Computer Science
Parallel and Distributed Computation

Message Passing Interface (MPI)

Kun Suo

Computer Science, Kennesaw State University

https://kevinsuo.github.io/

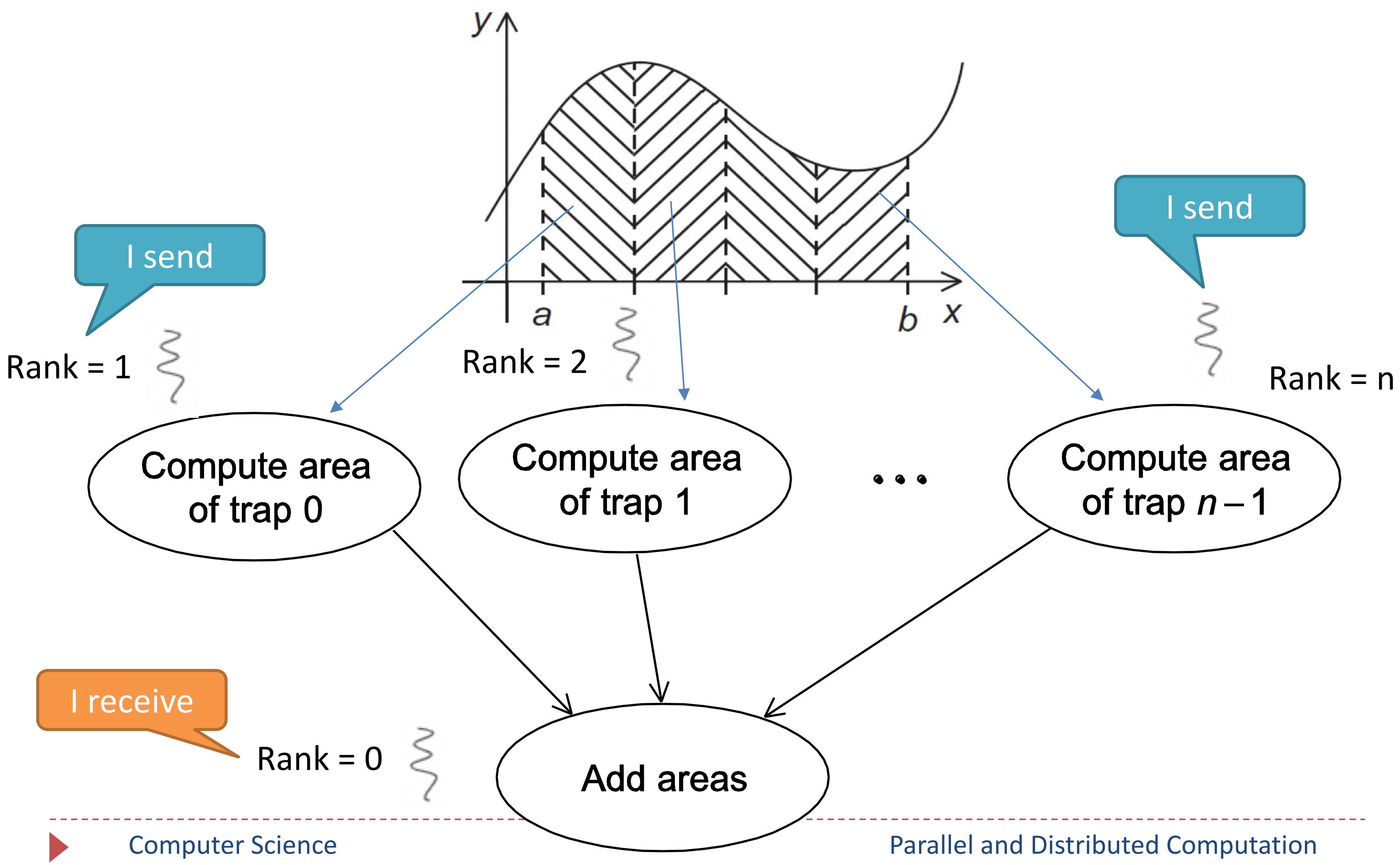
Review

- MPI introduction
  - Helloworld of MPI
- Performance evaluation
- Example: how to solve problems in MPI
  - Trapezoidal problem

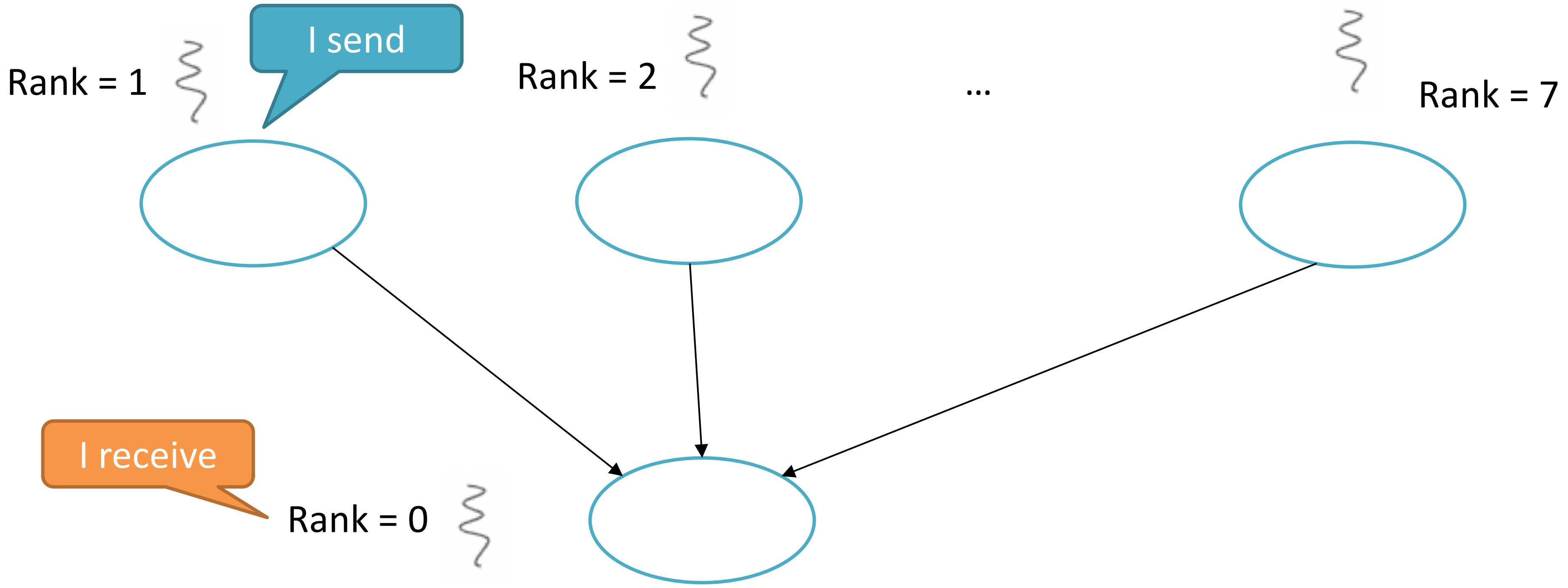
Outline

- MPI_Send/MPI_Receive
- MPI_Reduce/MPI_Allreduce
- MPI_Broadcast
- MPI_Scatter
- MPI_Gather

Communication



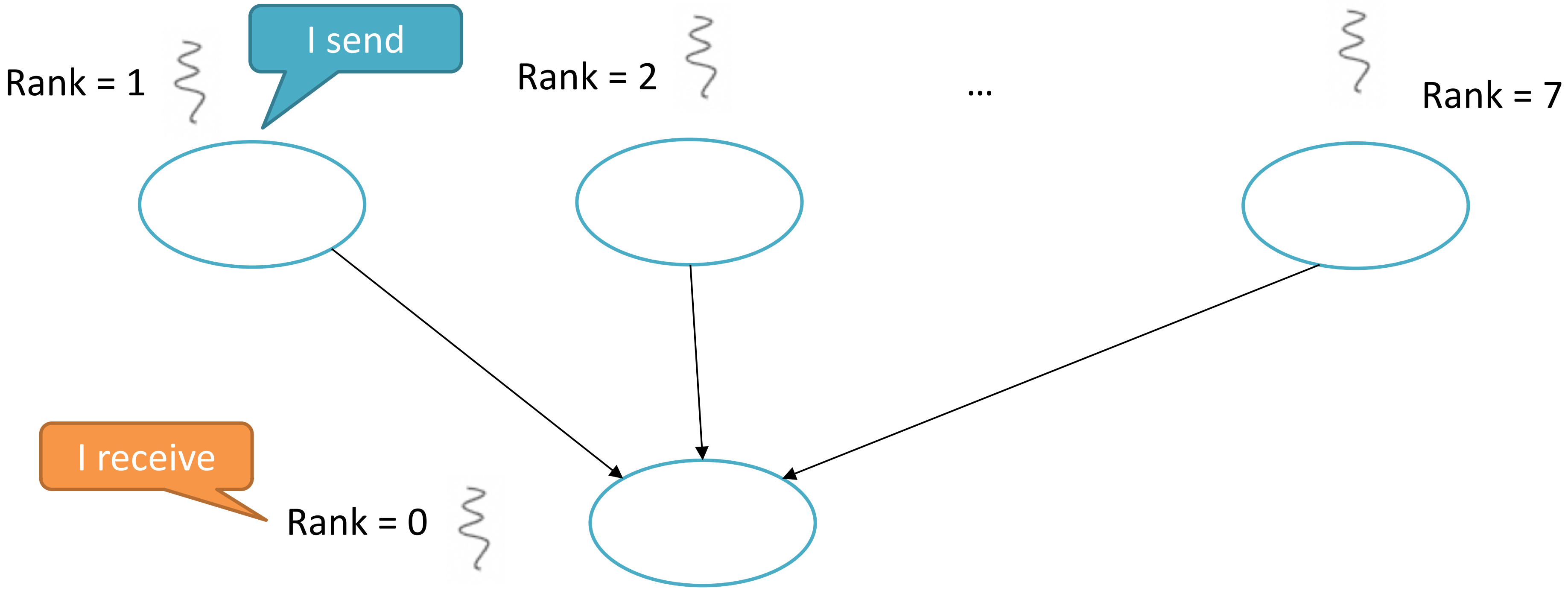
Point-to-Point communication



How many send/receive and add operation?

- 7 sends and 7 receives
- 7 adds

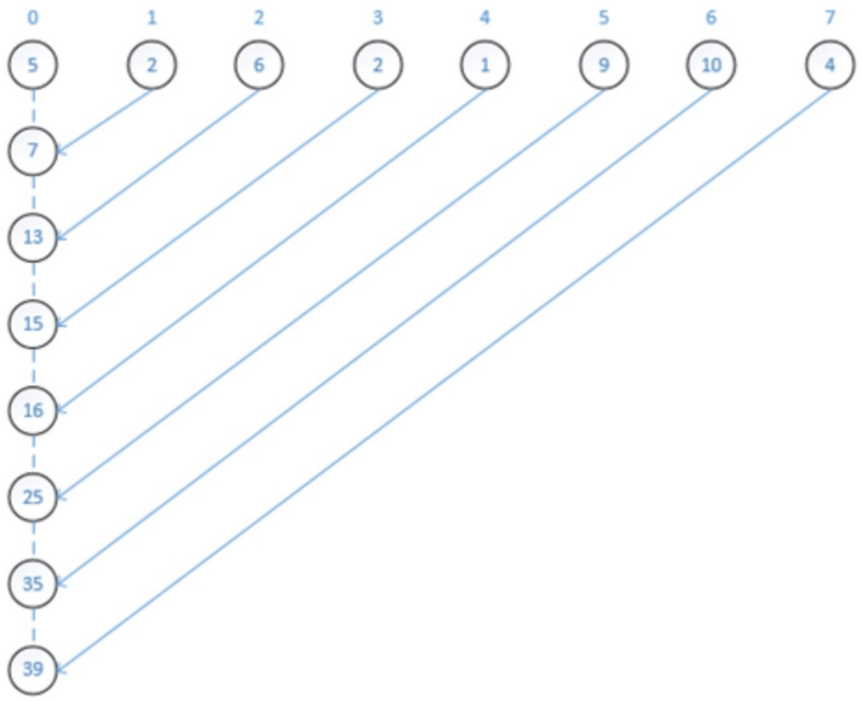
Point-to-Point communication



How many send/receive and add operation on master node (Rank = 0)?

