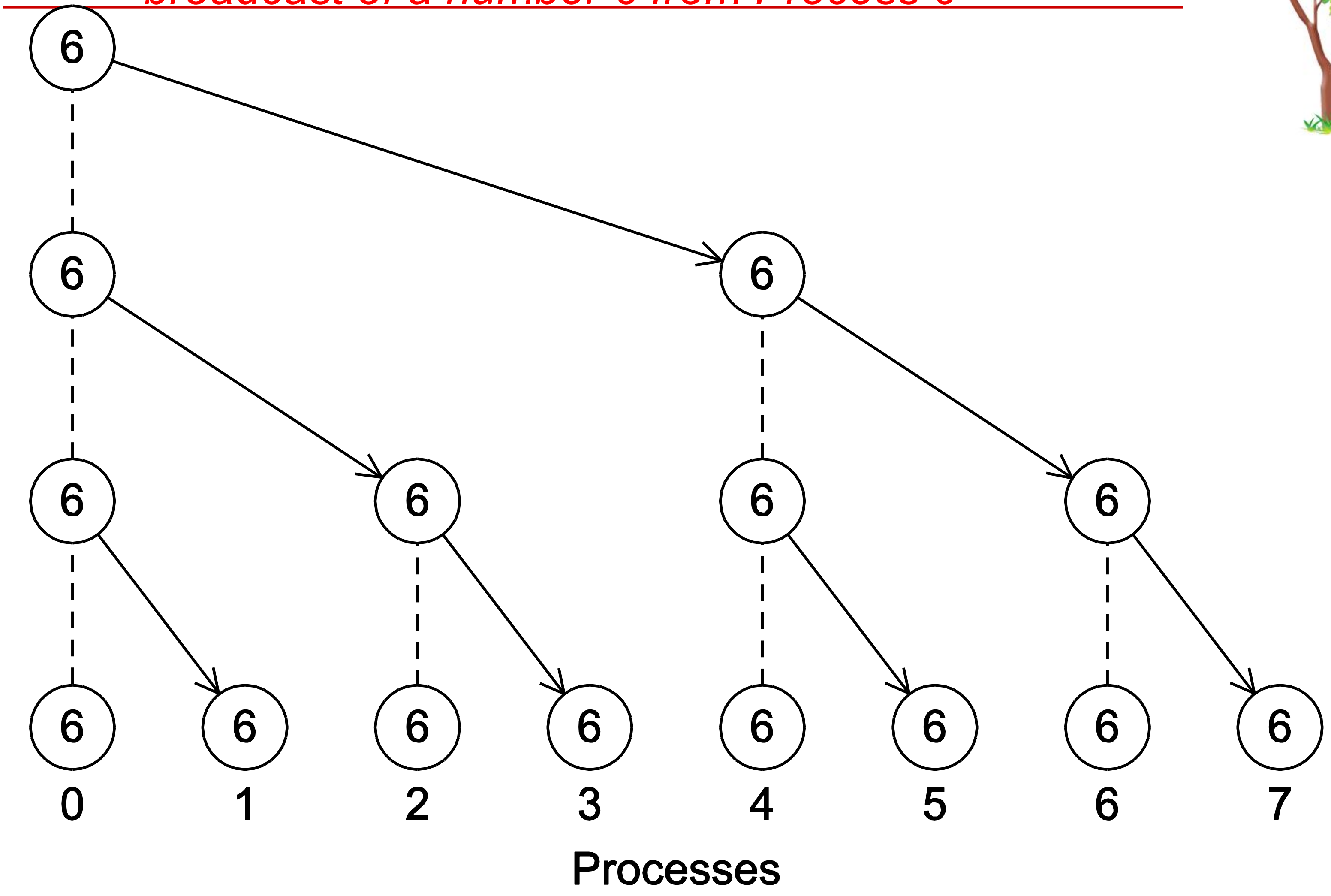
```
int MPI_Bcast(
        void*         data_p       /* in/out */,
        int           count        /* in     */,
        MPI_Datatype  datatype     /* in     */,
        int           source_proc  /* in     */,
        MPI_Comm      comm         /* in     */);
```

Comments on Broadcast

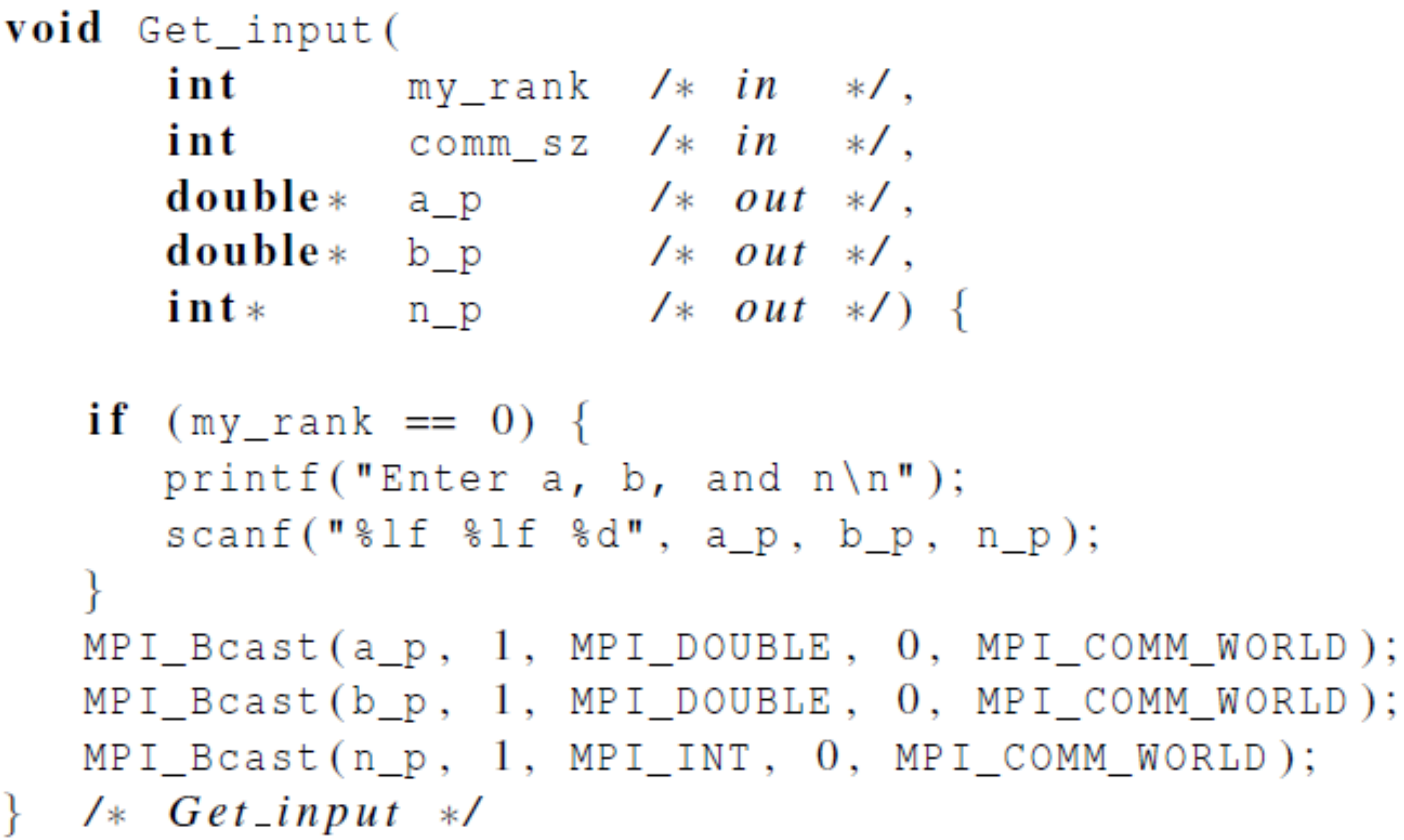
- **All collective operations must be called by *all* processes in the communicator**
- **MPI_Bcast is called by both the sender (called the root process) and the processes that are to receive the broadcast**
  - MPI_Bcast is not a “multi-send”
  - “root” argument is the rank of the sender; this tells MPI which process originates the broadcast and which receive



Implementation View: A tree-structured broadcast of a number 6 from Process 0

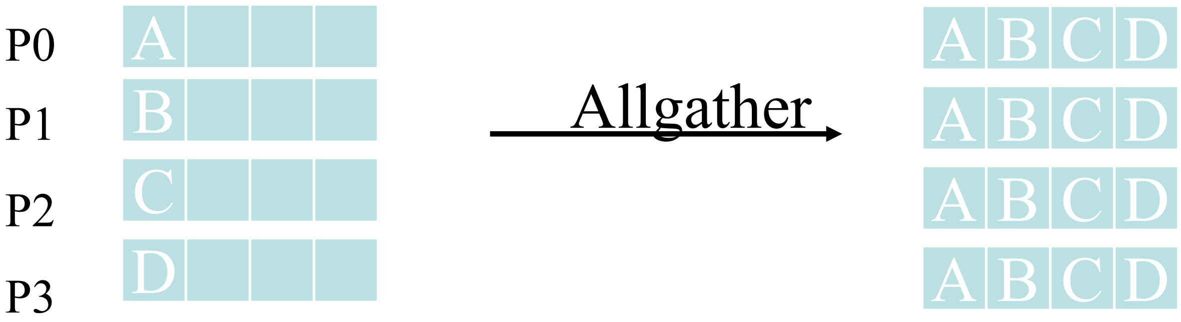


A version of Get_input that uses MPI_Bcast in the trapezoidal program



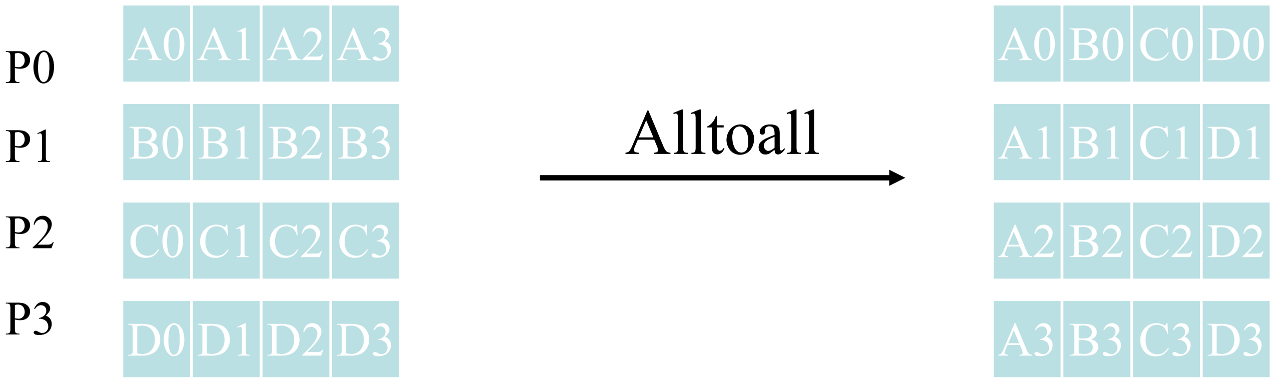
```
void Get_input(
      int      my_rank  /* in  */,
      int      comm_sz  /* in  */,
      double*  a_p      /* out */,
      double*  b_p      /* out */,
      int*     n_p      /* out */) {

   if (my_rank == 0) {
      printf("Enter a, b, and n\n");
      scanf("%lf %lf %d", a_p, b_p, n_p);
   }
   MPI_Bcast(a_p, 1, MPI_DOUBLE, 0, MPI_COMM_WORLD);
   MPI_Bcast(b_p, 1, MPI_DOUBLE, 0, MPI_COMM_WORLD);
   MPI_Bcast(n_p, 1, MPI_INT, 0, MPI_COMM_WORLD);
}  /* Get_input */
```

Collective Data Movement: Allgather and AlltoAll



Allgather

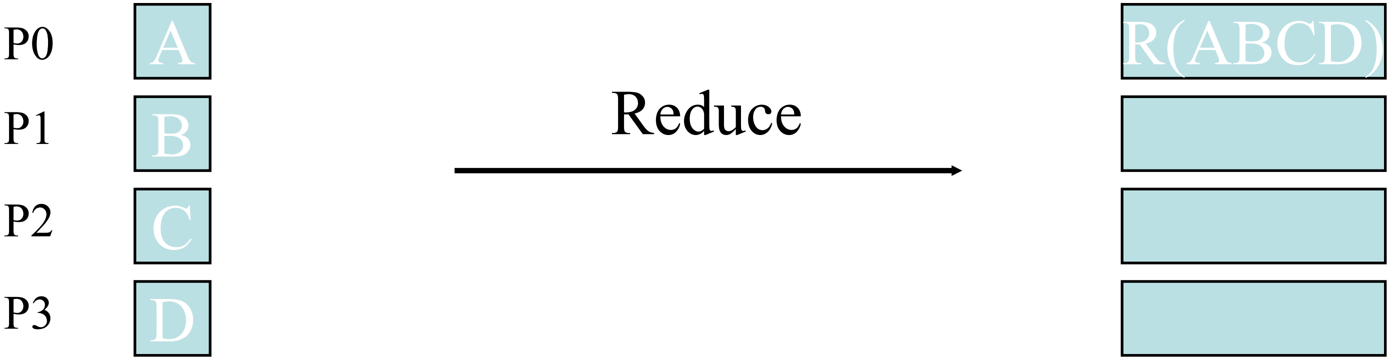
						→				
P0	A						A	B	C	D
P1	B						A	B	C	D
P2	C						A	B	C	D
P3	D						A	B	C	D