- 7 sends and 7 receives
- 7 adds

Point-to-Point communication



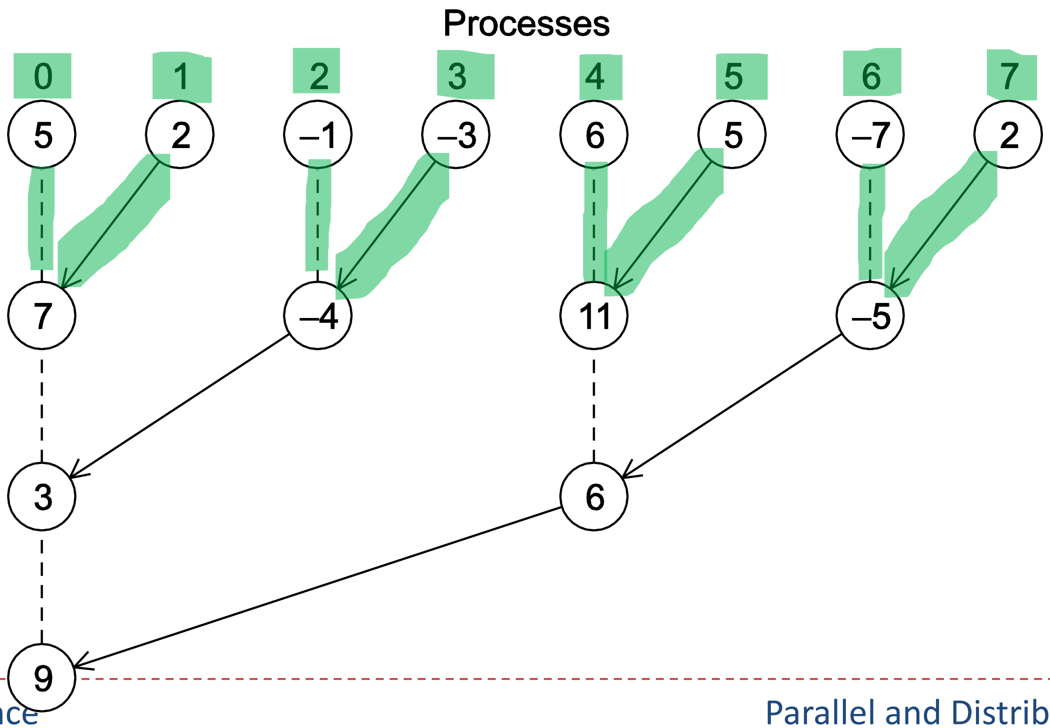
How many send/receive and add operation on master node (Rank = 0)?

- 7 sends and 7 receives
- 7 adds

Tree-structured communication

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.



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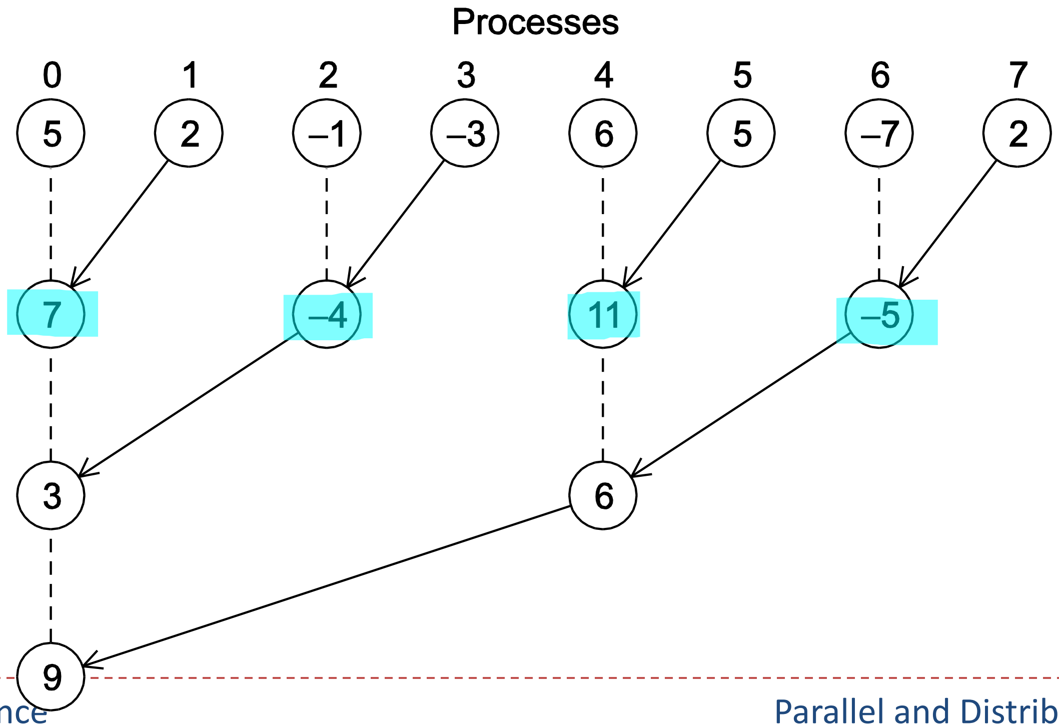

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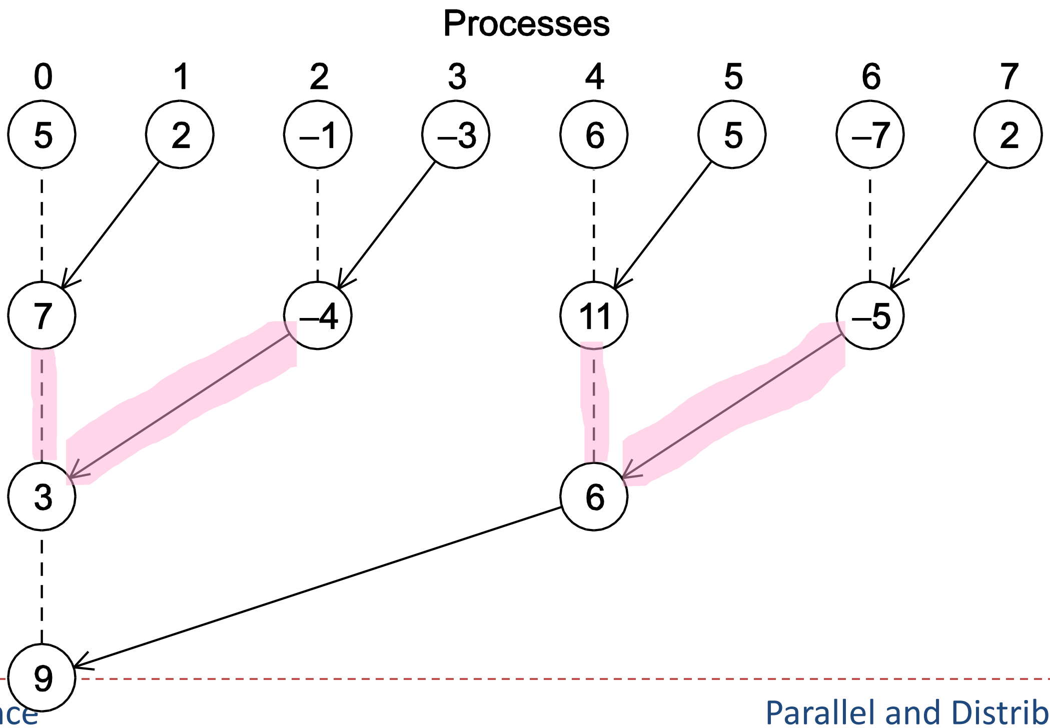

Tree-structured communication

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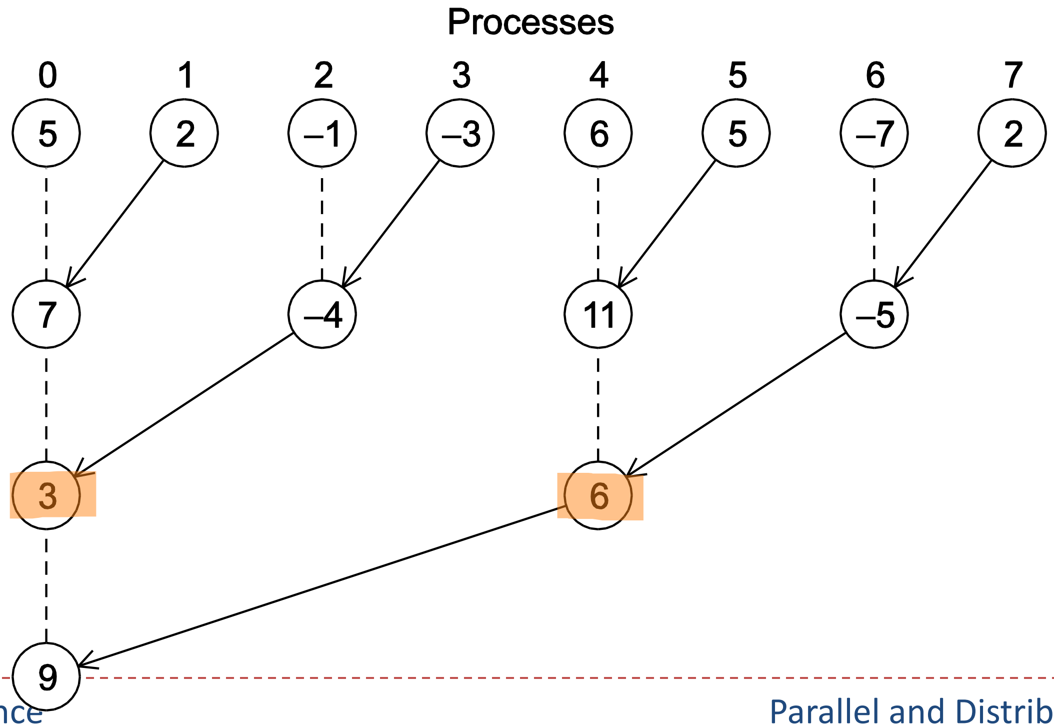
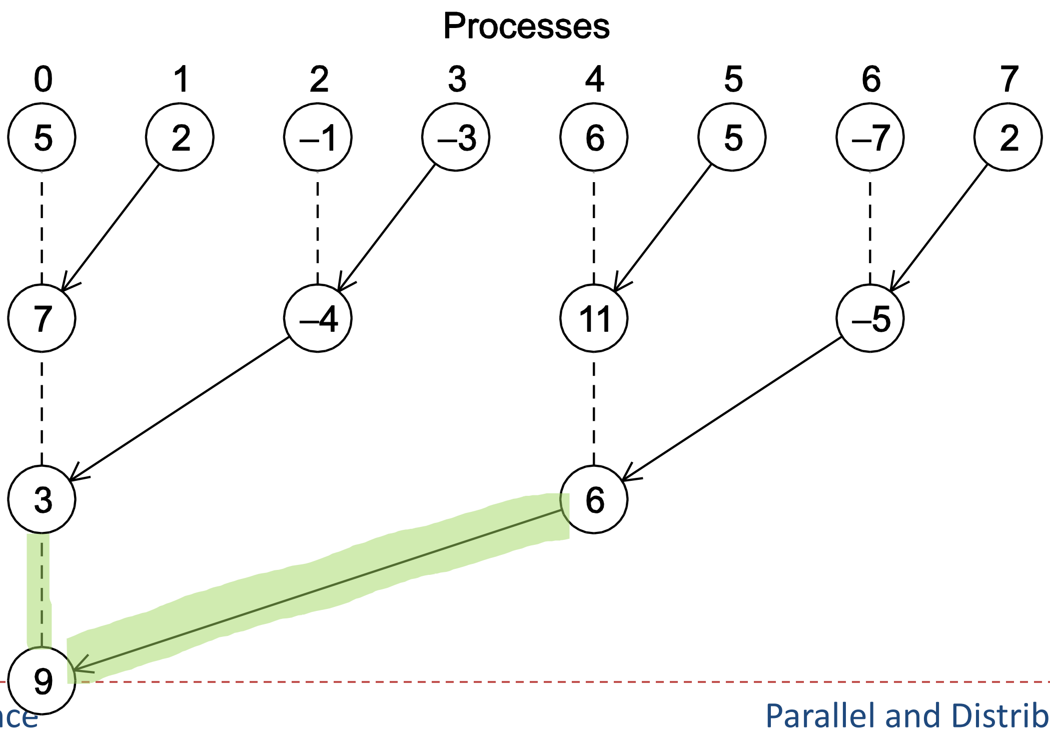


Tree-structured communication

In the second phase:

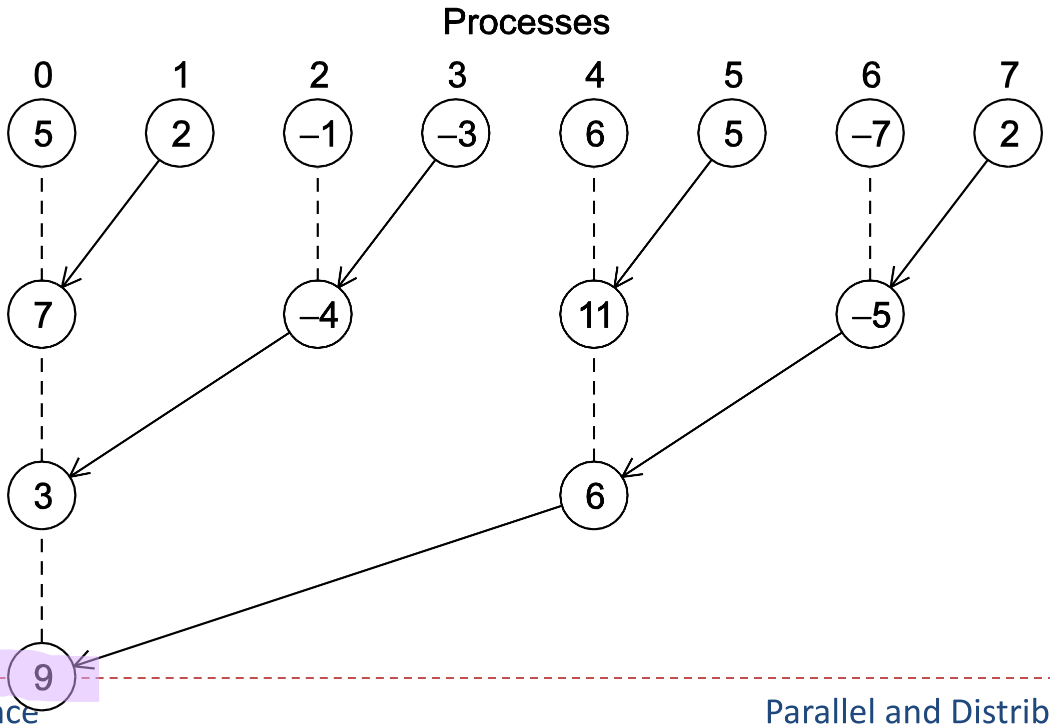
- (a) Process 4 sends its newest value to process 0.
- (b) Process 0 adds the received value to its newest value.



Tree-structured communication

In the second phase:

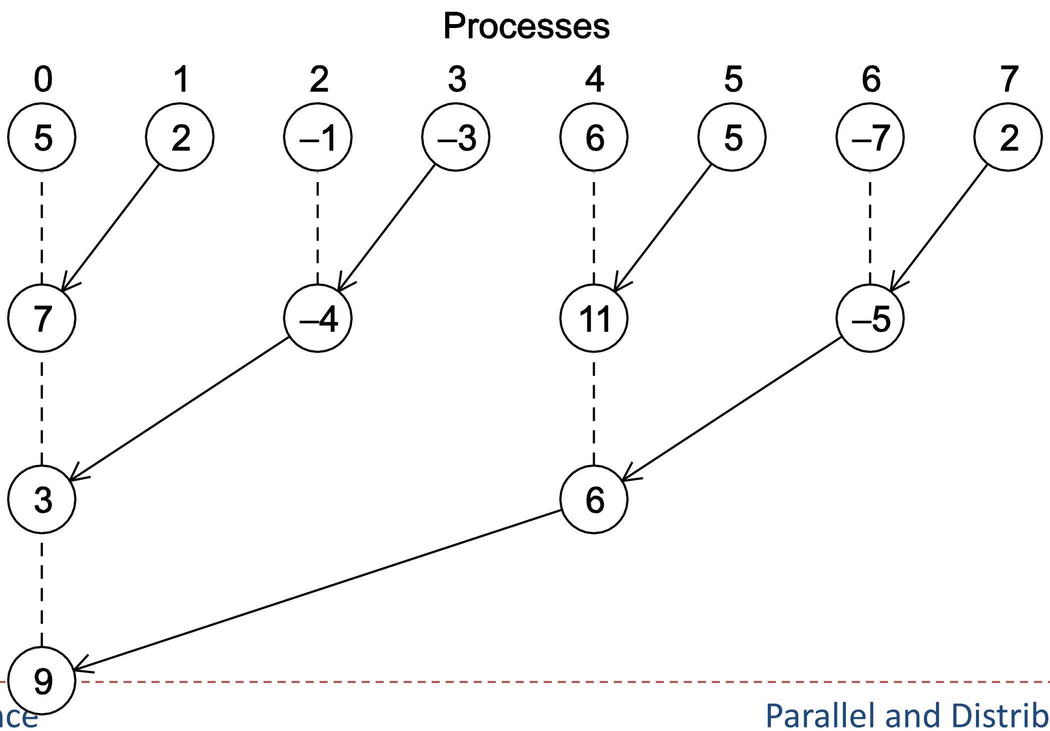
- (a) Process 4 sends its newest value to process 0.
- (b) Process 0 adds the received value to its newest value.



Tree-structured communication

How many send/receive and add operation?

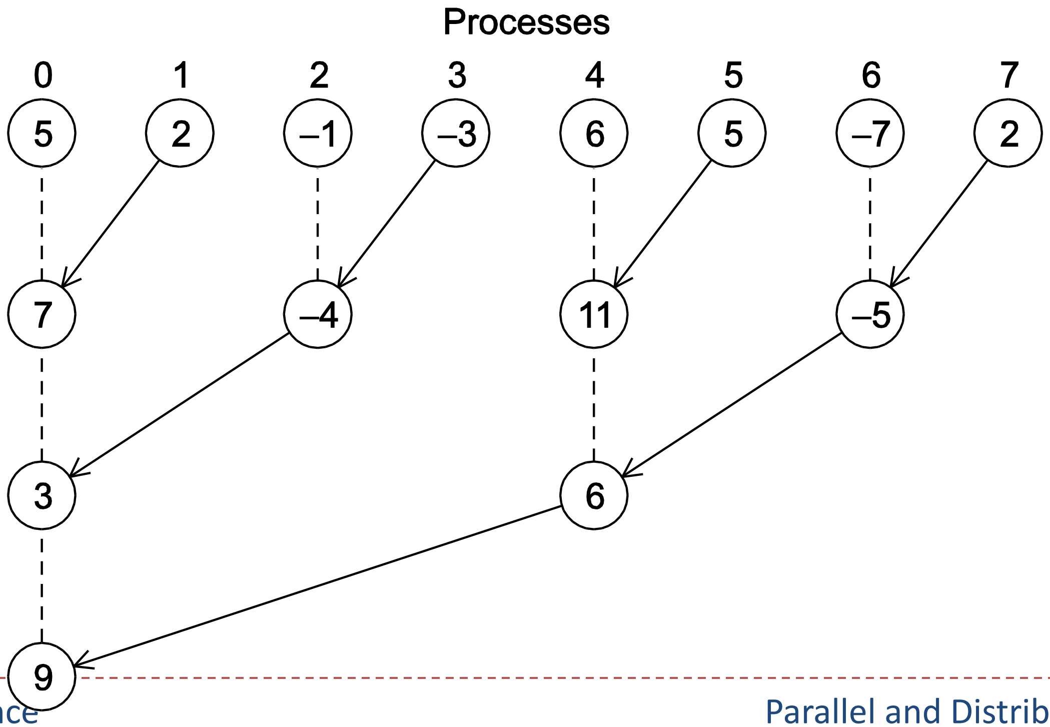
- 7 sends and 7 receives
- 7 adds



Tree-structured communication

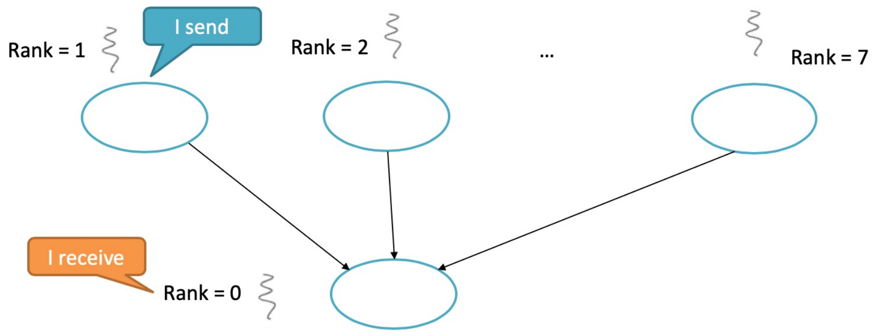
How many send/receive and add operation on master node (Rank = 0)?

- 3 sends and 3 receives
- 3 adds



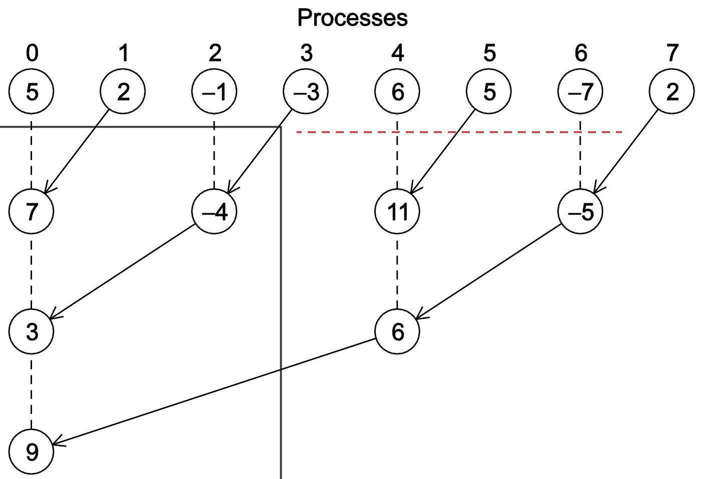
Point-to-Point communication code

```
int main(void) {
   int my_rank, comm_sz, n = 1024, local_n;
   double a = 0.0, b = 3.0, h, local_a, local_b;
   double local_int, total_int;
   int source;

   MPI_Init(NULL, NULL);
   MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);
   MPI_Comm_size(MPI_COMM_WORLD, &comm_sz);

   h = (b-a)/n;             /* h is the same for all processes */
   local_n = n/comm_sz;     /* So is the number of trapezoids  */

   local_a = a + my_rank*local_n*h;
   local_b = local_a + local_n*h;
   local_int = Trap(local_a, local_b, local_n, h);

   if (my_rank != 0) {
      MPI_Send(&local_int, 1, MPI_DOUBLE, 0, 0,
            MPI_COMM_WORLD);
   } else {
      total_int = local_int;
      for (source = 1; source < comm_sz; source++) {
         MPI_Recv(&local_int, 1, MPI_DOUBLE, source, 0,
               MPI_COMM_WORLD, MPI_STATUS_IGNORE);
         total_int += local_int;
      }
   }
```