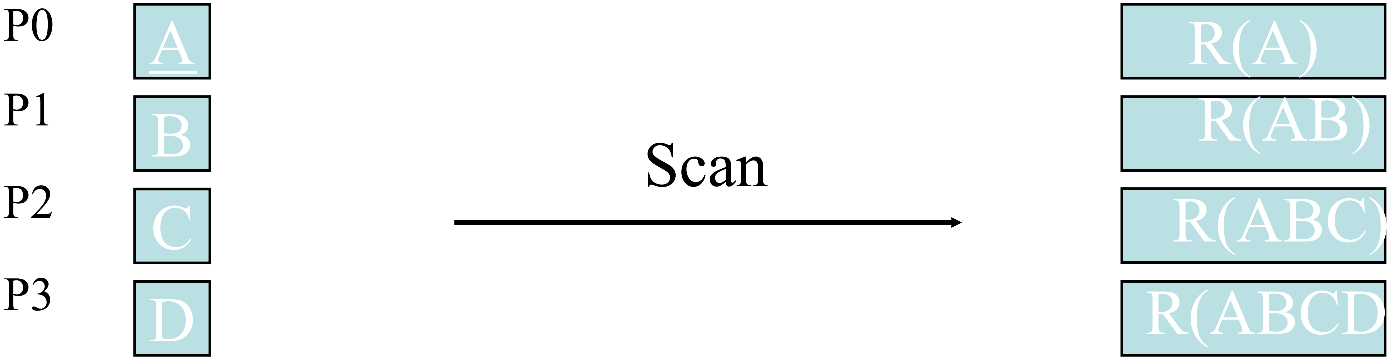


Alltoall

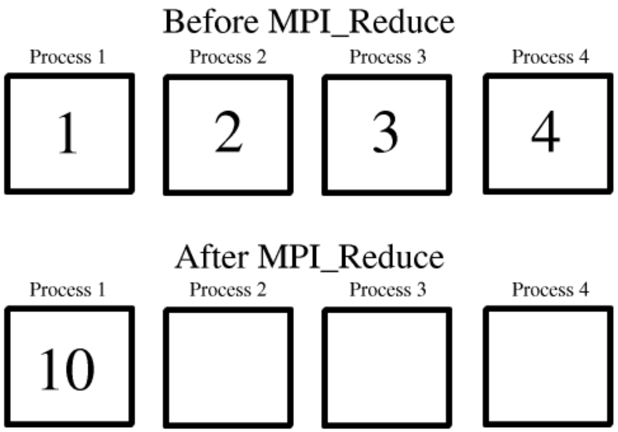
P0	A0	A1	A2	A3		A0	B0	C0	D0
P1	B0	B1	B2	B3		A1	B1	C1	D1
P2	C0	C1	C2	C3		A2	B2	C2	D2
P3	D0	D1	D2	D3		A3	B3	C3	D3

Collective Computation: Reduce vs. Scan





MPI_Reduce



Before MPI_Reduce

Process 1 Process 2 Process 3 Process 4

1 2 3 4

After MPI_Reduce

Process 1 Process 2 Process 3 Process 4

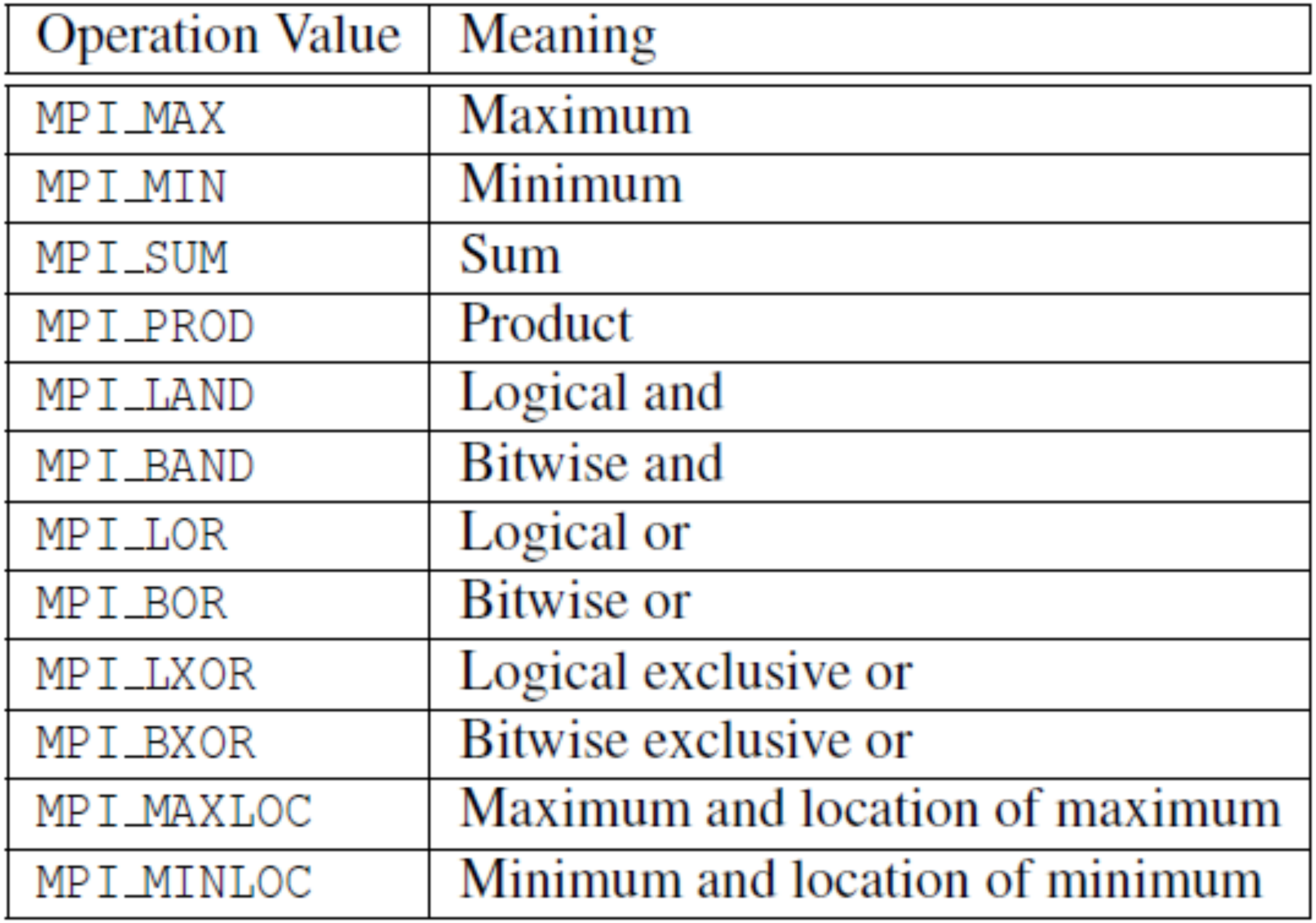
10

```
int MPI_Reduce(
      void*          input_data_p   /* in  */,
      void*          output_data_p  /* out */,
      int            count          /* in  */,
      MPI_Datatype   datatype       /* in  */,
      MPI_Op         operator       /* in  */,
      int            dest_process   /* in  */,
      MPI_Comm       comm           /* in  */);
```

```
MPI_Reduce(&local_int, &total_int, 1, MPI_DOUBLE, MPI_SUM, 0,
      MPI_COMM_WORLD);
```

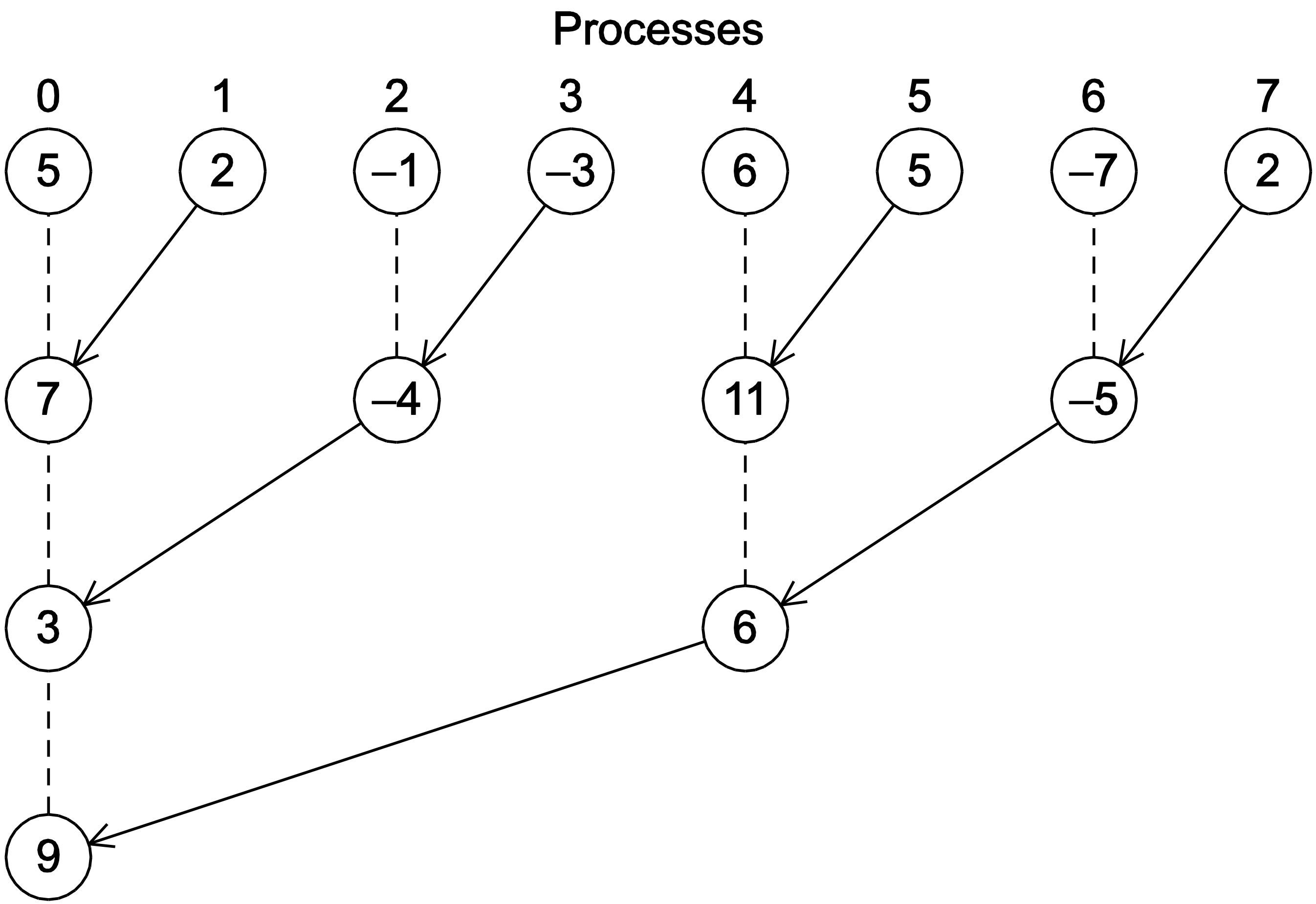
```
double local_x[N], sum[N];
. . .
MPI_Reduce(local_x, sum, N, MPI_DOUBLE, MPI_SUM, 0,
      MPI_COMM_WORLD);
```

Predefined reduction operators in MPI



Operation Value	Meaning
MPI_MAX	Maximum
MPI_MIN	Minimum
MPI_SUM	Sum
MPI_PROD	Product
MPI_LAND	Logical and
MPI_BAND	Bitwise and
MPI_LOR	Logical or
MPI_BOR	Bitwise or
MPI_LXOR	Logical exclusive or
MPI_BXOR	Bitwise exclusive or
MPI_MAXLOC	Maximum and location of maximum
MPI_MINLOC	Minimum and location of minimum

Implementation View of Global Reduction using a tree-structured sum

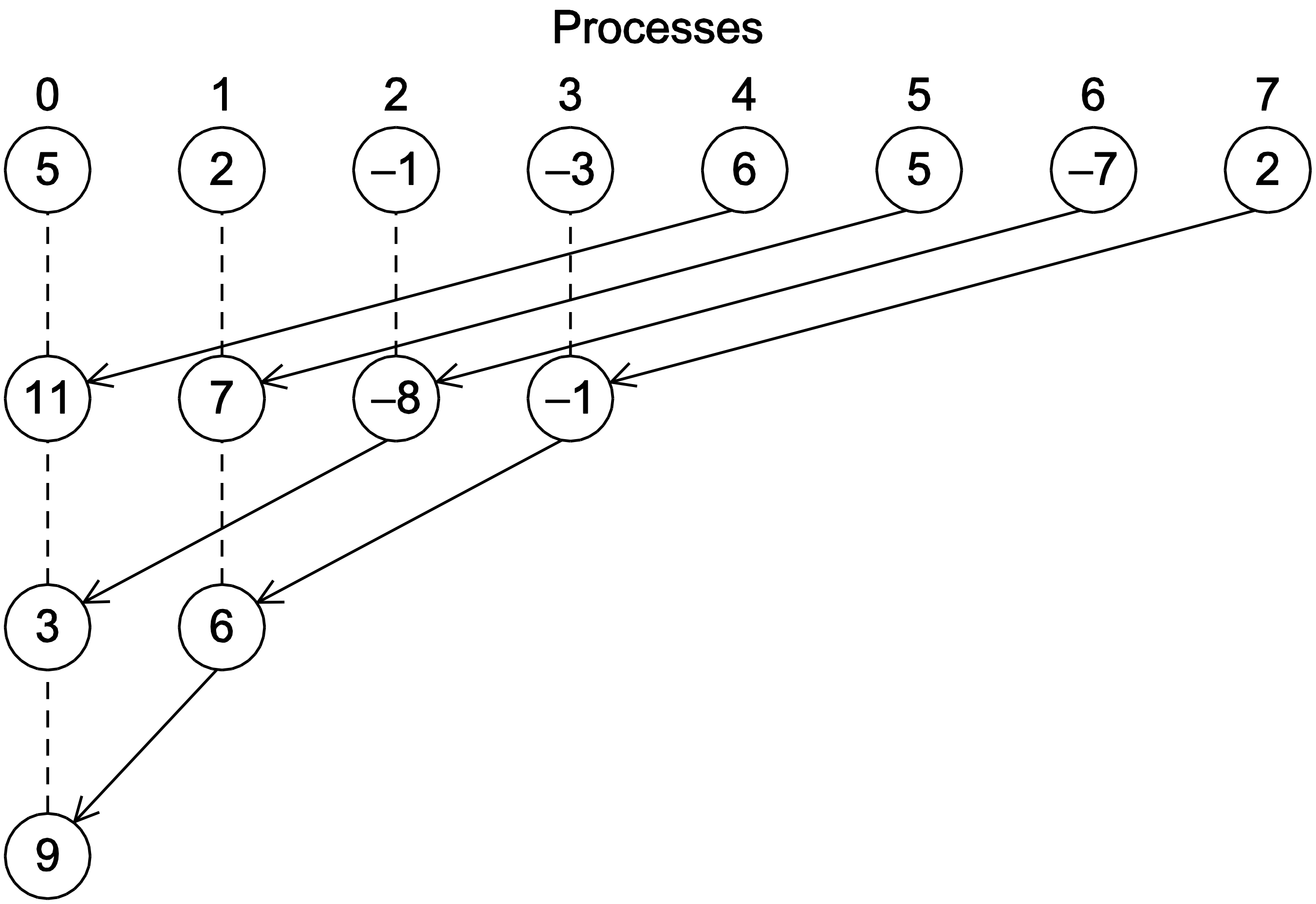


Implementation view: Tree-structured global reduction with sum operator

1. In the first phase:
   (a) Process 1 sends to 0, 3 sends to 2, 5 sends to 4, and 7 sends to 6.
   (b) Processes 0, 2, 4, and 6 add in the received values.
   (c) Processes 2 and 6 send their new values to processes 0 and 4, respectively.
   (d) Processes 0 and 4 add the received values into their new values.

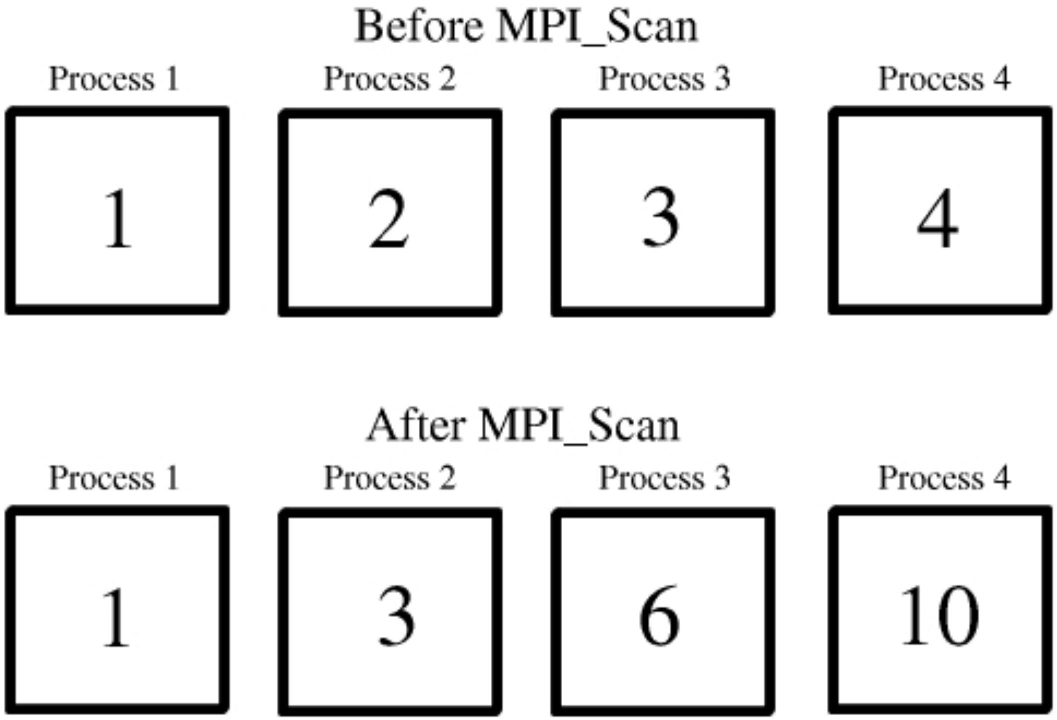
2. (a) Process 4 sends its newest value to process 0.
   (b) Process 0 adds the received value to its newest value.

An alternative tree-structured global sum



MPI Scan

```
MPI_Scan( void *sendbuf, void *recvbuf,  int count,
   MPI_Datatype datatype, MPI_Op op, MPI_Comm comm );
```



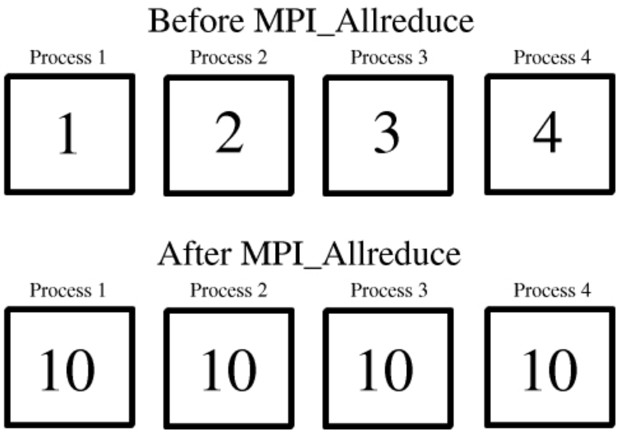
Before MPI_Scan

Process 1	Process 2	Process 3	Process 4
1	2	3	4

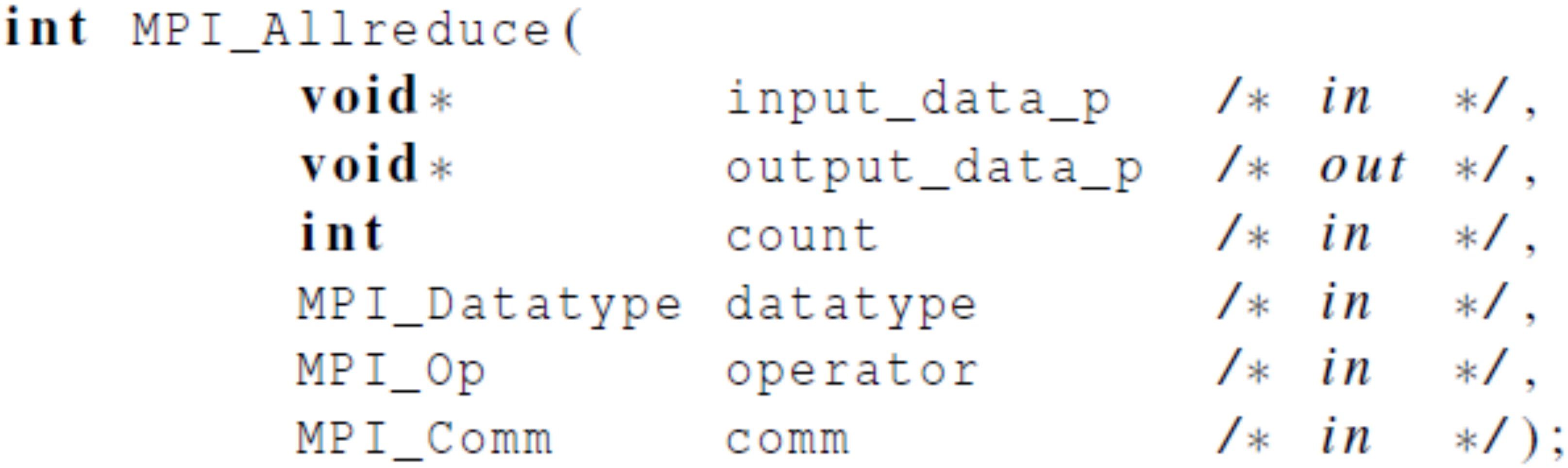
After MPI_Scan

Process 1	Process 2	Process 3	Process 4
1	3	6	10

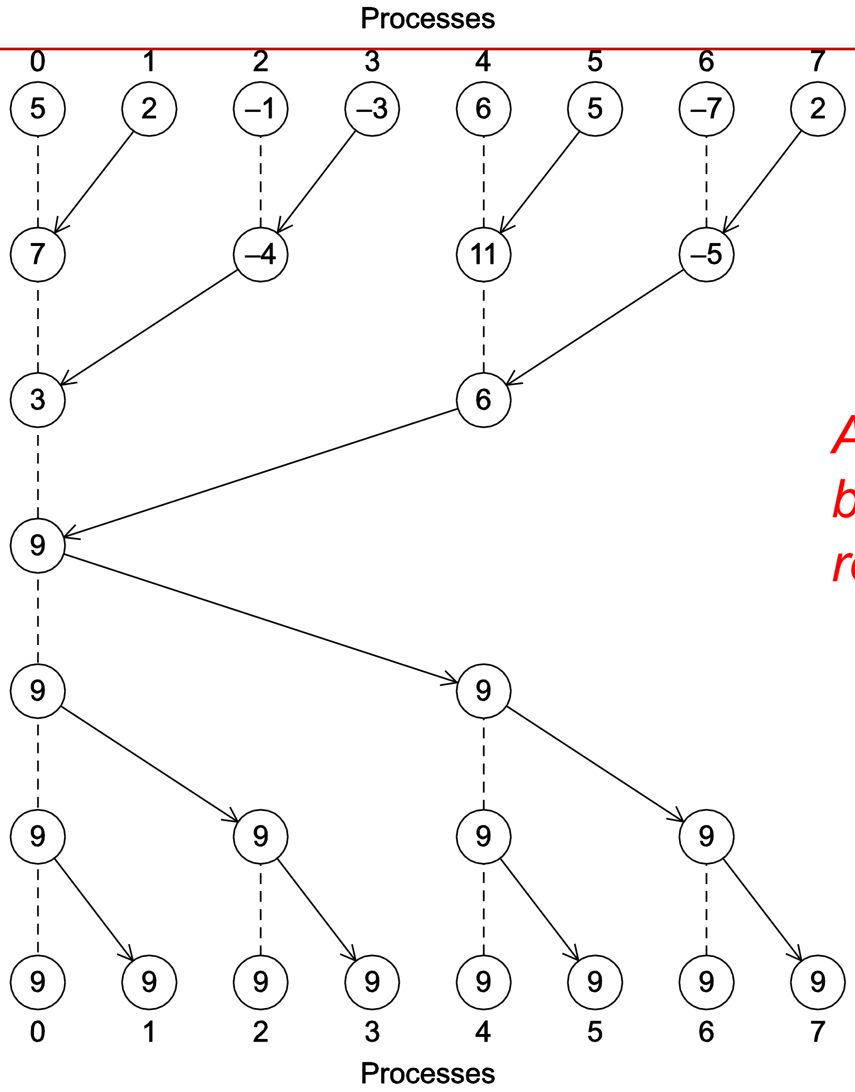
MPI_Allreduce



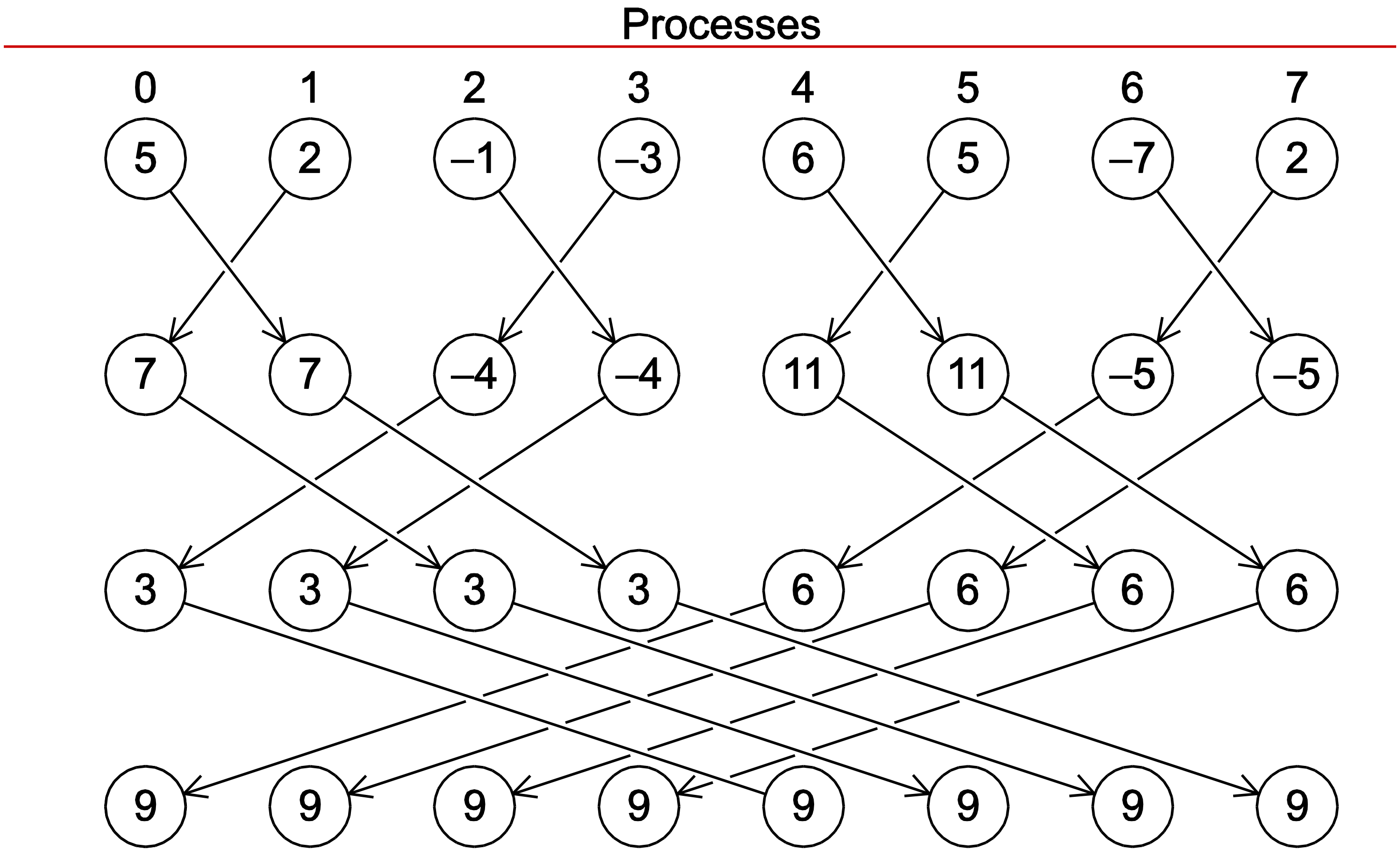
- **Useful in a situation in which all of the processes need the result of a global sum in order to complete some larger computation.**



```
int MPI_Allreduce(
          void*         input_data_p   /* in  */,
          void*         output_data_p  /* out */,
          int           count          /* in  */,
          MPI_Datatype  datatype       /* in  */,
          MPI_Op        operator       /* in  */,
          MPI_Comm      comm           /* in  */);
```



A global sum followed by distribution of the result.



A butterfly-structured global sum.