Collective (tree-structure) communication code

```
int main(void) {
   int my_rank, comm_sz, n = 1024, local_n;
   double a = 0.0, b = 3.0, h, local_a, local_b;
   double local_int, total_int;
   int source;

   MPI_Init(NULL, NULL);
   MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);
   MPI_Comm_size(MPI_COMM_WORLD, &comm_sz);

   h = (b-a)/n;            /* h is the same for all processes */
   local_n = n/comm_sz;    /* So is the number of trapezoids  */

   local_a = a + my_rank*local_n*h;
   local_b = local_a + local_n*h;
   local_int = Trap(local_a, local_b, local_n, h);

   if (my_rank != 0) {
     MPI_Send(&local_int, 1, MPI_DOUBLE, 0, 0,
           MPI_COMM_WORLD);
   } else {
     total_int = local_int;
     for (source = 1; source < comm_sz; source++) {
       MPI_Recv(&local_int, 1, MPI_DOUBLE, source, 0,
             MPI_COMM_WORLD, MPI_STATUS_IGNORE);
       total_int += local_int;
     }
   }
```



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

MPI_Reduce

```
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);
```

input

output

Will do sum up for the inputs

Process 0 will do it

MPI_Reduce

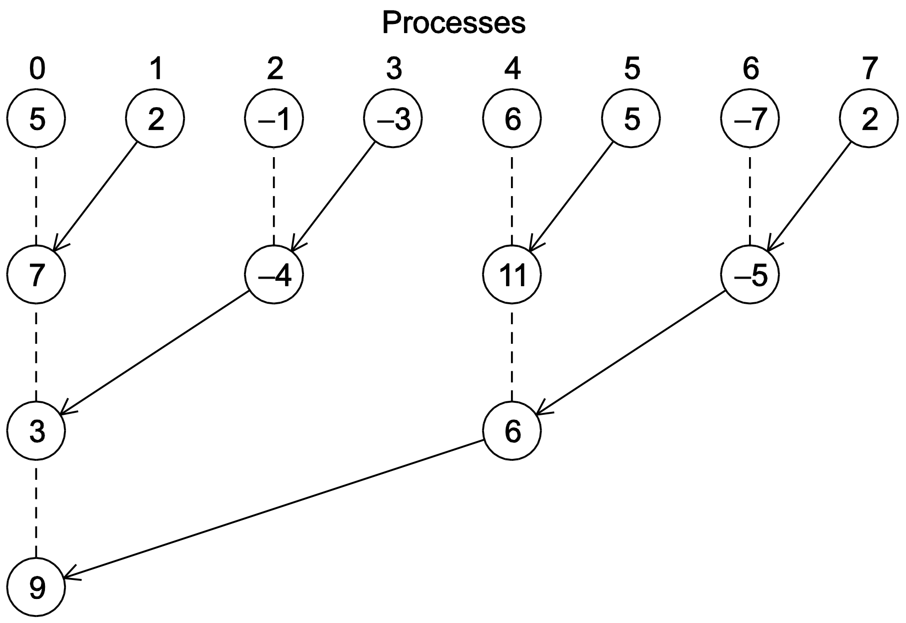
```
MPI_Reduce(&local_int, &total_int, 1, MPI_DOUBLE, MPI_SUM, 0,
     MPI_COMM_WORLD);
```

input

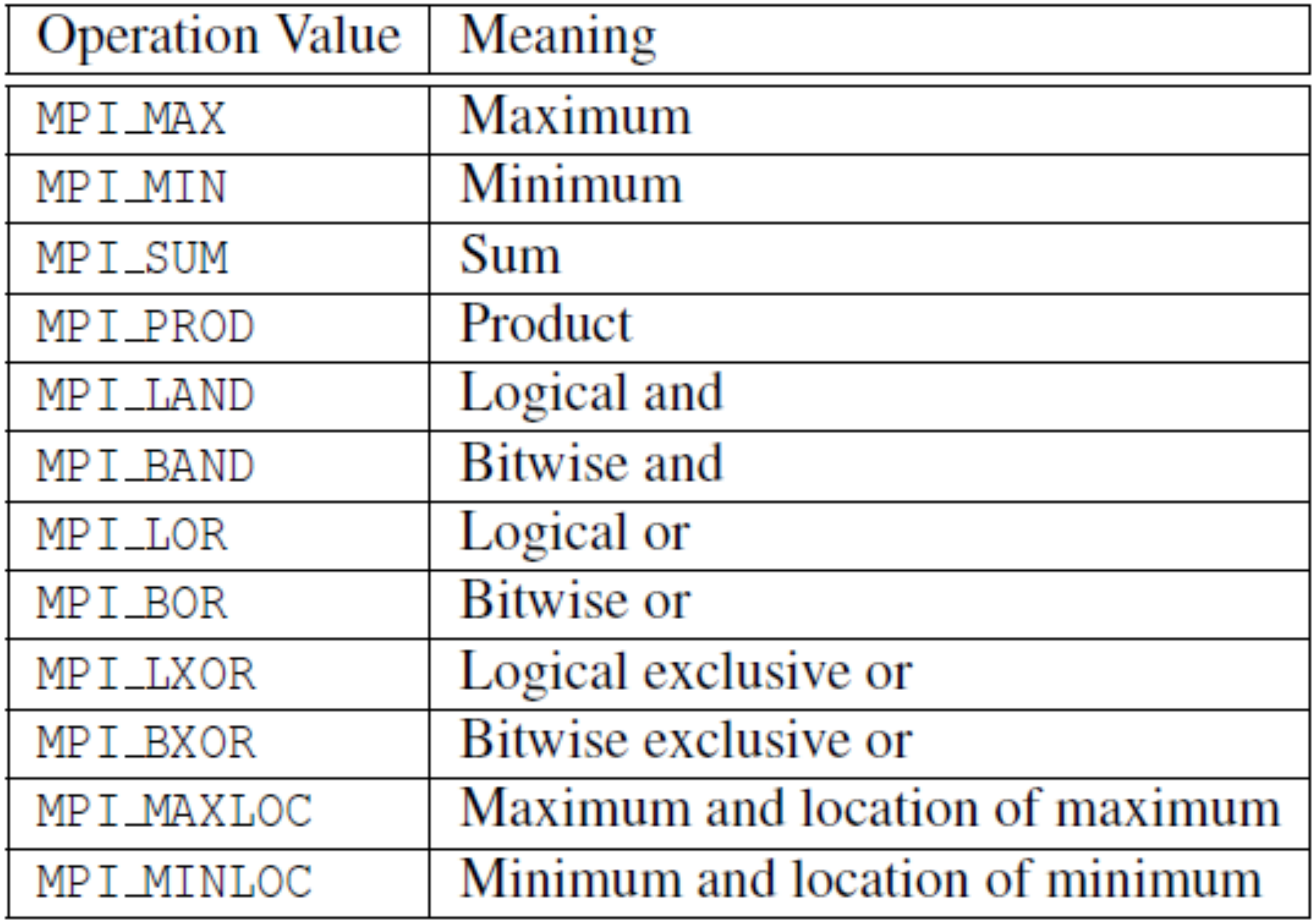
output

Will do sum up for the inputs

Process 0 will do it



Besides Sumup, it can also do:



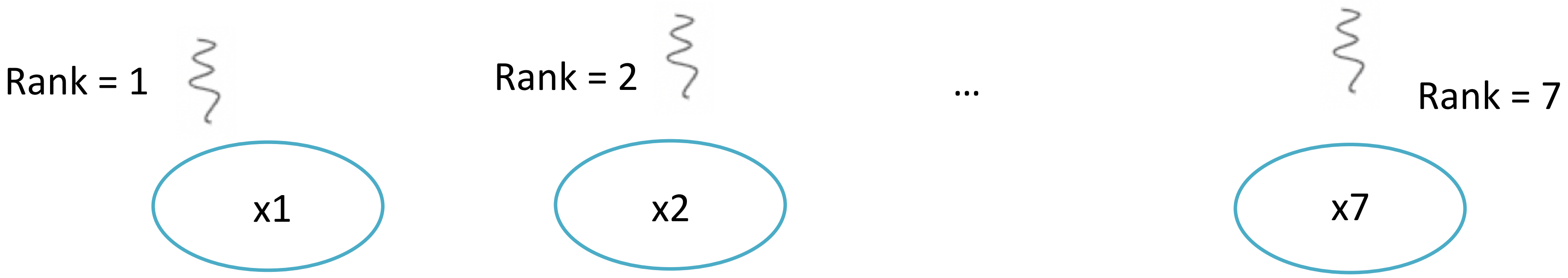
Operation Value	Meaning
MPI_MAX	Maximum
MPI_MIN	Minimum
MPI_SUM	Sum
MPI_PROD	Product
MPI_LAND	Logical and
MPI_BAND	Bitwise and
MPI_LOR	Logical or
MPI_BOR	Bitwise or
MPI_LXOR	Logical exclusive or
MPI_BXOR	Bitwise exclusive or
MPI_MAXLOC	Maximum and location of maximum
MPI_MINLOC	Minimum and location of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

Besides Sumup, it can also do:

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

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

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



MAX(x1, x2, …, x7)

MIN(x1, x2, …, x7)

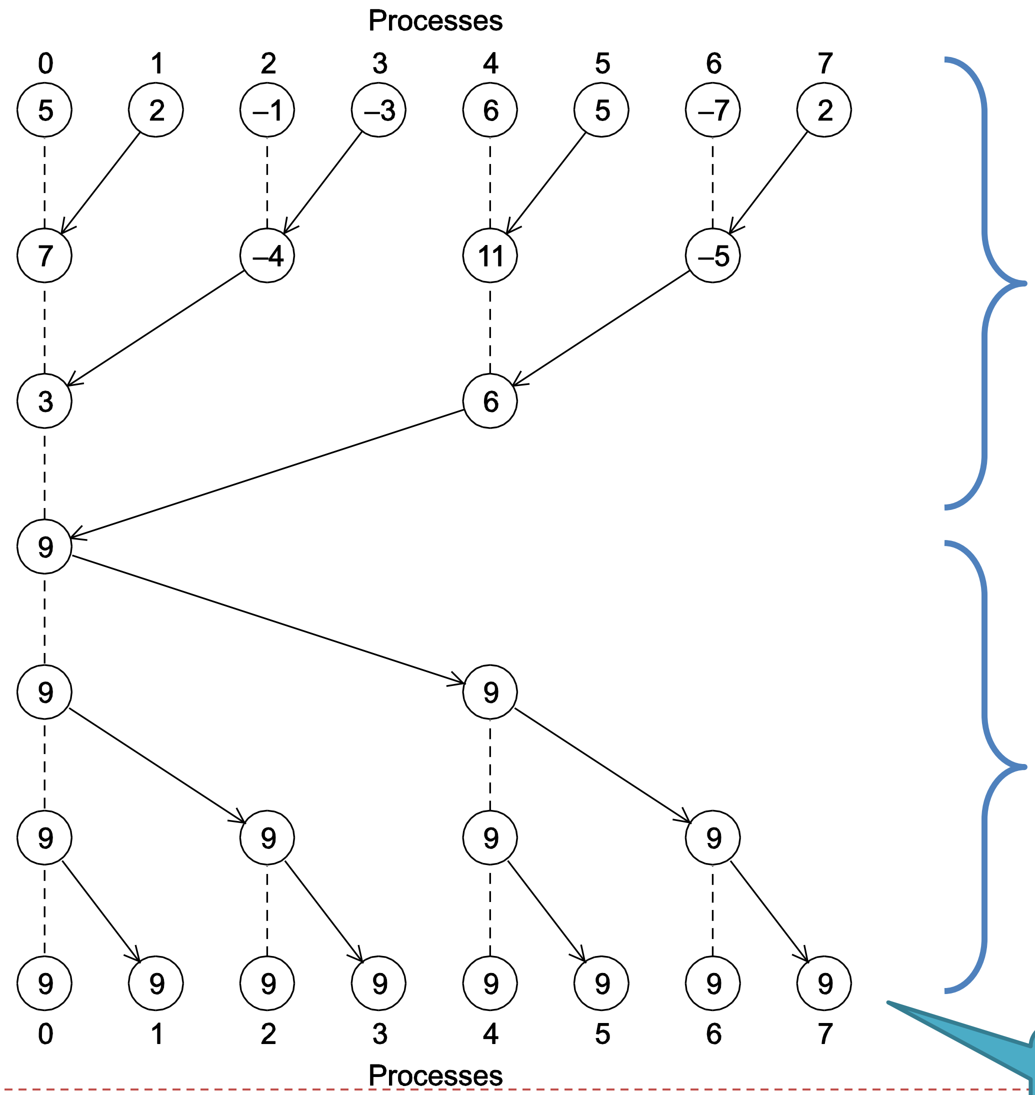
x1 * x2 * … * x7

MPI_Allreduce

- Useful in a situation in which all of the processes need the final result.
  - Sum up first and then distribute to everyone

```
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



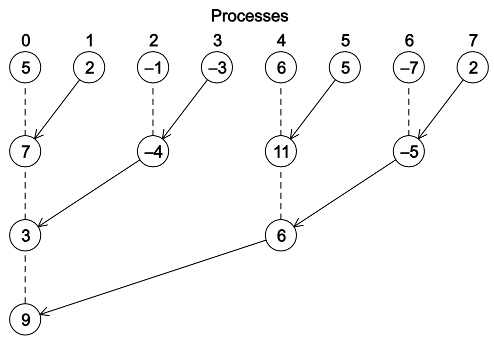
9 is distributed to every process

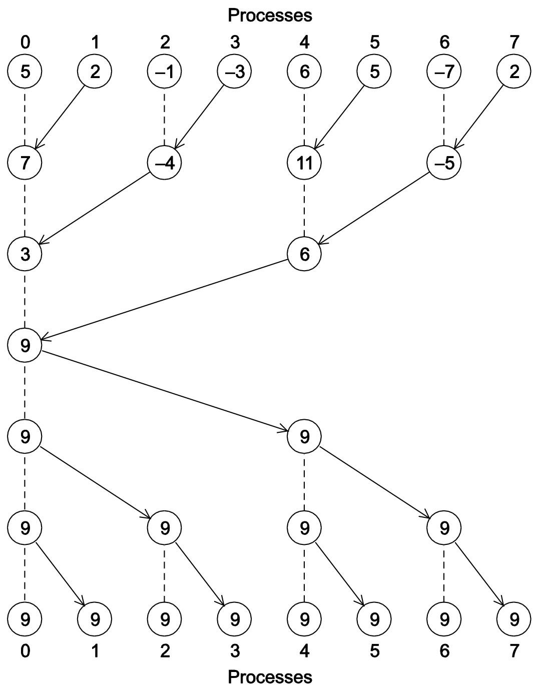
What if I only need to distribute?

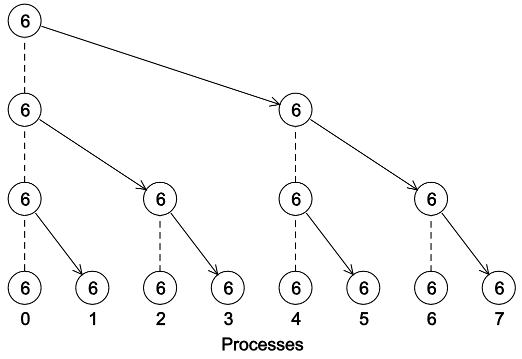
MPI_Reduce

MPI_Allreduce

?





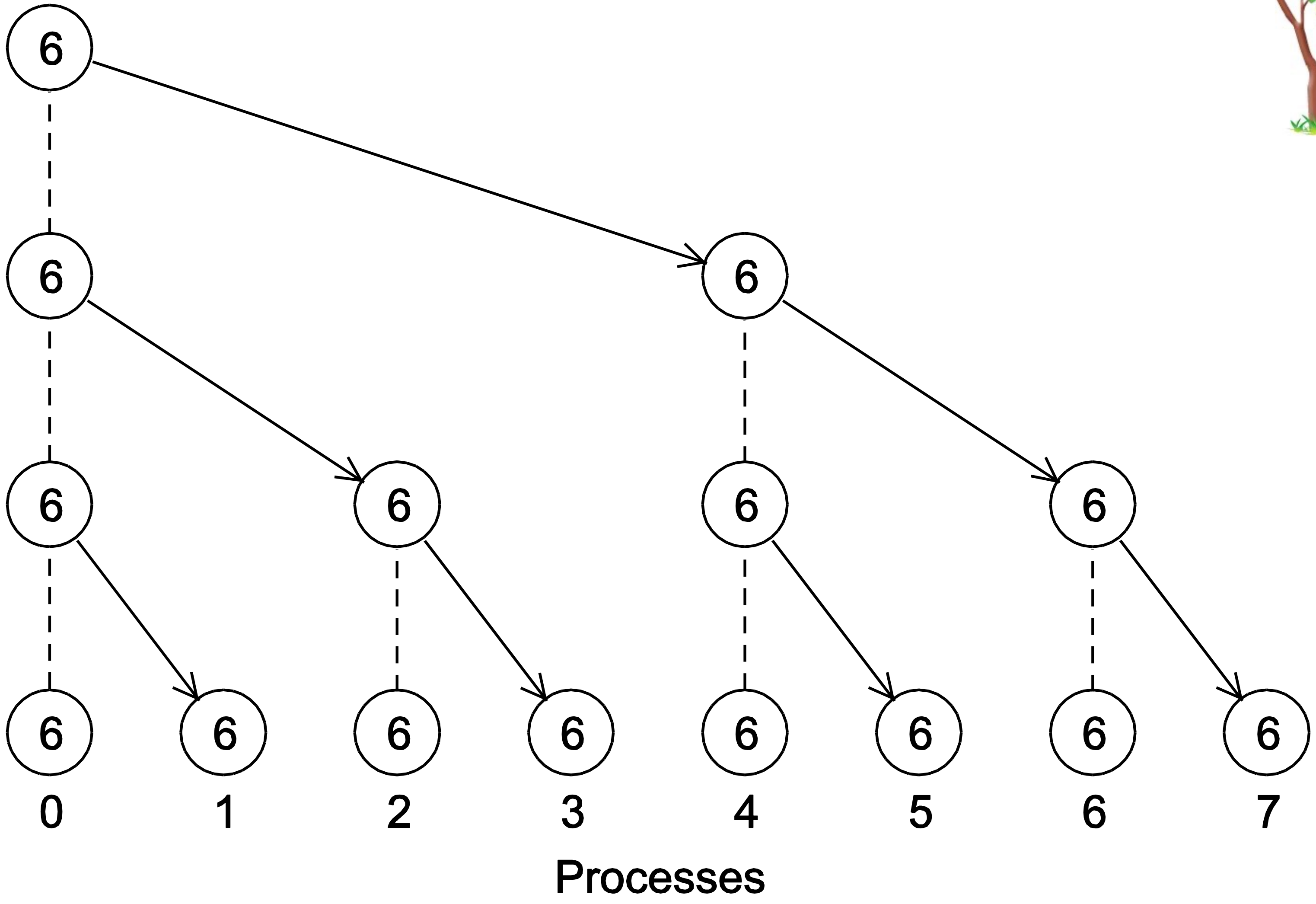


Broadcast

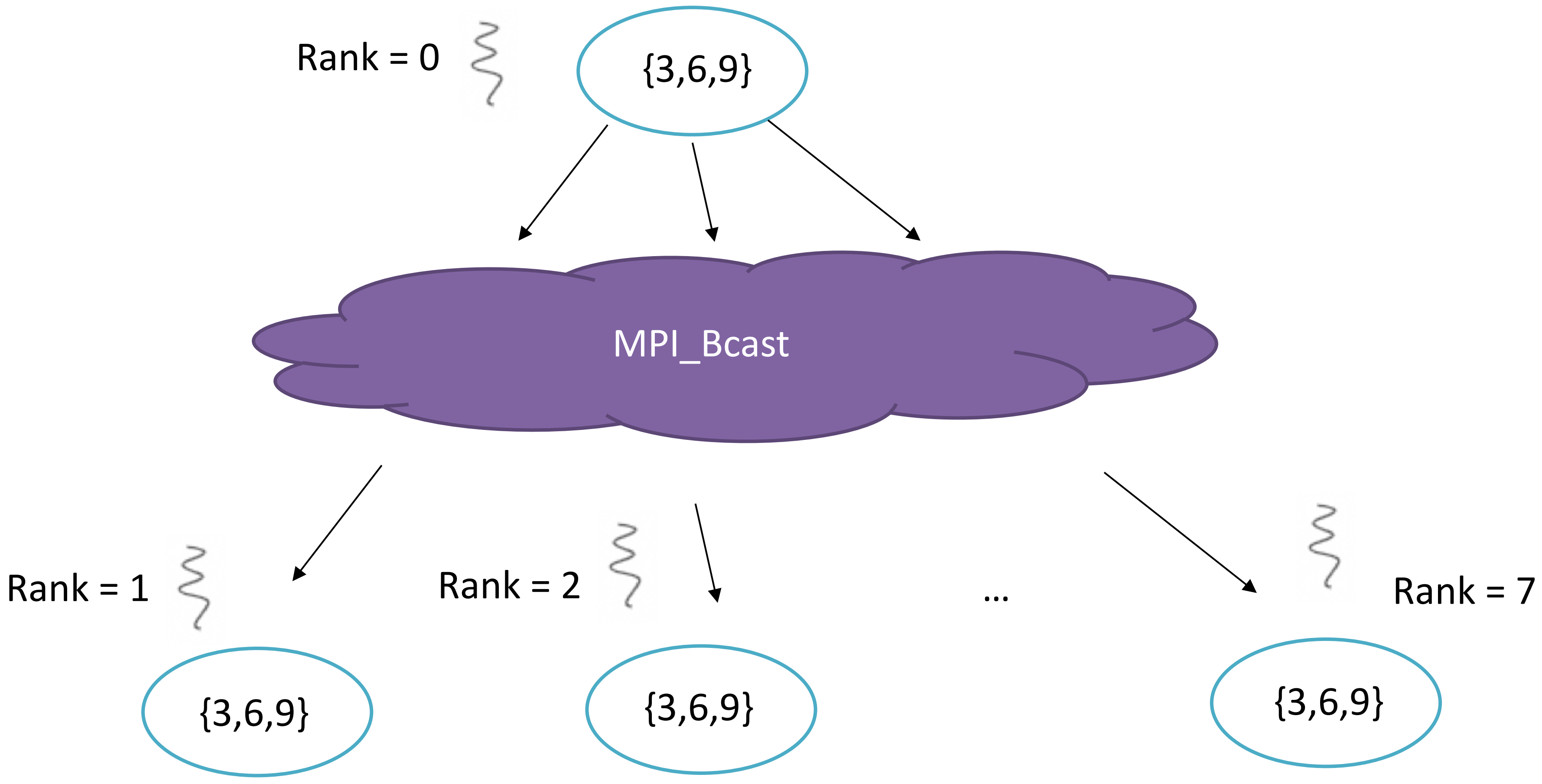
- Data belonging to a single process is sent to all of the processes in the communicator.

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

A tree-structured broadcast



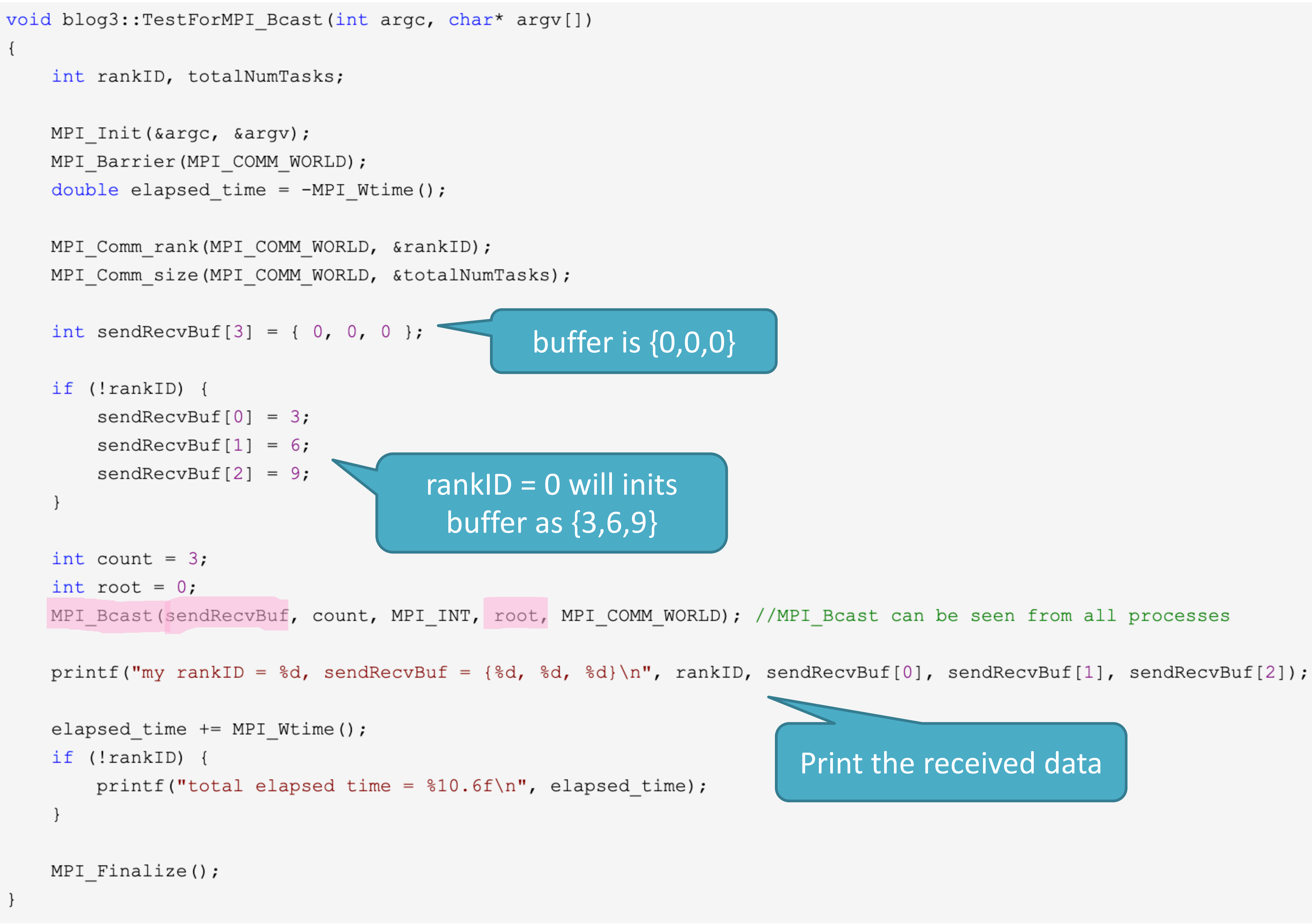
Example of MPI_Bcast



Example of MPI_Bcast