MPI Collective Routines: Summary

- Many Routines: `Allgather, Allgatherv, Allreduce, Alltoall, Alltoallv, Bcast, Gather, Gatherv, Reduce, Reduce_scatter, Scan, Scatter, Scatterv`
- `All` versions deliver results to all participating processes.
- V versions allow the hunks to have variable sizes.
- `Allreduce`, `Reduce`, `Reduce_scatter`, and `Scan` take both built-in and user-defined combiner functions.
- MPI-2 adds `Alltoallw`, `Exscan`, intercommunicator versions of most routines

Example of MPI PI program using 6 Functions

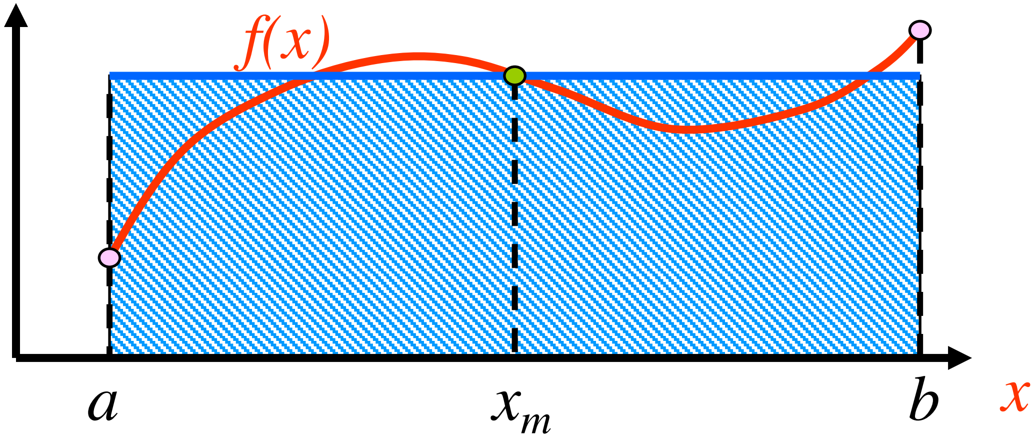
$$\pi = 4\int_0^1 \frac{1}{1+x^2}\,dx$$

- Using basic MPI functions:
  - `MPI_INIT`
  - `MPI_FINALIZE`
  - `MPI_COMM_SIZE`
  - `MPI_COMM_RANK`
- Using MPI collectives:
  - `MPI_BCAST`
  - `MPI_REDUCE`

Slide source: Bill Gropp, ANL

Midpoint Rule for $\pi = 4\int_0^1 \frac{1}{1+x^2}\,dx$

$$\int_a^b f(x)dx \approx (b-a)f(x_m)$$



$$\int_{x=0}^1 \frac{1}{1+x^2} \approx \sum_{i=1}^n \frac{1}{1+(\frac{i-0.5}{n})^2}$$

Example: PI in C - 1

$$\pi = 4\int_0^1 \frac{1}{1+x^2}\,\mathrm{d}x$$

```
#include "mpi.h"
#include <math.h>
   #include <stdio.h>
int main(int argc, char *argv[])
{
   int done = 0, n, myid, numprocs, i, rc;
   double PI25DT = 3.141592653589793238462643;
   double mypi, pi, h, sum, x, a;
   MPI_Init(&argc,&argv);
   MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
   MPI_Comm_rank(MPI_COMM_WORLD,&myid);
```

```
   while (!done)  {
     if (myid == 0) {
       printf("Enter the number of intervals: (0 quits) ");
       scanf("%d",&n);
     }
   MPI_Bcast(&n, 1, MPI_INT, 0, MPI_COMM_WORLD);
   if (n == 0) break;
```

Input and broadcast parameters

Slide source: Bill Gropp, ANL

Example: PI in C - 2

$$\int_{x=0}^{1} \frac{1}{1+x^2} \approx \sum_{i=1}^{n} \frac{1}{1+(\frac{i-0.5}{n})^2}$$

```
h   = 1.0 / (double) n;
sum = 0.0;
for (i = myid + 1; i <= n; i += numprocs) {
  x = h * ((double)i - 0.5);
  sum += 4.0 / (1.0 + x*x);
}
mypi = h * sum;
```

Compute local pi values

```
MPI_Reduce(&mypi, &pi, 1, MPI_DOUBLE, MPI_SUM, 0,
           MPI_COMM_WORLD);
```

Compute summation

```
  if (myid == 0)
    printf("pi is approximately %.16f, Error is .16f\n",
           pi, fabs(pi - PI25DT));
 }
 MPI_Finalize();
 return 0;
}
```

Slide source: Bill Gropp, ANL

Collective vs. Point-to-Point Communications

- **All the processes in the communicator must call the same collective function.**
  - Will this program work?

```
if(my_rank==0)  MPI_Reduce(&a,&b,1, MPI_INT,
   MPI_SUM, 0, MPI_COMM_WORLD);
else MPI_Recv(&a, MPI_INT, MPI_SUM,0,0,
   MPI_COMM_WORLD);
```

Collective vs. Point-to-Point Communications

- **All the processes in the communicator must call the same collective function.**
  - For example, a program that attempts to match a call to MPI_Reduce on one process with a call to MPI_Recv on another process is erroneous, and, in all likelihood, the program will hang or crash.

```
if(my_rank==0)  MPI_Reduce(&a,&b,1, MPI_INT,
    MPI_SUM, 0, MPI_COMM_WORLD);
else MPI_Recv(&a, MPI_INT, MPI_SUM,0,0,
    MPI_COMM_WORLD);
```

Collective vs. Point-to-Point Communications

- **The arguments passed by each process to an MPI collective communication must be "compatible."**
  - Will this program work?

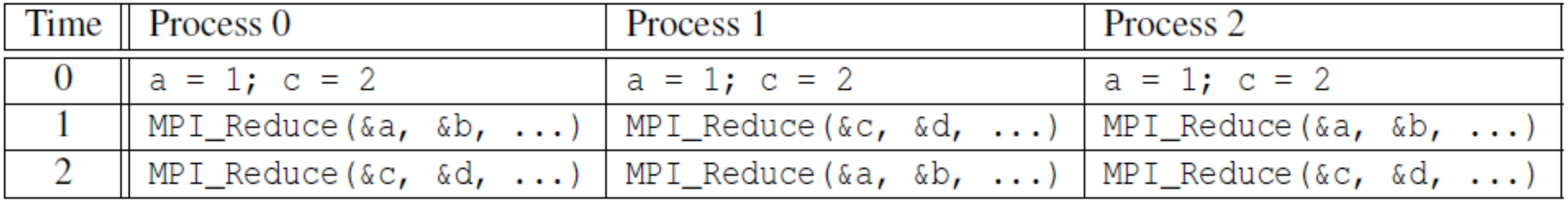
```
if(my_rank==0)  MPI_Reduce(&a,&b,1, MPI_INT,
   MPI_SUM, 0, MPI_COMM_WORLD);
else MPI_Reduce(&a,&b,1, MPI_INT, MPI_SUM, 1,
   MPI_COMM_WORLD);
```

Collective vs. Point-to-Point Communications

- **The arguments passed by each process to an MPI collective communication must be "compatible."**
  - For example, if one process passes in 0 as the dest_process and another passes in 1, then the outcome of a call to MPI_Reduce is erroneous, and, once again, the program is likely to hang or crash.

```
if(my_rank==0)  MPI_Reduce(&a,&b,1, MPI_INT,
   MPI_SUM, 0, MPI_COMM_WORLD);
else MPI_Reduce(&a,&b,1, MPI_INT, MPI_SUM, 1,
   MPI_COMM_WORLD);
```

Example of MPI_Reduce execution

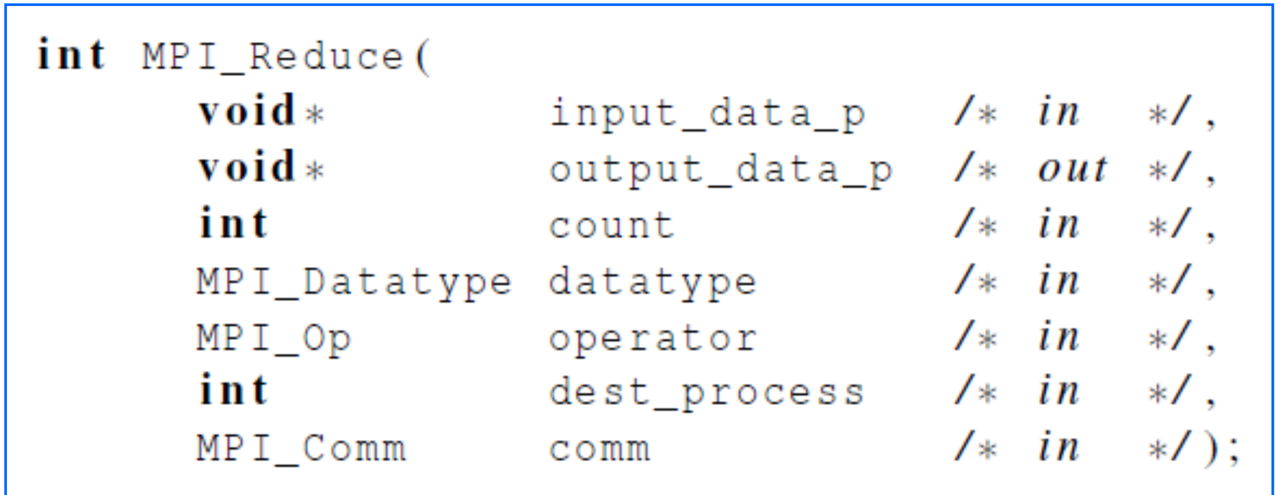


Time	Process 0	Process 1	Process 2
0	`a = 1; c = 2`	`a = 1; c = 2`	`a = 1; c = 2`
1	`MPI_Reduce(&a, &b, ...)`	`MPI_Reduce(&c, &d, ...)`	`MPI_Reduce(&a, &b, ...)`
2	`MPI_Reduce(&c, &d, ...)`	`MPI_Reduce(&a, &b, ...)`	`MPI_Reduce(&c, &d, ...)`

Multiple calls to MPI_Reduce with MPI_SUM and Proc 0 as destination (root)

Is b=3 on Proc 0 after two MPI_Reduce() calls?

Is d=6 on Proc 0?

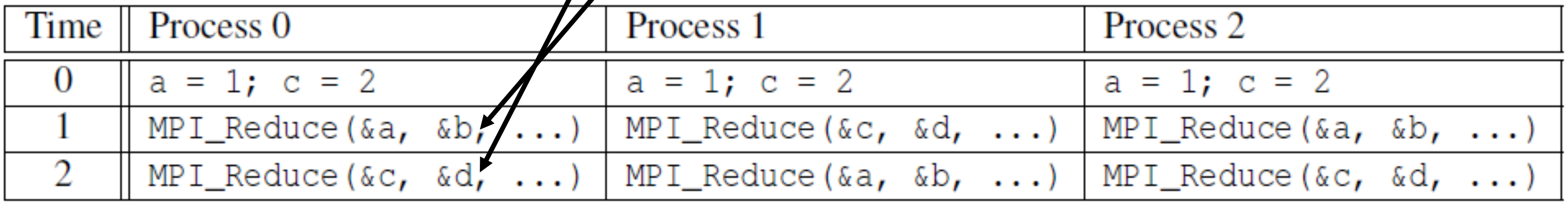


```
int MPI_Reduce(
      void*         input_data_p   /* in   */,
      void*         output_data_p  /* out  */,
      int           count          /* in   */,
      MPI_Datatype  datatype       /* in   */,
      MPI_Op        operator       /* in   */,
      int           dest_process   /* in   */,
      MPI_Comm      comm           /* in   */);
```

Example: Output results

- However, the names of the memory locations are irrelevant to the matching of the calls to MPI_Reduce.

- The order of the calls will determine the matching so the value stored in b will be 1+2+1 = 4, and the value stored in d will be 2+1+2 = 5.



Time	Process 0	Process 1	Process 2
0	`a = 1; c = 2`	`a = 1; c = 2`	`a = 1; c = 2`
1	`MPI_Reduce(&a, &b, ...)`	`MPI_Reduce(&c, &d, ...)`	`MPI_Reduce(&a, &b, ...)`
2	`MPI_Reduce(&c, &d, ...)`	`MPI_Reduce(&a, &b, ...)`	`MPI_Reduce(&c, &d, ...)`

Parallel Matrix Vector Multiplication

Collective Communication Application

Textbook p. 113-116

Matrix-vector multiplication: y= A * x

$$\begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{pmatrix} * \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} = \begin{pmatrix} 1*1+2*2+3*3 \\ 4*1+5*2+6*3 \\ 7*1+8*2+9*3 \end{pmatrix} = \begin{pmatrix} 14 \\ 32 \\ 50 \end{pmatrix}$$

Problem: $y = A * x$ where A is a $n \times n$ matrix and x is a column vector of dimension n.

Sequential code:

```
for $i = 1$ to $n$ do
    $y_i = 0;$
    for $j = 1$ to $n$ do
        $y_i = y_i + a_{i,j} * x_j;$
   endfor
endfor
```

Partitioning and Task graph for matrix-vector multiplication

Partitioned code:

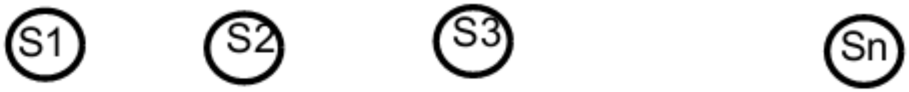
```
for $i = 1$ to $n$ do
    $S_i$ :    $y_i = 0$;
               for $j = 1$ to $n$ do
                   $y_i = y_i + a_{i,j} * x_j$;
               endfor
endfor
```

S_i : Read row A_i and vector x.

Write element y_i

$y_i = Row\ A_i * x$

Task graph:



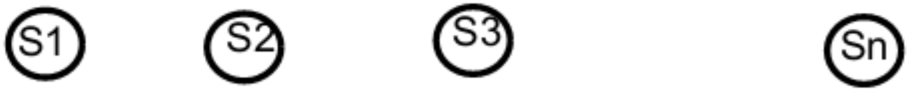
Execution Schedule and Task Mapping

S_i : Read row A_i and vector x.

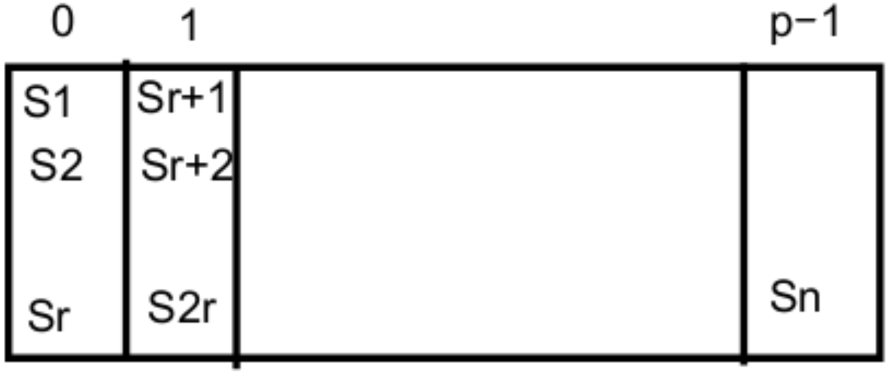
Write element y_i

$y_i = Row\ A_i\ ^{*}\ x$

Task graph:



Schedule:



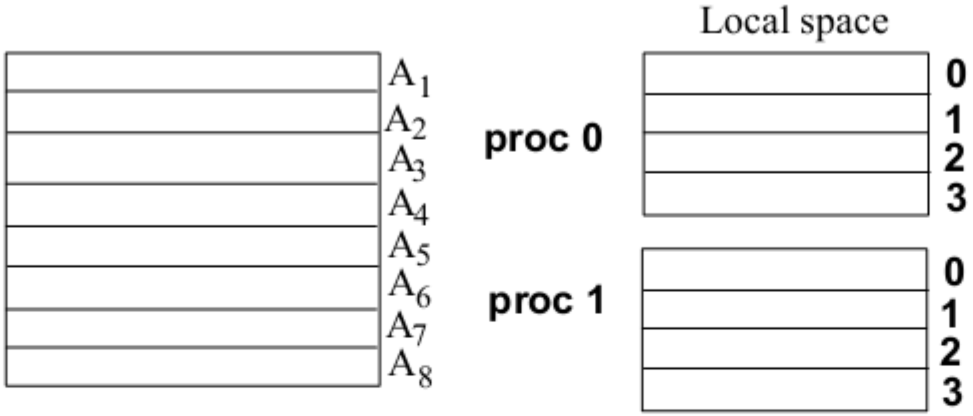
Mapping function of tasks S_i:

$$proc\_map(i) = \lfloor \frac{i-1}{r} \rfloor \text{ where } r = \lceil \frac{n}{p} \rceil.$$

Data Partitioning and Mapping for y= A*x

Data partitioning: for the above schedule:

Matrix A is divided into n rows $A_1, A_2, \cdots A_n$.