```
int main(int argc, char* argv[])
{
    blog3 test;
    test.TestForMPI_Bcast(argc, argv);
}
```

```
void blog3::TestForMPI_Bcast(int argc, char* argv[])
{
    int rankID, totalNumTasks;

    MPI_Init(&argc, &argv);
    MPI_Barrier(MPI_COMM_WORLD);
    double elapsed_time = -MPI_Wtime();

    MPI_Comm_rank(MPI_COMM_WORLD, &rankID);
    MPI_Comm_size(MPI_COMM_WORLD, &totalNumTasks);

    int sendRecvBuf[3] = { 0, 0, 0 };
```

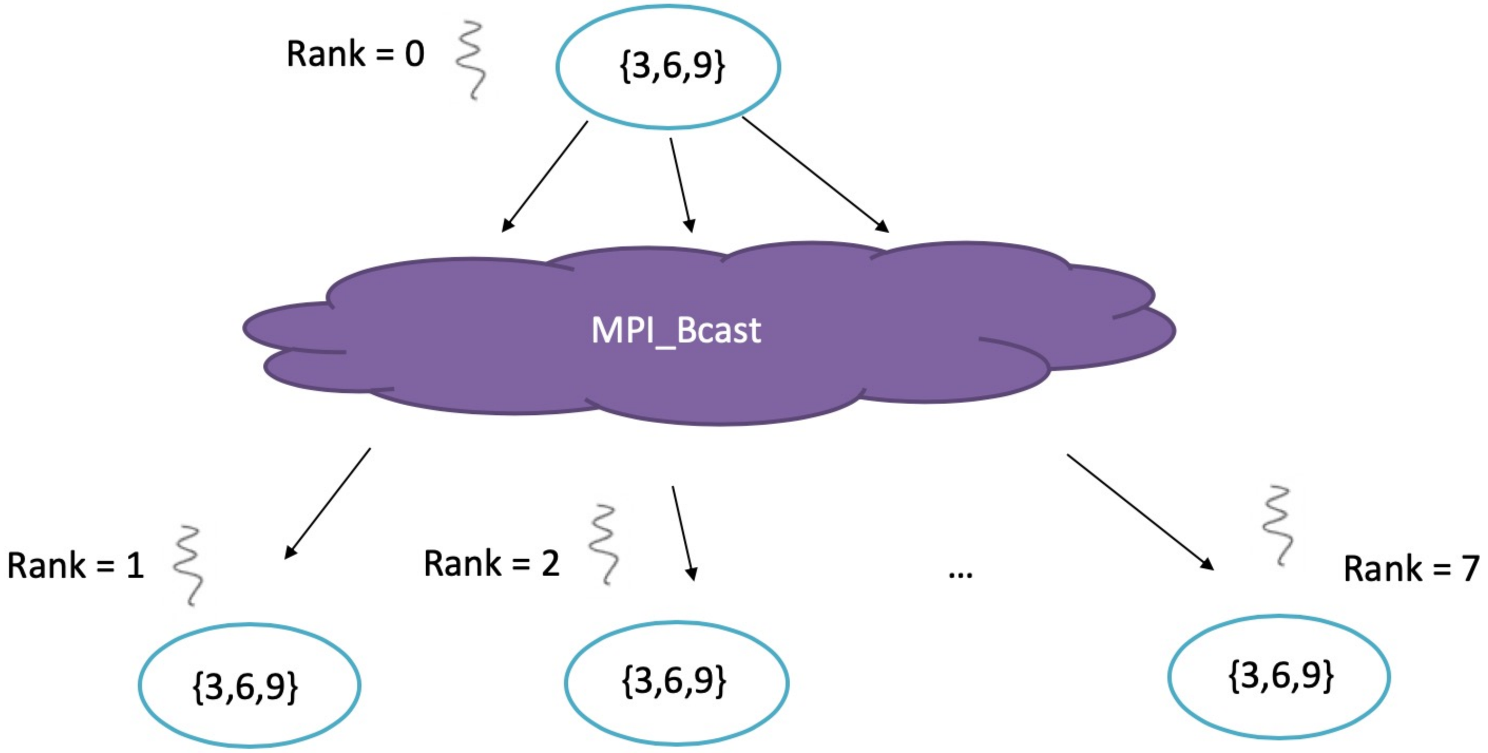


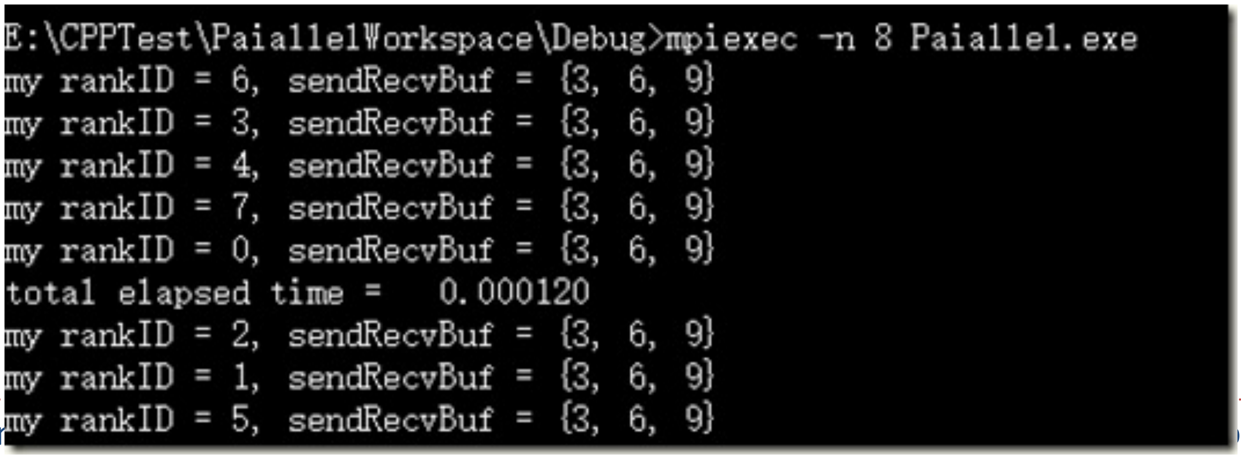
```
void blog3::TestForMPI_Bcast(int argc, char* argv[])
{
    int rankID, totalNumTasks;

    MPI_Init(&argc, &argv);
    MPI_Barrier(MPI_COMM_WORLD);
    double elapsed_time = -MPI_Wtime();

    MPI_Comm_rank(MPI_COMM_WORLD, &rankID);
    MPI_Comm_size(MPI_COMM_WORLD, &totalNumTasks);

    int sendRecvBuf[3] = { 0, 0, 0 };

    if (!rankID) {
        sendRecvBuf[0] = 3;
        sendRecvBuf[1] = 6;
        sendRecvBuf[2] = 9;
    }

    int count = 3;
    int root = 0;
    MPI_Bcast(sendRecvBuf, count, MPI_INT, root, MPI_COMM_WORLD); //MPI_Bcast can be seen from all processes

    printf("my rankID = %d, sendRecvBuf = {%d, %d, %d}\n", rankID, sendRecvBuf[0], sendRecvBuf[1], sendRecvBuf[2]);

    elapsed_time += MPI_Wtime();
    if (!rankID) {
        printf("total elapsed time = %10.6f\n", elapsed_time);
    }