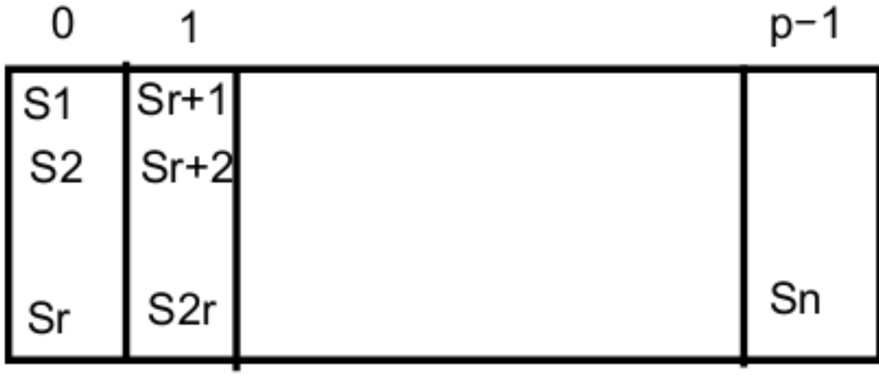


Data mapping:

Row A_i is mapped to processor $proc\_map(i)$, the same as task i. The indexing function is: $local(i) = (i-1) \bmod r$. Vectors x and y are replicated to all processors.

SPMD Code for y= A*x

Schedule:



0 1 p−1

S1 S2 Sr

Sr+1 Sr+2 S2r

Sn

```
int x[n], y[n], a[r][n];
me=mynode();
for $i = 1$ to $n$ do
    if $proc\_map(i) == me$, then do $S_i$:
        $S_i$ :    $y[i] = 0;$
               for $j = 1$ to $n$ do
                 $y[i] = y[i] + a[local(i)][j] * x[j];$
               endfor
endfor
```

Evaluation: Parallel Time

- Ignore the cost of local address calculation.

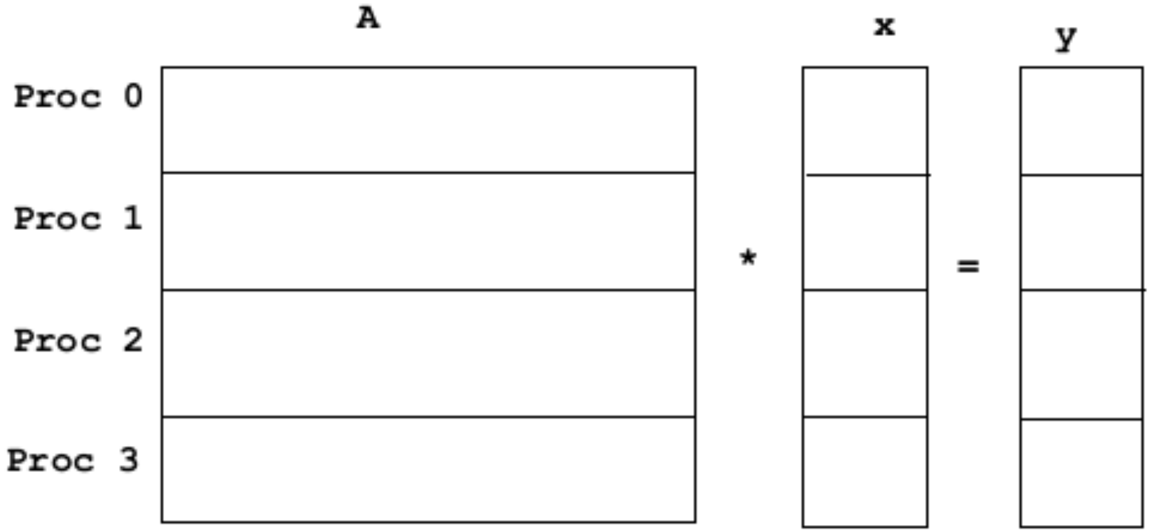
- Each task performs *n* additions and *n* multiplications.

- Each addition/multiplication costs ω

- The parallel time is approximately $\frac{n}{p} \times 2n\omega$

How is initial data distributed?

Assume initially matrix A and vector x are distributed evenly among processes

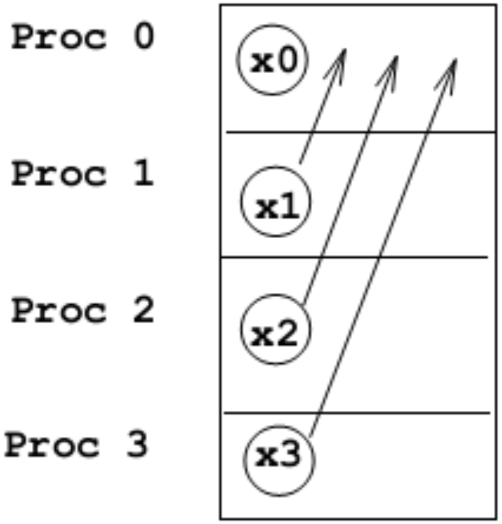


Need to redistribute vector *x* to everybody in order to perform parallel computation!

What MPI collective communication is needed?

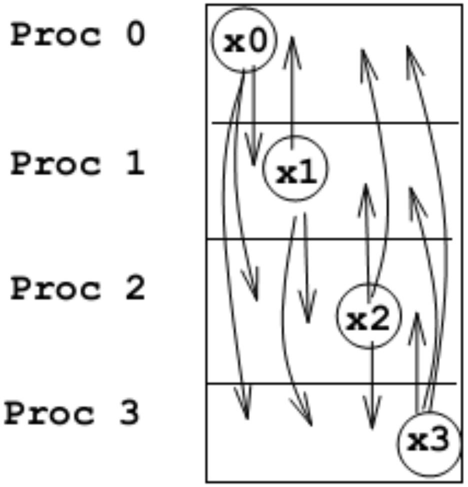
Communication Pattern for Data Redistribution

Data requirement for Process 0



MPI_Gather

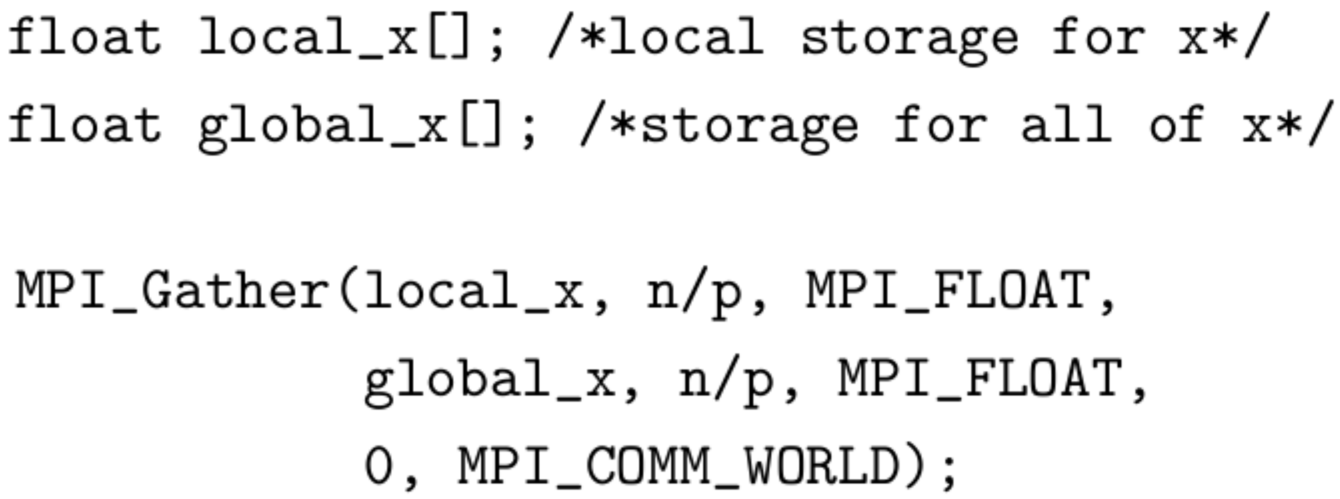
Data requirement for all processes



MPI_Allgather

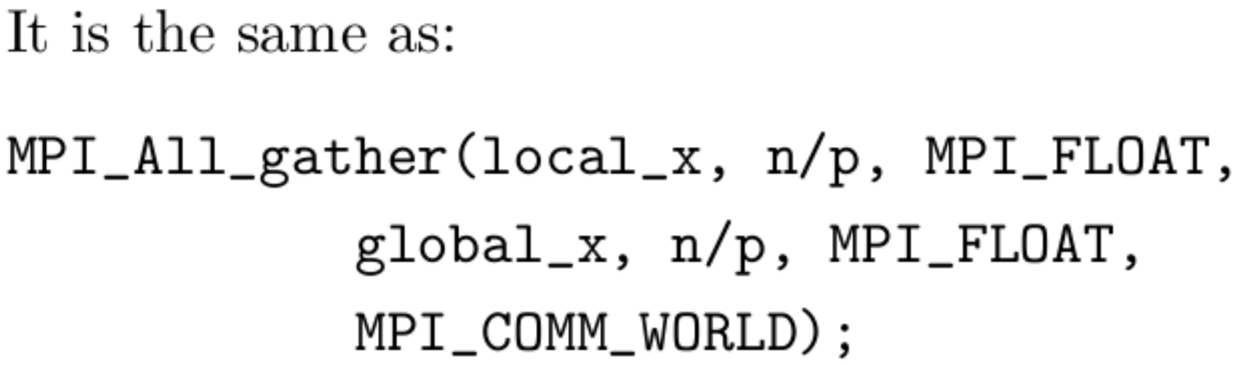
MPI Code for Gathering Data

Data gather for Process 0



```
float local_x[]; /*local storage for x*/
float global_x[]; /*storage for all of x*/

MPI_Gather(local_x, n/p, MPI_FLOAT,
           global_x, n/p, MPI_FLOAT,
           0, MPI_COMM_WORLD);
```

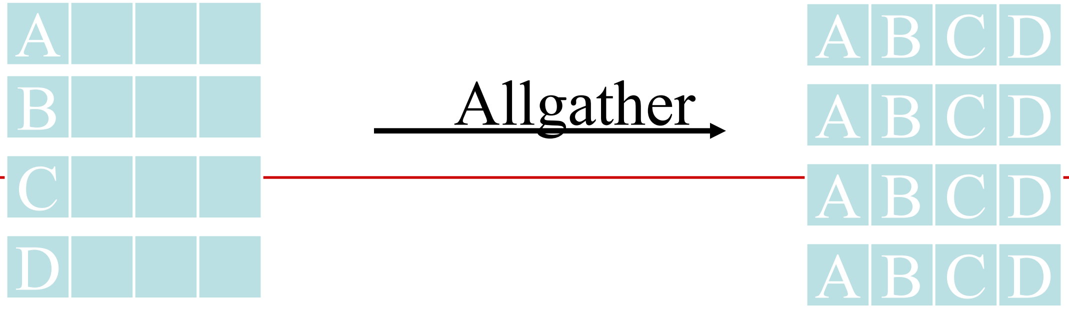
Repeat for all processes



It is the same as:

```
MPI_All_gather(local_x, n/p, MPI_FLOAT,
               global_x, n/p, MPI_FLOAT,
               MPI_COMM_WORLD);
```

Allgather

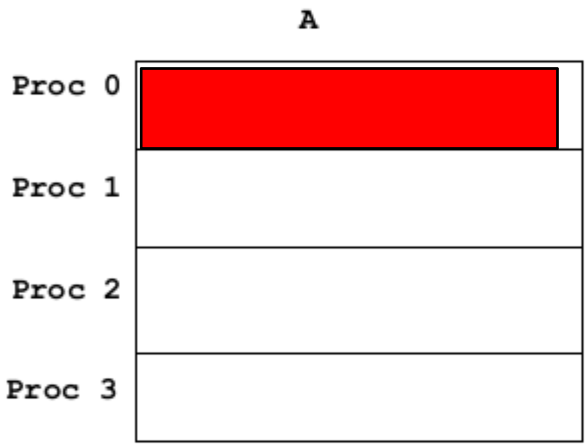


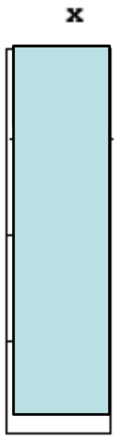
- Concatenates the contents of each process' send_buf_p and stores this in each process' recv_buf_p.
- As usual, recv_count is the amount of data being received from each process.

```
int MPI_Allgather(
      void*         send_buf_p   /* in  */,
      int           send_count   /* in   */,
      MPI_Datatype  send_type    /* in   */,
      void*         recv_buf_p   /* out  */,
      int           recv_count   /* in   */,
      MPI_Datatype  recv_type    /* in   */,
      MPI_Comm      comm         /* in   */);
```

MPI SPMD Code for y=A*x

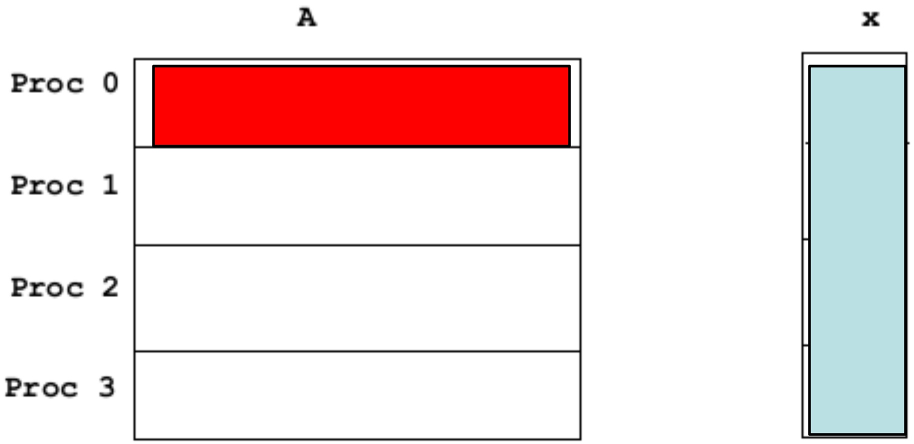
```
void Parallel_matrix_vector_prod(
         LOCAL_MATRIX_T  local_A
         int             m
         int             n
         float           local_x[]
         float           global_x[]
         float           local_y[]
         int             local_m
         int             local_n) {
 /* local_m = n/p, local_n = n/p */
 MPI_Allgather(local_x, local_n, MPI_FLOAT
               global_x, local_n, MPI_FLOAT,
                 MPI_COMM_WORLD);
```





MPI SPMD Code for y=A*x

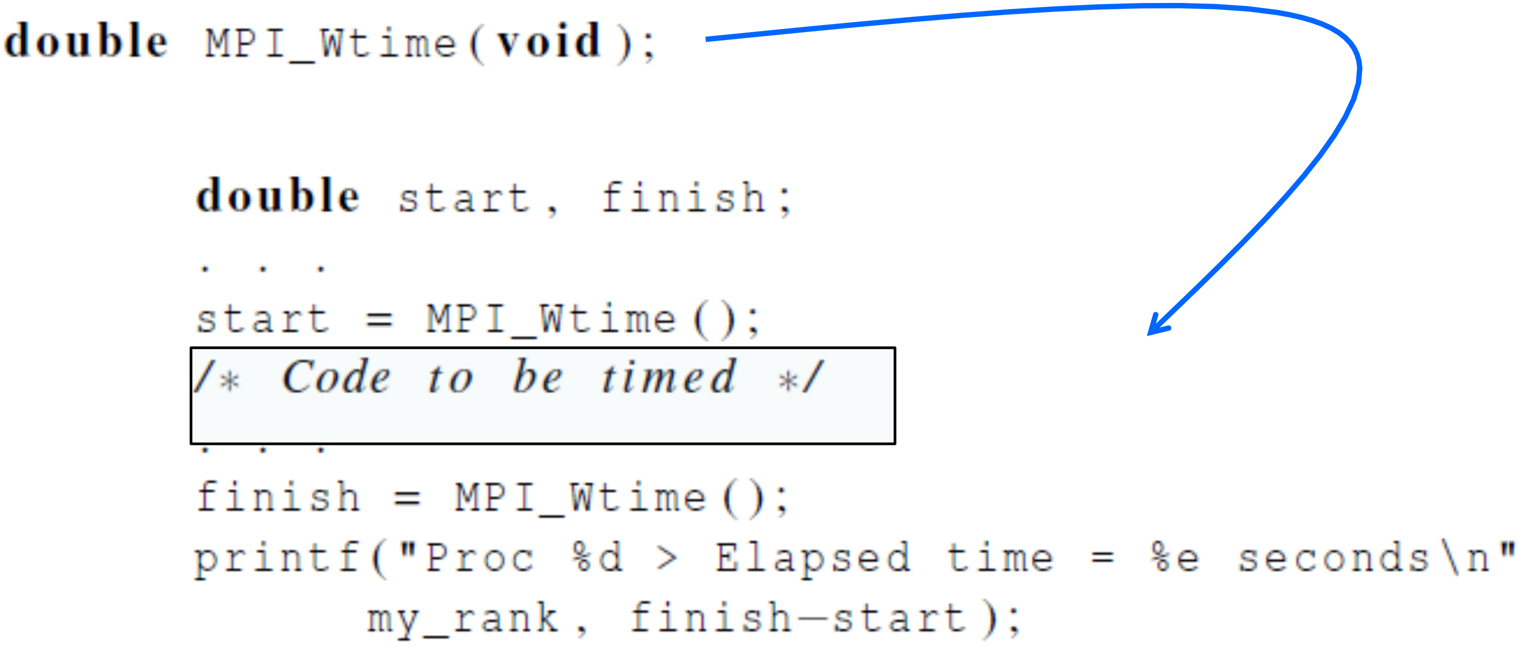
```
 for (i = 0; i < local_m; i++) {
    local_y[i] = 0.0;
    for (j = 0; j < n; j++)
     local_y[i] = local_y[i] +
       local_A[i][j]*global_x[j];
  }
}
```



Performance Evaluation of Matrix Vector Multiplication

How to measure elapsed parallel time

- Use MPI_Wtime() that returns the number of seconds that have elapsed since some time in the past.



```
double MPI_Wtime(void);

      double start, finish;
      . . .
      start = MPI_Wtime();
      /* Code to be timed */
      . . .
      finish = MPI_Wtime();
      printf("Proc %d > Elapsed time = %e seconds\n"
            my_rank, finish-start);
```

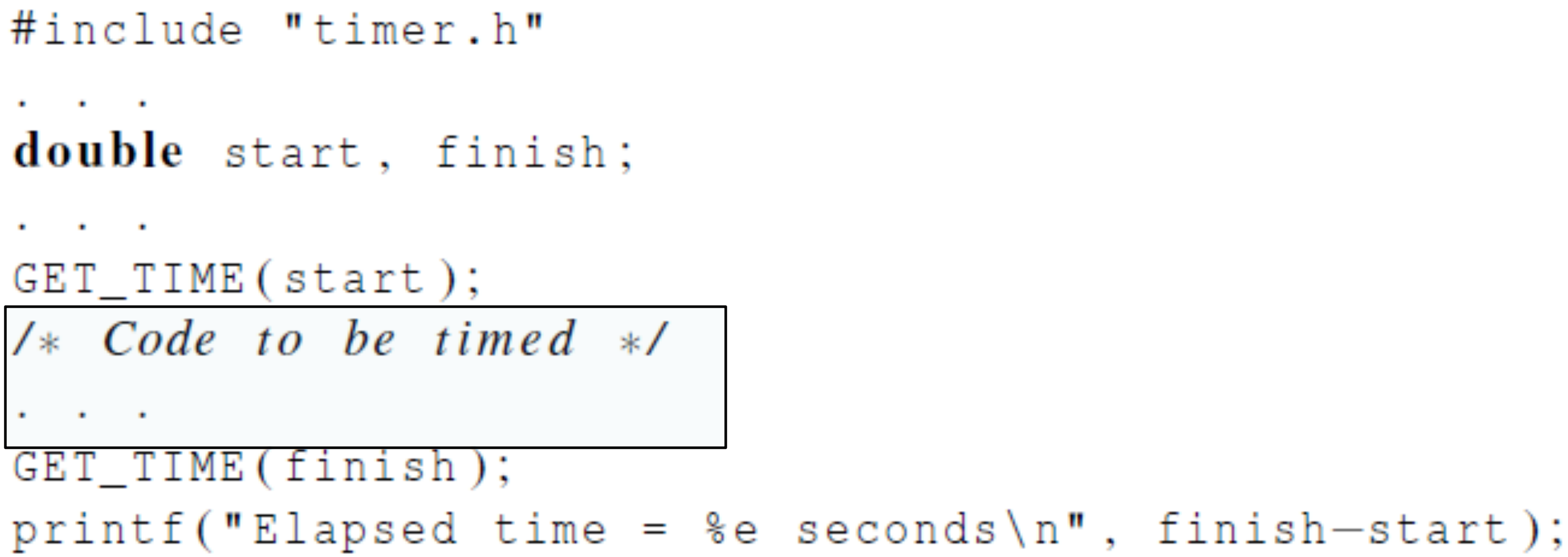
Measure elapsed sequential time in Linux

- This code works for Linux without using MPI functions
- Use GET_TIME() which returns time in microseconds elapsed from some point in the past.

- Sample code for GET_TIME()

```
  #include <sys/time.h>
/* The argument now should be a double (not a pointer to a
    double) */
 #define GET_TIME(now) {
      struct timeval t;
      gettimeofday(&t, NULL);
     now = t.tv_sec + t.tv_usec/1000000.0;
  }
```

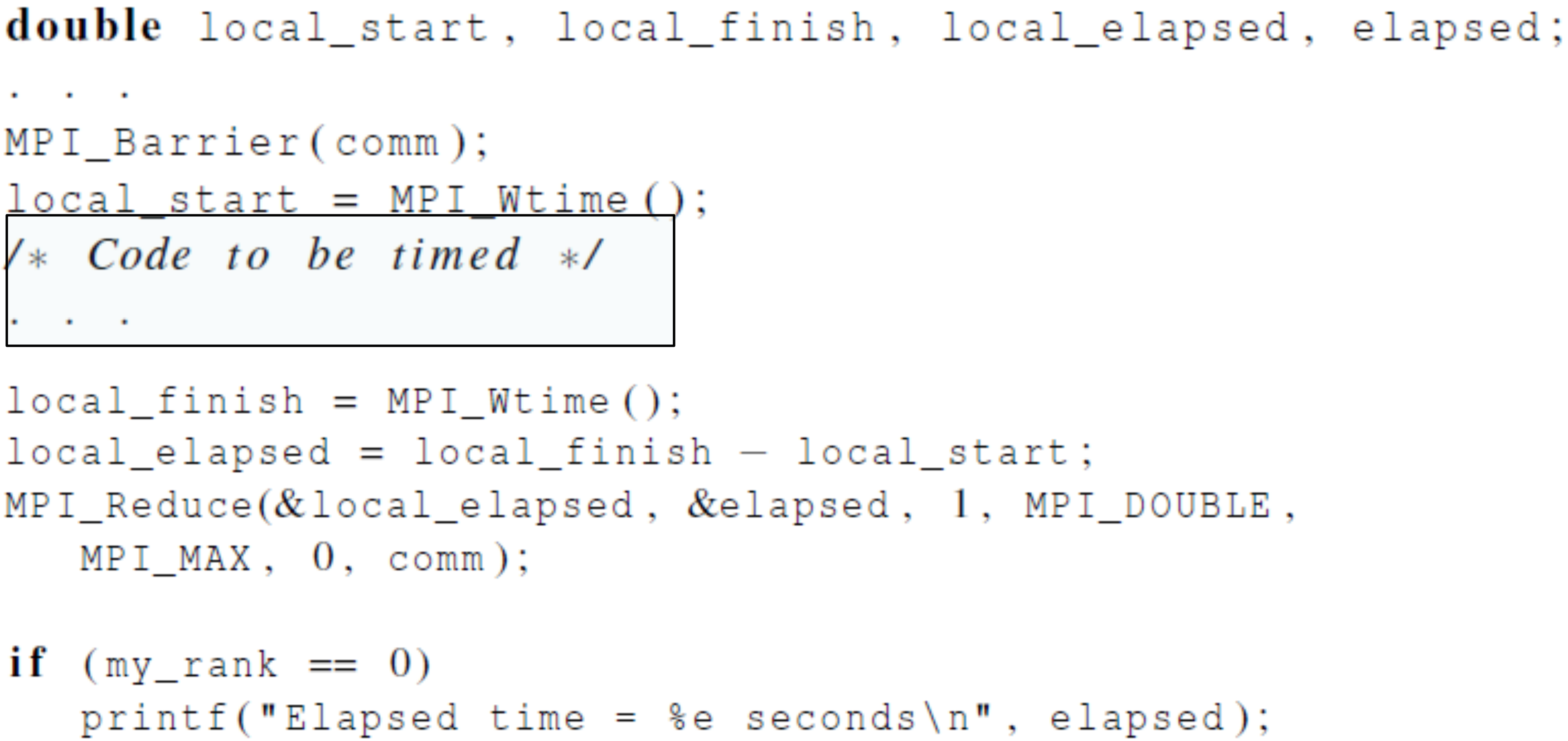
Measure elapsed sequential time



```
#include "timer.h"
. . .
double start, finish;
. . .
GET_TIME(start);
/* Code to be timed */
. . .
GET_TIME(finish);
printf("Elapsed time = %e seconds\n", finish-start);
```

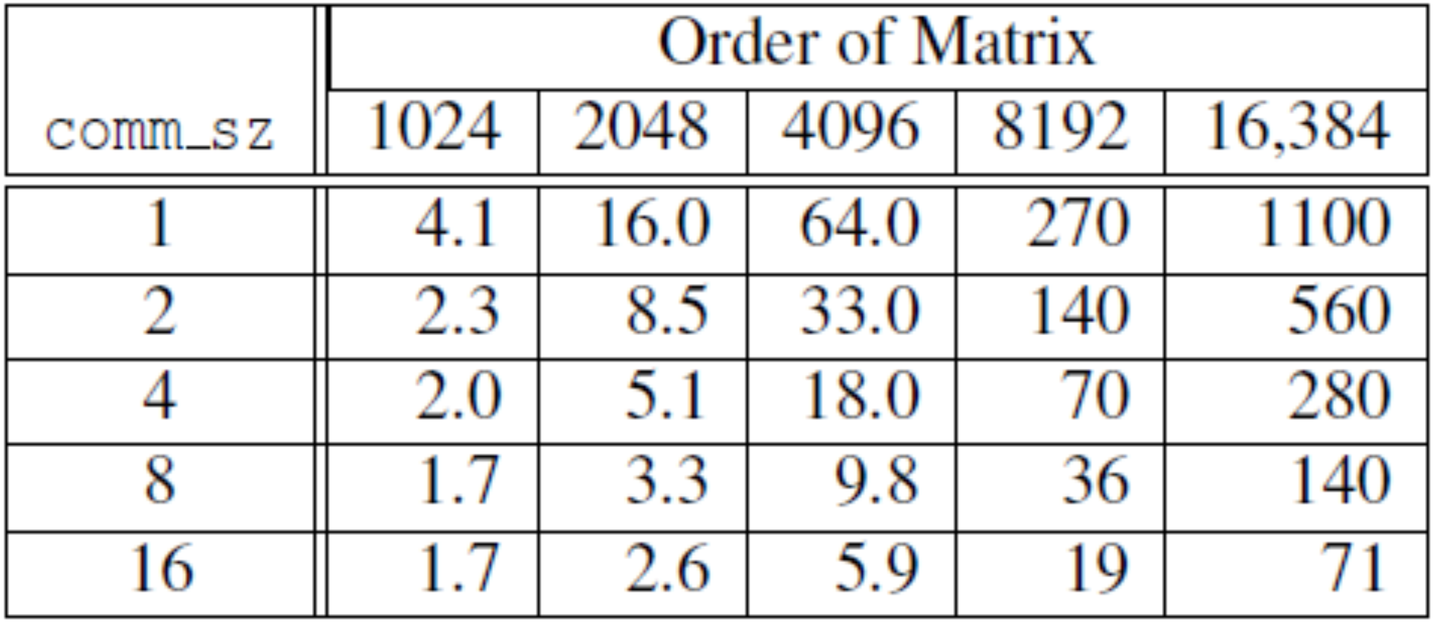
Use MPI_Barrier() before time measurement

Start timing until every process in the communicator has reached the same time stamp



```
double local_start, local_finish, local_elapsed, elapsed;
. . .
MPI_Barrier(comm);
local_start = MPI_Wtime();
/* Code to be timed */
. . .
local_finish = MPI_Wtime();
local_elapsed = local_finish − local_start;
MPI_Reduce(&local_elapsed, &elapsed, 1, MPI_DOUBLE,
   MPI_MAX, 0, comm);

if (my_rank == 0)
   printf("Elapsed time = %e seconds\n", elapsed);
```

Run-times of serial and parallel matrix-vector multiplication



comm_sz	Order of Matrix				
	1024	2048	4096	8192	16,384
1	4.1	16.0	64.0	270	1100
2	2.3	8.5	33.0	140	560
4	2.0	5.1	18.0	70	280
8	1.7	3.3	9.8	36	140
16	1.7	2.6	5.9	19	71