    MPI_Finalize();
}
```

buffer is {0,0,0}

rankID = 0 will inits buffer as {3,6,9}

Print the received data

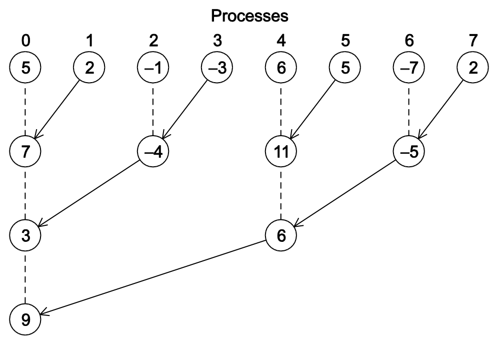




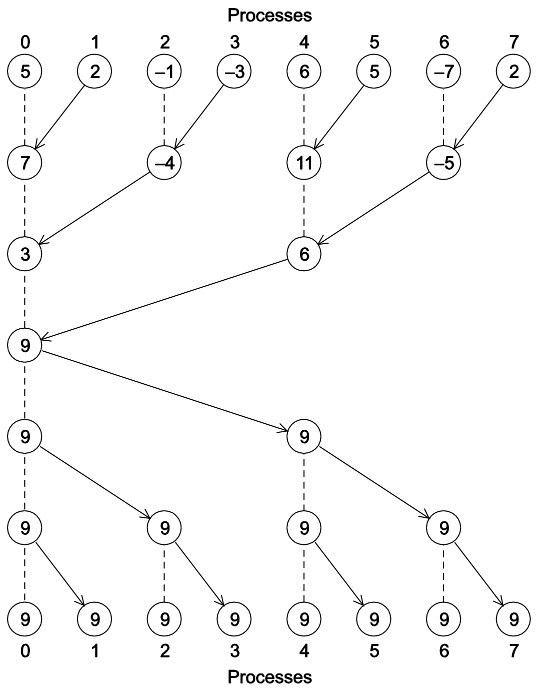
```
E:\CPPTest\Paiallel Workspace\Debug>mpiexec -n 8 Paiallel.exe
my rankID = 6, sendRecvBuf = {3, 6, 9}
my rankID = 3, sendRecvBuf = {3, 6, 9}
my rankID = 4, sendRecvBuf = {3, 6, 9}
my rankID = 7, sendRecvBuf = {3, 6, 9}
my rankID = 0, sendRecvBuf = {3, 6, 9}
total elapsed time =    0.000120
my rankID = 2, sendRecvBuf = {3, 6, 9}
my rankID = 1, sendRecvBuf = {3, 6, 9}
my rankID = 5, sendRecvBuf = {3, 6, 9}
```

What if I only need to distribute?

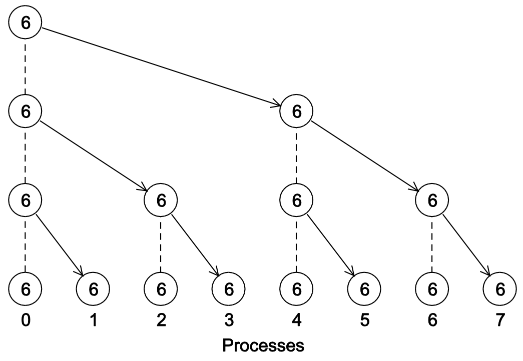
MPI_Reduce



MPI_Allreduce



MPI_Bcast



Data distributions: vector addition

a

$$\begin{bmatrix} 1 \\ 0.6 \\ -2 \end{bmatrix} + \begin{bmatrix} -1 \\ 0 \\ 0.2 \end{bmatrix} + \begin{bmatrix} 3 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 3 \\ 1.6 \\ -1.8 \end{bmatrix}$$

b

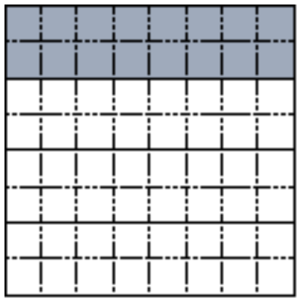
$$\begin{bmatrix} 1 & 0 \\ -1 & 0 \end{bmatrix} + \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ -2 & 0 \end{bmatrix}$$

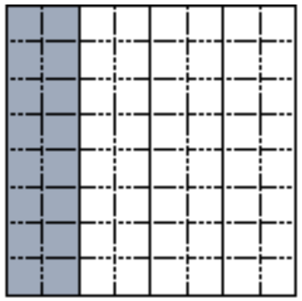
Partitioning options

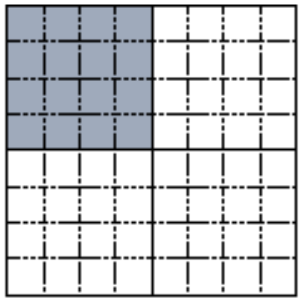
- Block partitioning
  - Assign blocks of consecutive components to each process.
- Cyclic partitioning
  - Assign components in a round robin fashion.
- Block-cyclic partitioning
  - Use a cyclic distribution of blocks of components.

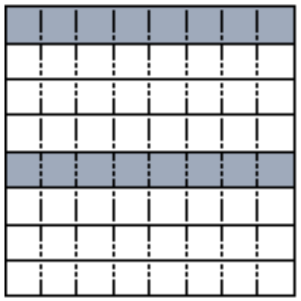
Partitioning options

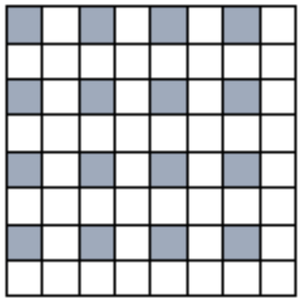
- Block partitioning vs Cyclic partitioning

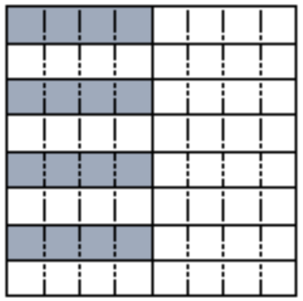

(BLOCK,*)


(*,BLOCK)


(BLOCK,BLOCK)

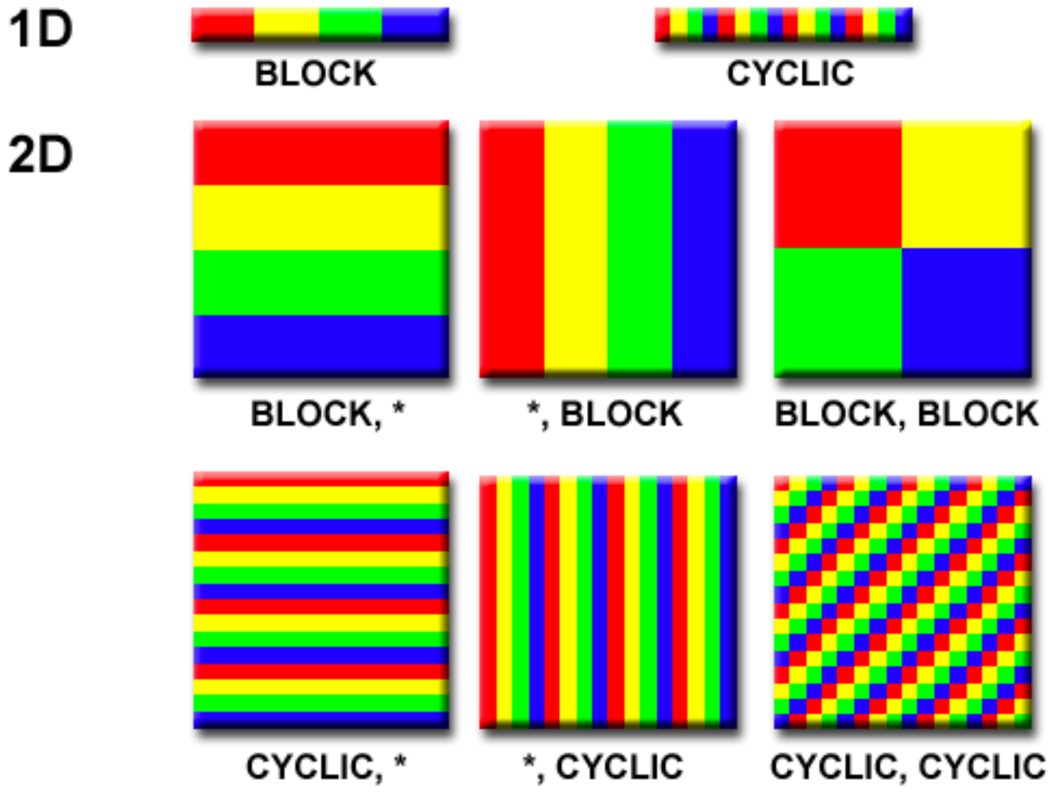

(CYCLIC,*)


(CYCLIC,CYCLIC)


(CYCLIC,BLOCK)

Partitioning options

- Block partitioning vs Cyclic partitioning

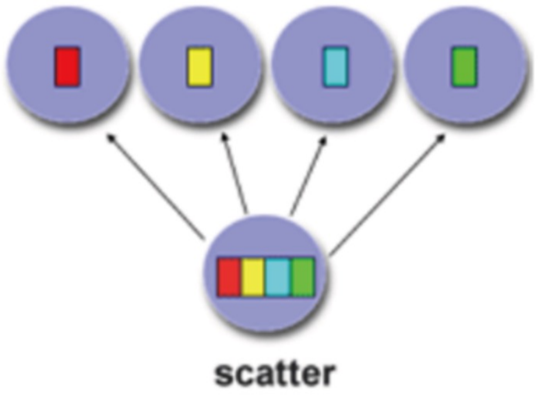


Scatter: partition & distribution

- MPI_Scatter can be used in a function that reads in an entire vector on process 0 but only sends the needed components to each of the other processes.

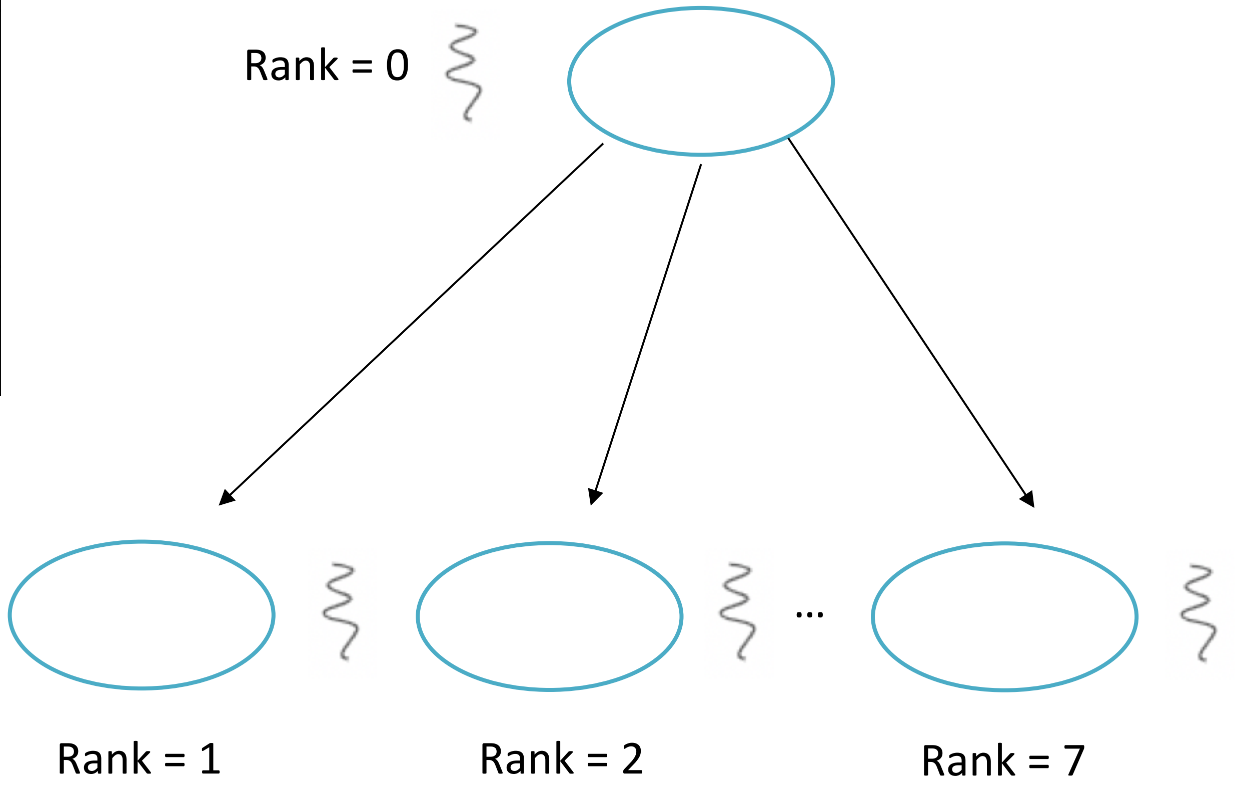
sendCount, each process gets n data