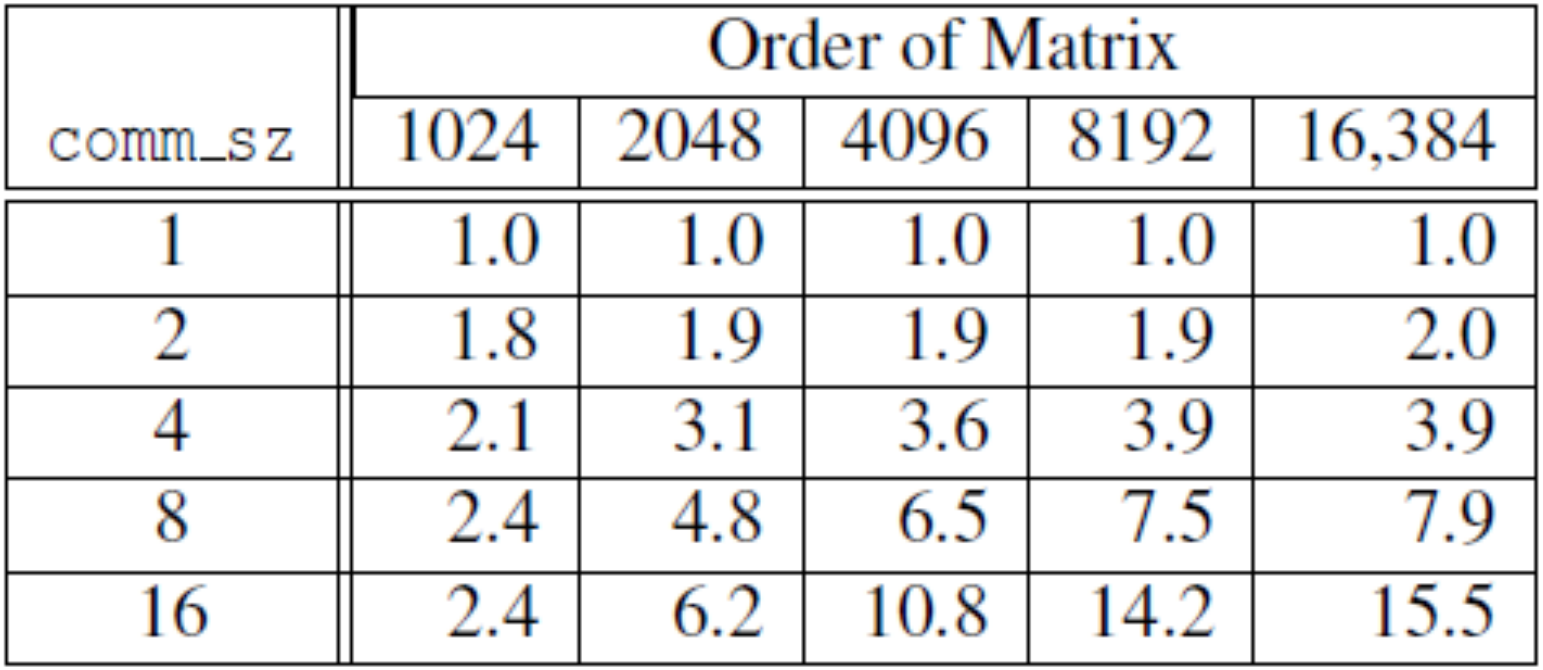
(Seconds)

Speedup and Efficiency

$$S(n,p) = \frac{T_{\text{serial}}(n)}{T_{\text{parallel}}(n,p)}$$

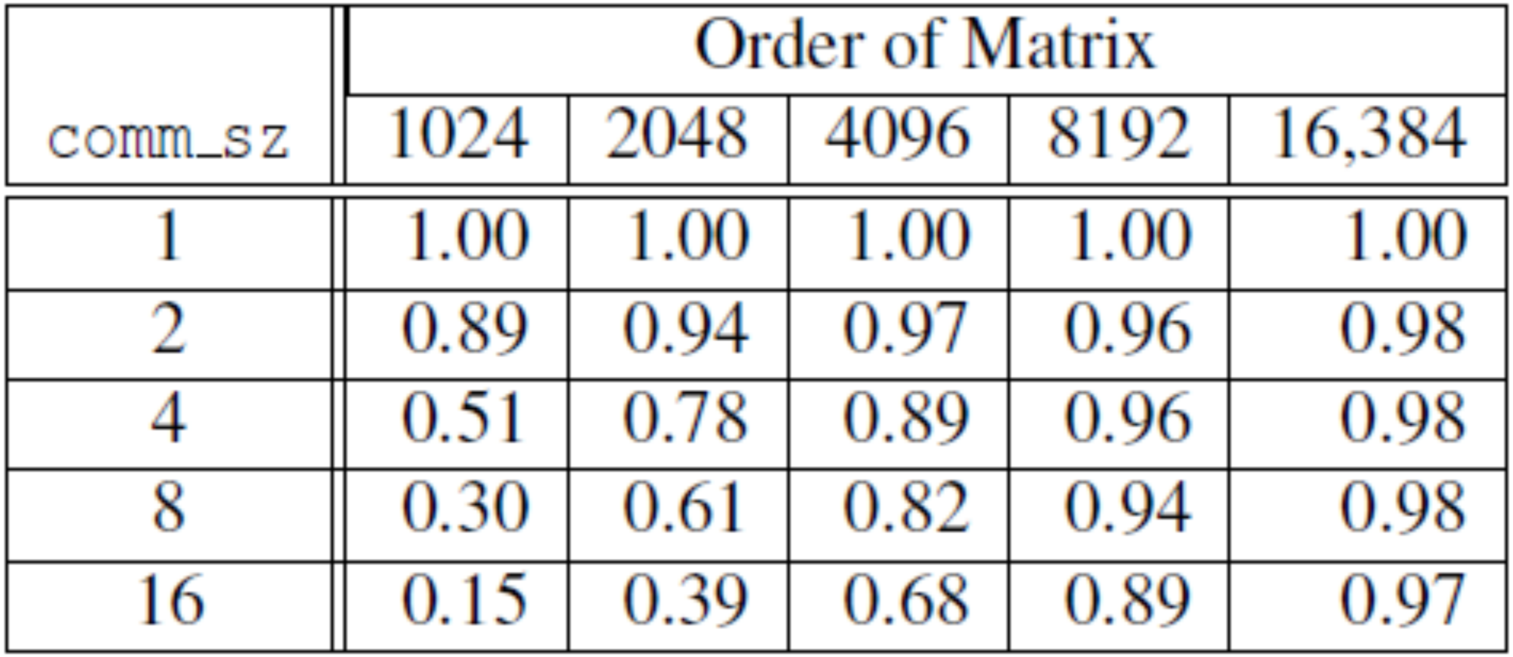
$$E(n,p) = \frac{S(n,p)}{p} = \frac{T_{\text{serial}}(n)}{p \times T_{\text{parallel}}(n,p)}$$

Speedups of Parallel Matrix-Vector Multiplication



	Order of Matrix				
comm_sz	1024	2048	4096	8192	16,384
1	1.0	1.0	1.0	1.0	1.0
2	1.8	1.9	1.9	1.9	2.0
4	2.1	3.1	3.6	3.9	3.9
8	2.4	4.8	6.5	7.5	7.9
16	2.4	6.2	10.8	14.2	15.5

Efficiencies of Parallel Matrix-Vector Multiplication



comm_sz	Order of Matrix				
	1024	2048	4096	8192	16,384
1	1.00	1.00	1.00	1.00	1.00
2	0.89	0.94	0.97	0.96	0.98
4	0.51	0.78	0.89	0.96	0.98
8	0.30	0.61	0.82	0.94	0.98
16	0.15	0.39	0.68	0.89	0.97

Scalability

- A program is scalable if the problem size can be increased at a rate so that the efficiency doesn’t decrease as the number of processes increase.

- Programs that can maintain a constant efficiency without increasing the problem size are sometimes said to be strongly scalable.

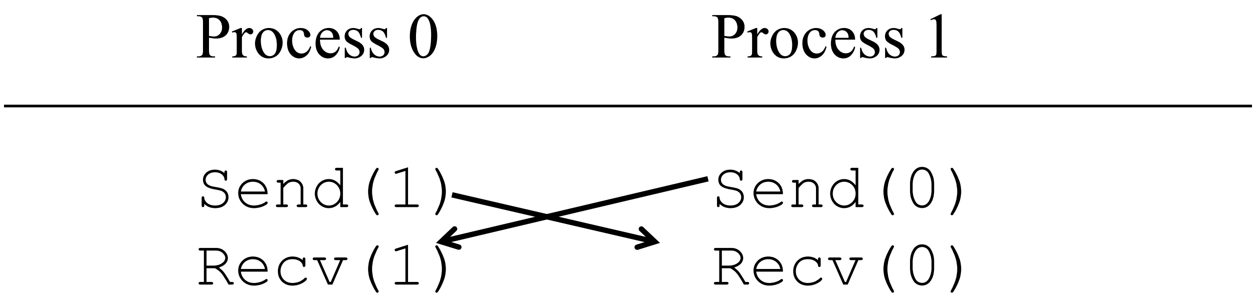
- Programs that can maintain a constant efficiency if the problem size increases at the same rate as the number of processes are sometimes said to be weakly scalable.

-

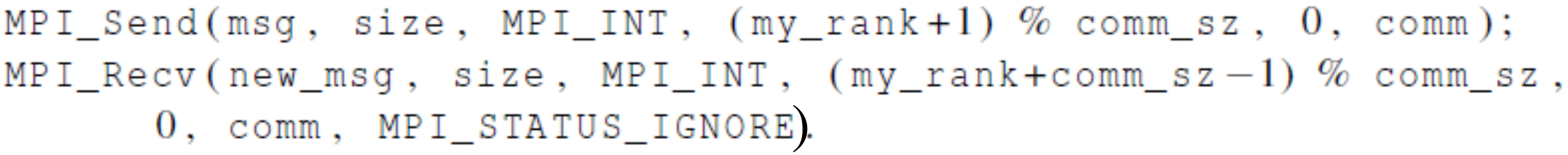
Safety Issues in MPI programs

Safety in MPI programs

- **Is it a safe program? (Assume tag/process ID is assigned properly)**



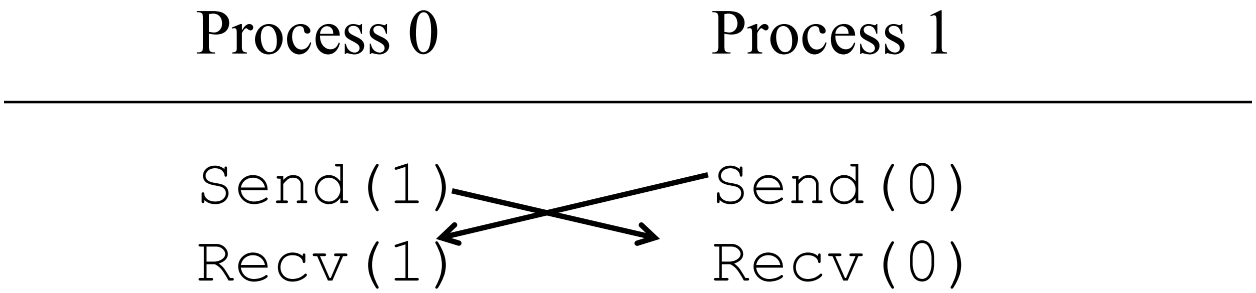
Process 0	Process 1
Send(1)	Send(0)
Recv(1)	Recv(0)



```
MPI_Send(msg, size, MPI_INT, (my_rank+1) % comm_sz, 0, comm);
MPI_Recv(new_msg, size, MPI_INT, (my_rank+comm_sz−1) % comm_sz,
      0, comm, MPI_STATUS_IGNORE).
```

Safety in MPI programs

- **Is it a safe program? (Assume tag/process ID is assigned properly)**

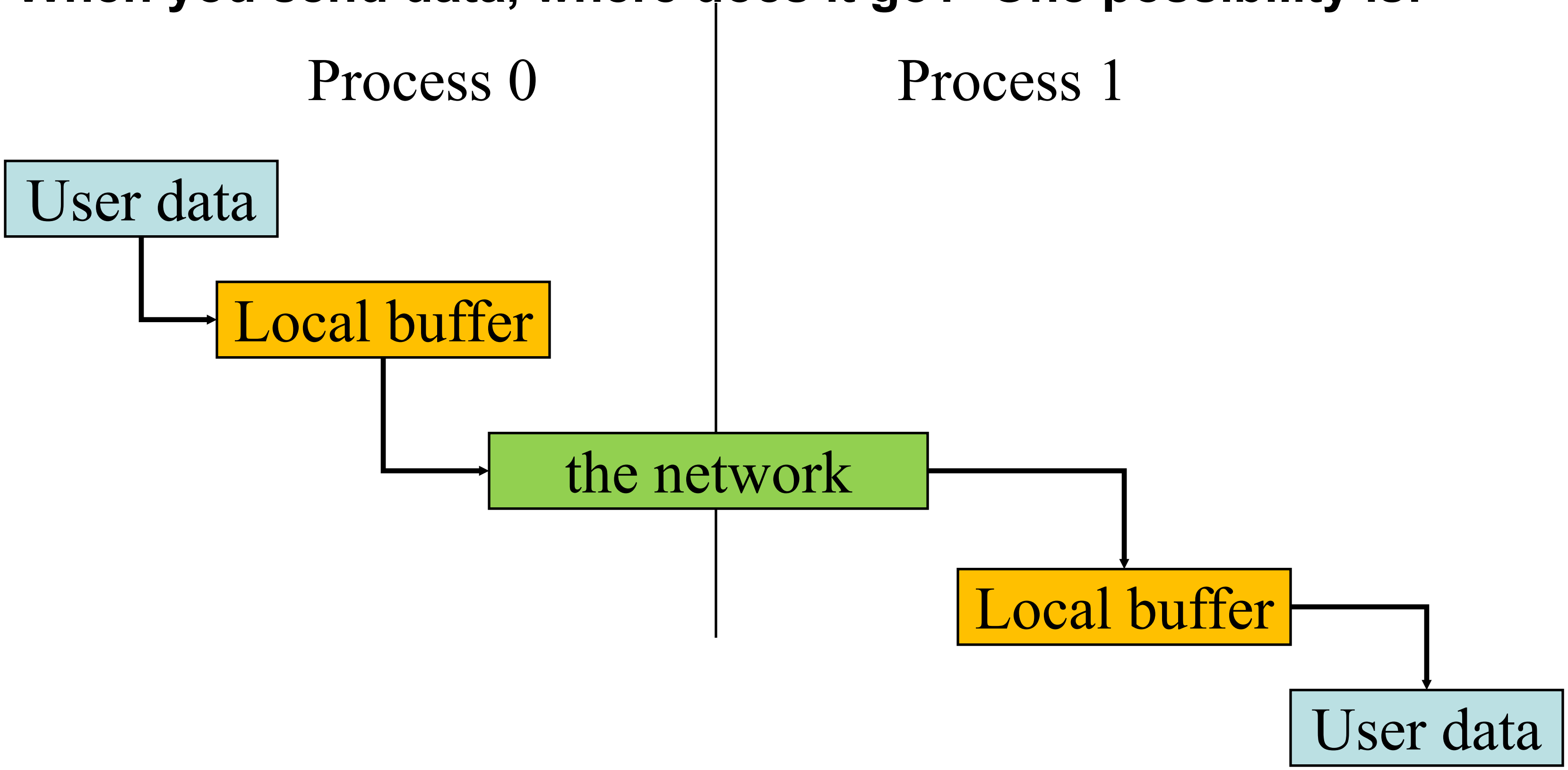


Process 0	Process 1
`Send(1)`	`Send(0)`
`Recv(1)`	`Recv(0)`

- **May be unsafe because MPI standard allows MPI_Send to behave in two different ways:**
  - it can simply copy the message into an MPI managed buffer and return,
  - or it can block until the matching call to MPI_Recv starts.

Buffer a message implicitly during MPI_Send()

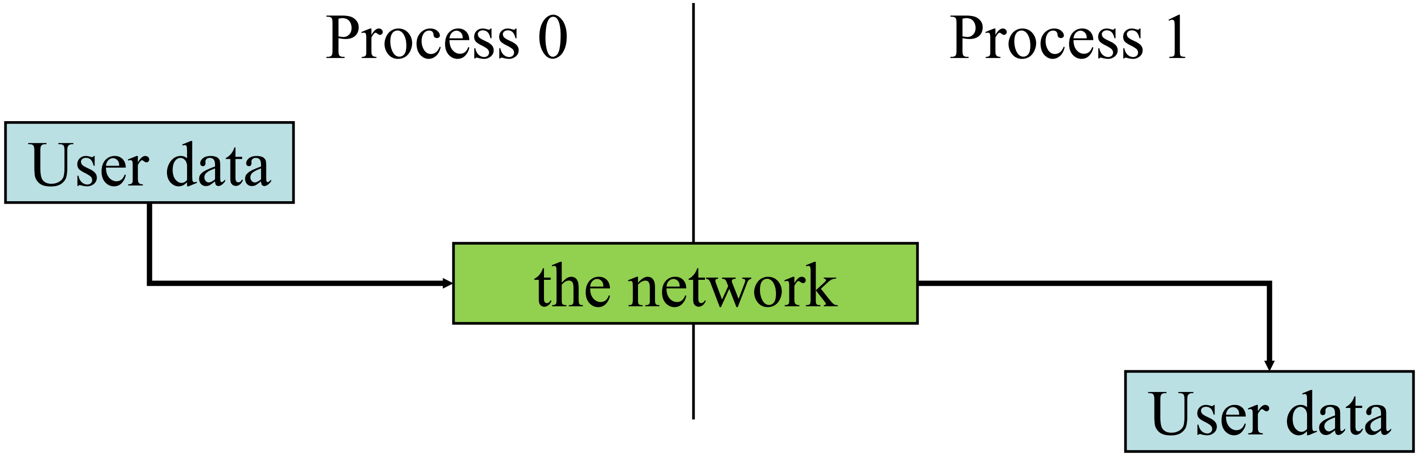
- **When you send data, where does it go? One possibility is:**



Slide source: Bill Gropp, ANL

Avoiding Buffering

- **Avoiding copies uses less memory**
- **May use more time**



`MPI_Send`() waits until a matching receive is executed.

Slide source: Bill Gropp, ANL

Safety in MPI programs

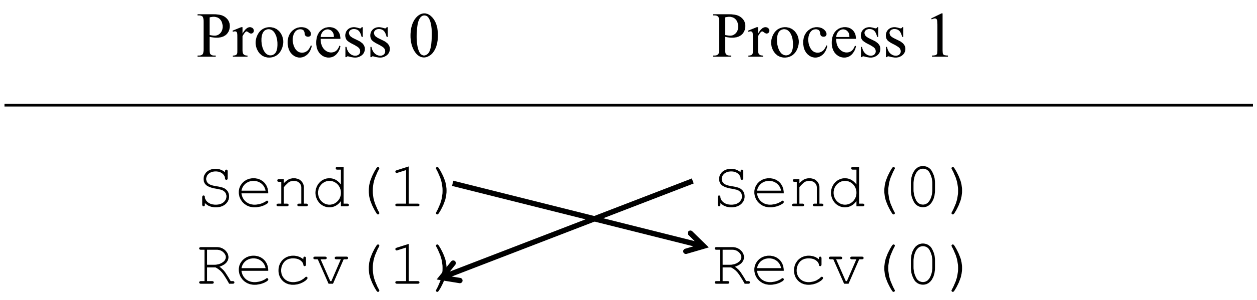
- Many implementations of MPI set a threshold at which the system switches from buffering to blocking.
  - Relatively small messages will be buffered by MPI_Send.
  - Larger messages, will cause it to block.

If the MPI_Send() executed by each process blocks, no process will be able to start executing a call to MPI_Recv, and the program will hang or deadlock.

  - Each process is blocked waiting for an event that will never happen.

Example of unsafe MPI code with possible deadlocks

- **Send a large message from process 0 to process 1**
  - If there is insufficient storage at the destination, the send must wait for the user to provide the memory space (through a receive)



Process 0	Process 1
`Send(1)`	`Send(0)`
`Recv(1)`	`Recv(0)`

- This may be "unsafe" because it depends on the availability of system buffers in which to store the data sent until it can be received

Slide source: Bill Gropp, ANL

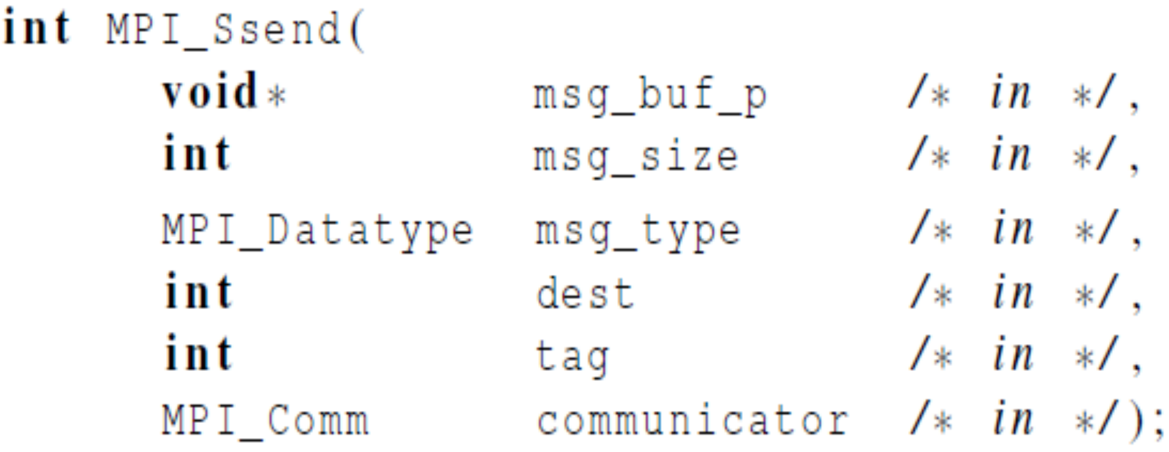
Safety in MPI programs

- A program that relies on MPI provided buffering is said to be unsafe.

- Such a program may run without problems for various sets of input, but it may hang or crash with other sets.

How can we tell if a program is unsafe

- Replace MPI_Send() with MPI_Ssend()
- The extra “s” stands for synchronous and MPI_Ssend is guaranteed to block until the matching receive starts.
- **If the new program does not hang/crash, the original program is safe.**
- MPI_Send() and MPI_Ssend() have the same arguments



```
int MPI_Ssend(
        void*           msg_buf_p     /* in */,
        int             msg_size      /* in */,
        MPI_Datatype    msg_type      /* in */,
        int             dest          /* in */,
        int             tag           /* in */,
        MPI_Comm        communicator  /* in */);
```

Some Solutions to the “unsafe” Problem

- Order the operations more carefully:

Process 0	Process 1
`Send(1)`	`Recv(0)`
`Recv(1)`	`Send(0)`

- Simultaneous send and receive in one call

Process 0	Process 1
`Sendrecv(1)`	`Sendrecv(0)`

Slide source: Bill Gropp, ANL

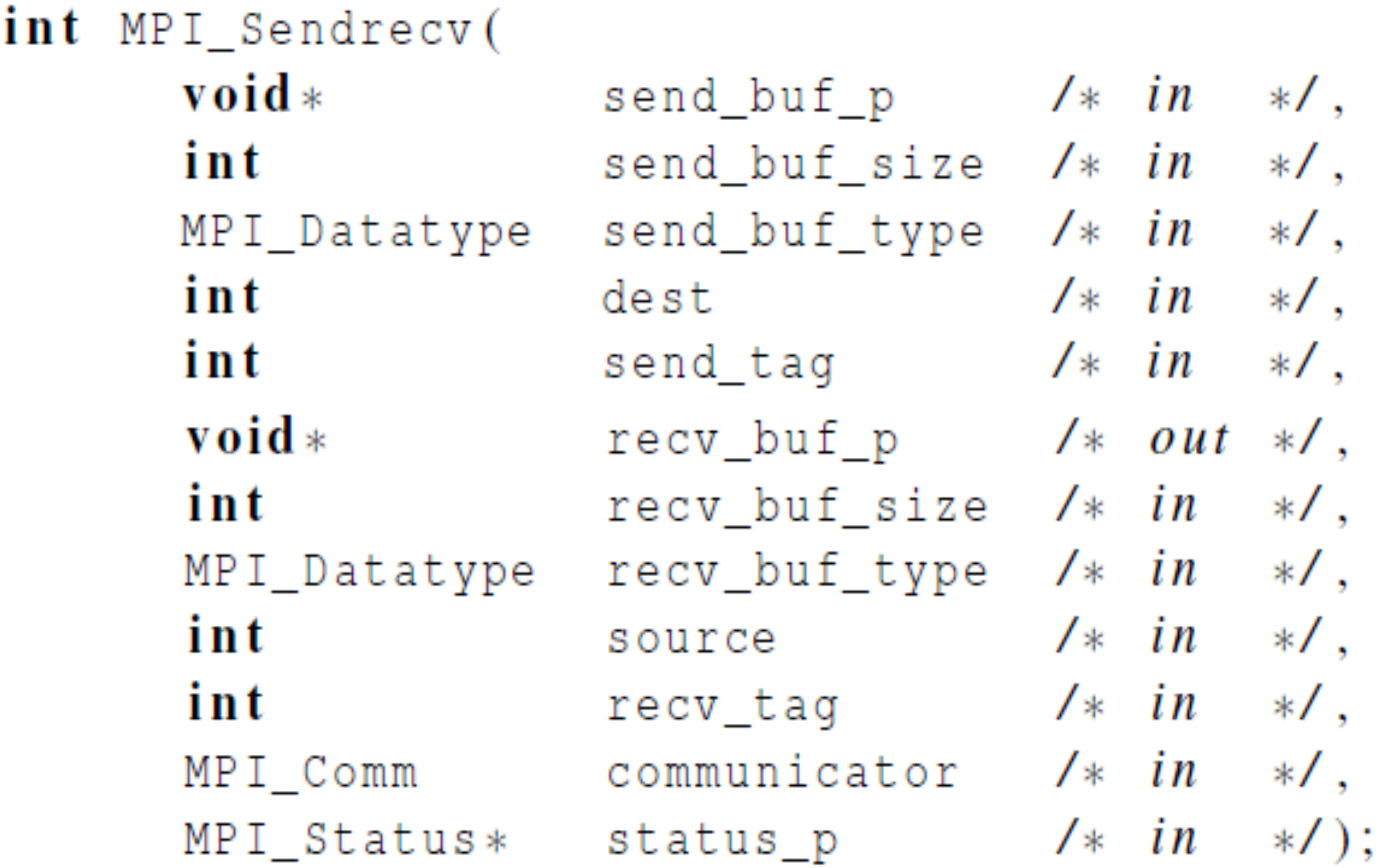
Restructuring communication in odd-even sort

```
MPI_Send(msg, size, MPI_INT, (my_rank+1) % comm_sz, 0, comm);
MPI_Recv(new_msg, size, MPI_INT, (my_rank+comm_sz−1) % comm_sz,
      0, comm, MPI_STATUS_IGNORE.
```

```
if (my_rank % 2 == 0) {
   MPI_Send(msg, size, MPI_INT, (my_rank+1) % comm_sz, 0, comm);
   MPI_Recv(new_msg, size, MPI_INT, (my_rank+comm_sz−1) % comm_sz,
         0, comm, MPI_STATUS_IGNORE.
} else {
   MPI_Recv(new_msg, size, MPI_INT, (my_rank+comm_sz−1) % comm_sz,
         0, comm, MPI_STATUS_IGNORE.
   MPI_Send(msg, size, MPI_INT, (my_rank+1) % comm_sz, 0, comm);
}
```

Use MPI_Sendrecv()

to conduct a blocking send and a receive in a single call.



```
int MPI_Sendrecv(
      void*          send_buf_p     /* in  */,
      int            send_buf_size  /* in  */,
      MPI_Datatype   send_buf_type  /* in  */,
      int            dest           /* in  */,
      int            send_tag       /* in  */,
      void*          recv_buf_p     /* out */,
      int            recv_buf_size  /* in  */,
      MPI_Datatype   recv_buf_type  /* in  */,
      int            source         /* in  */,
      int            recv_tag       /* in  */,
      MPI_Comm       communicator   /* in  */,
      MPI_Status*    status_p       /* in  */);
```

More Solutions to the “unsafe” Problem

- Supply own space as buffer for send

Process 0	Process 1
`Bsend(1)`	`Bsend(0)`
`Recv(1)`	`Recv(0)`

- Use non-blocking operations:

Process 0	Process 1
`Isend(1)`	`Isend(0)`
`Irecv(1)`	`Irecv(0)`
`Waitall`	`Waitall`

Concluding Remarks (1)

- **MPI works in C, C++, or Fortran.**
- **A communicator is a collection of processes that can send messages to each other.**
- **Many parallel programs use the SPMD approach.**
- **Most serial programs are deterministic:** if we run the same program with the same input we'll get the same output.
    - Parallel programs often don't possess this property.
- **Collective communications involve all the processes in a communicator.**

Concluding Remarks (2)

- **Performance evaluation**
  - Use elapsed time or "wall clock time".
  - Speedup = sequential/parallel time
  - Efficiency = Speedup/ p
  - If it's possible to increase the problem size (n) so that the efficiency doesn't decrease as p is increased, a parallel program is said to be scalable.
- **An MPI program is unsafe if its correct behavior depends on the fact that MPI_Send is buffering its input.**