```
int MPI_Scatter(
      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   */,
      int            src_proc     /* in   */,
      MPI_Comm       comm         /* in   */);
```

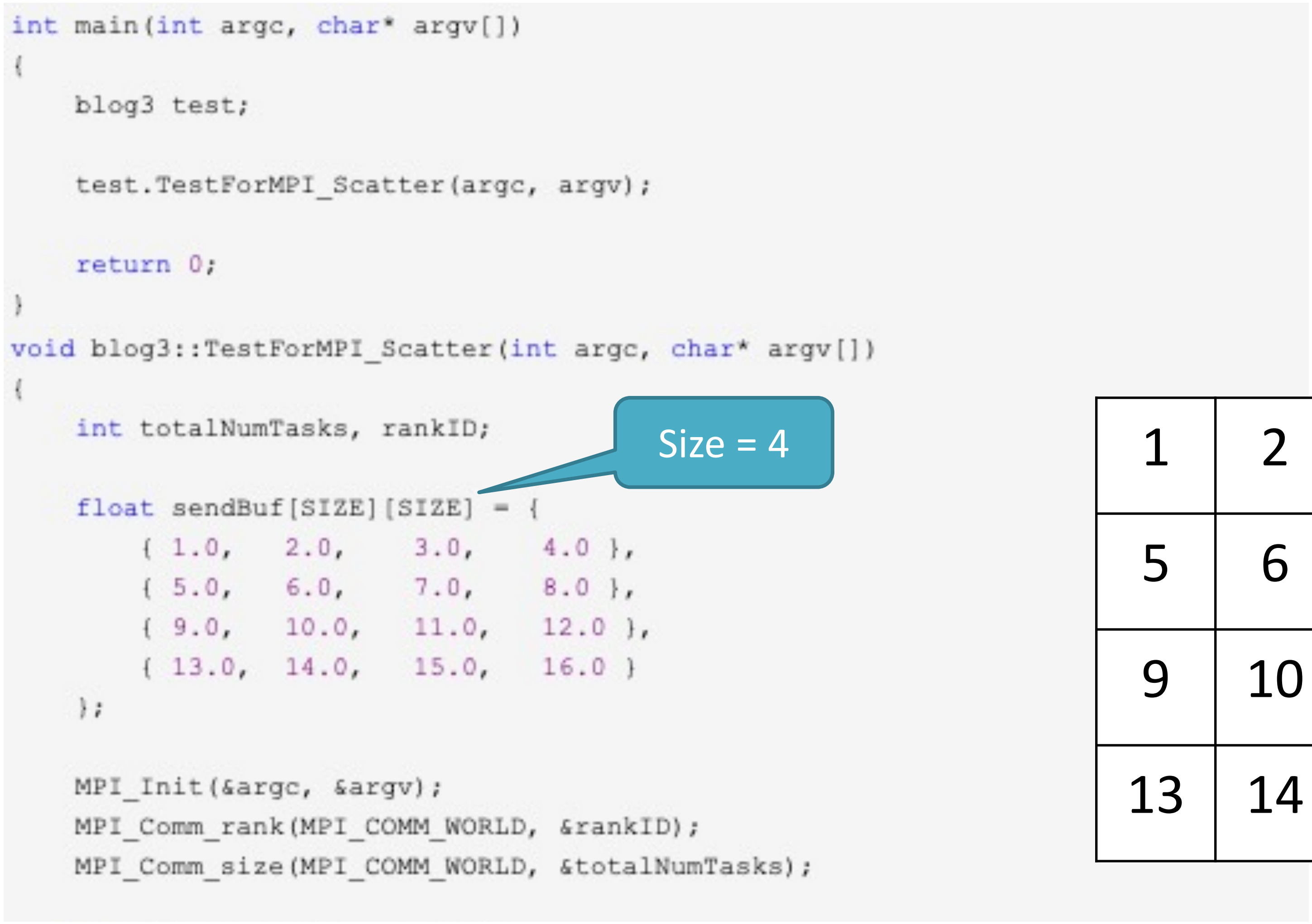


Example of MPI_Scatter

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16



Example of MPI_Scatter



```
int main(int argc, char* argv[])
{
    blog3 test;

    test.TestForMPI_Scatter(argc, argv);

    return 0;
}
void blog3::TestForMPI_Scatter(int argc, char* argv[])
{
    int totalNumTasks, rankID;

    float sendBuf[SIZE][SIZE] = {
        { 1.0,    2.0,     3.0,     4.0 },
        { 5.0,    6.0,     7.0,     8.0 },
        { 9.0,    10.0,    11.0,    12.0 },
        { 13.0,   14.0,    15.0,    16.0 }
    };

    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &rankID);
    MPI_Comm_size(MPI_COMM_WORLD, &totalNumTasks);
```

Size = 4

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

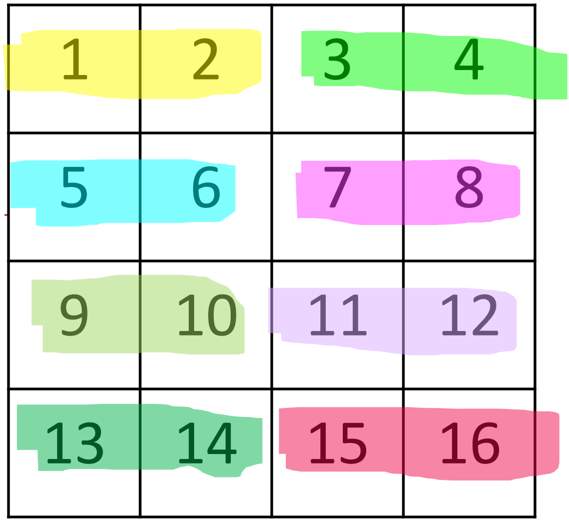
Example of MPI_Scatter

```
if (totalNumTasks == SIZE) {
    int source = 0;
    int sendCount = SIZE;
    int recvCount = SIZE;
    float recvBuf[SIZE];
    //scatter data from source process to all processes in MPI_COMM_WORLD
    MPI_Scatter(sendBuf, sendCount, MPI_FLOAT,
        recvBuf, recvCount, MPI_FLOAT, source, MPI_COMM_WORLD);

    printf("my rankID = %d, receive Results: %f %f %f %f, total = %f\n",
        rankID, recvBuf[0], recvBuf[1], recvBuf[2], recvBuf[3],
        recvBuf[0] + recvBuf[1] + recvBuf[2] + recvBuf[3]);
}
else if (totalNumTasks == 8) {
    int source = 0;
    int sendCount = 2;
    int recvCount = 2;
    float recvBuf[2];

    MPI_Scatter(sendBuf, sendCount, MPI_FLOAT,
        recvBuf, recvCount, MPI_FLOAT, source, MPI_COMM_WORLD);

    printf("my rankID = %d, receive result: %f %f, total = %f\n",
        rankID, recvBuf[0], recvBuf[1], recvBuf[0] + recvBuf[1]);
}
else {
    printf("Please specify -n %d or -n %d\n", SIZE, 2 * SIZE);
}

MPI_Finalize();
```

Size = 4

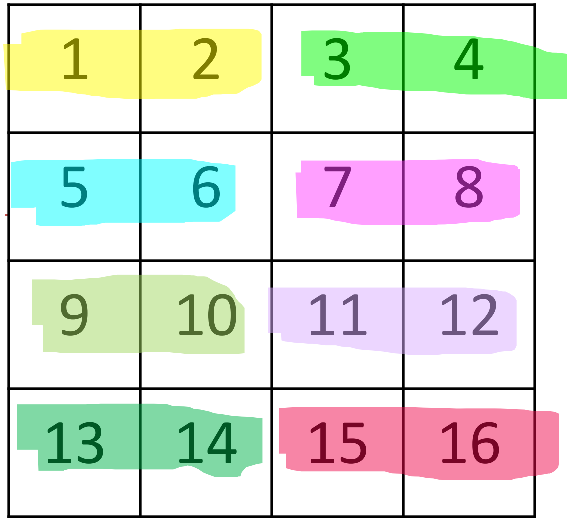
sendCount = 2, each process gets 2 data

After each process receives the data, sum them up

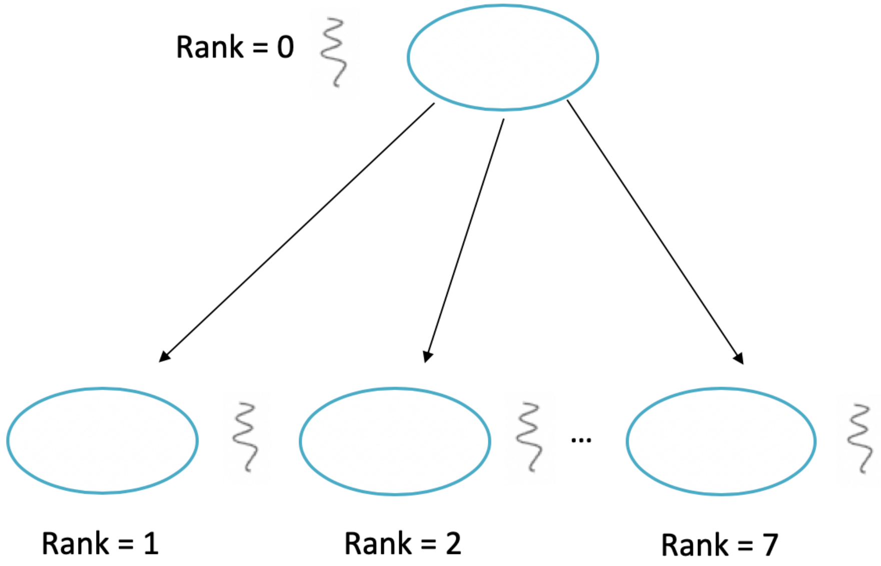


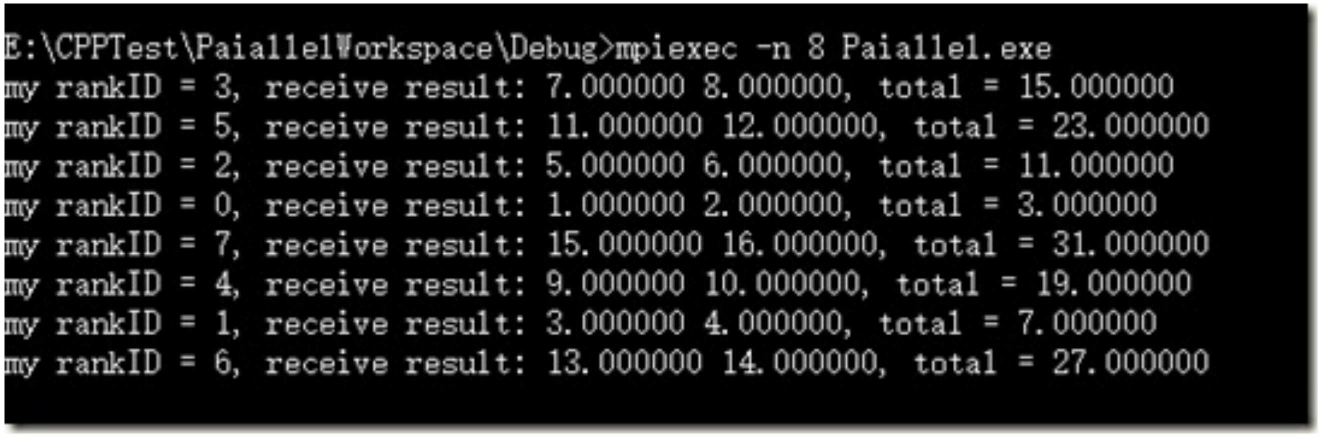
1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

Example of MPI_Scatter



1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16





```
E:\CPPTest\PaiallelWorkspace\Debug>mpiexec -n 8 Paiallel.exe
my rankID = 3, receive result: 7.000000 8.000000, total = 15.000000
my rankID = 5, receive result: 11.000000 12.000000, total = 23.000000
my rankID = 2, receive result: 5.000000 6.000000, total = 11.000000
my rankID = 0, receive result: 1.000000 2.000000, total = 3.000000
my rankID = 7, receive result: 15.000000 16.000000, total = 31.000000
my rankID = 4, receive result: 9.000000 10.000000, total = 19.000000
my rankID = 1, receive result: 3.000000 4.000000, total = 7.000000
my rankID = 6, receive result: 13.000000 14.000000, total = 27.000000
```

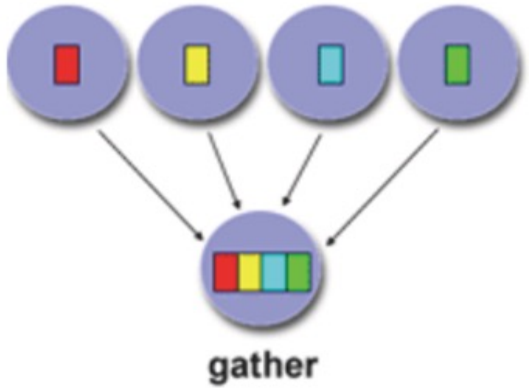
Gather

- Collect all of the components of the vector onto process 0, and then process 0 can process all of the components.

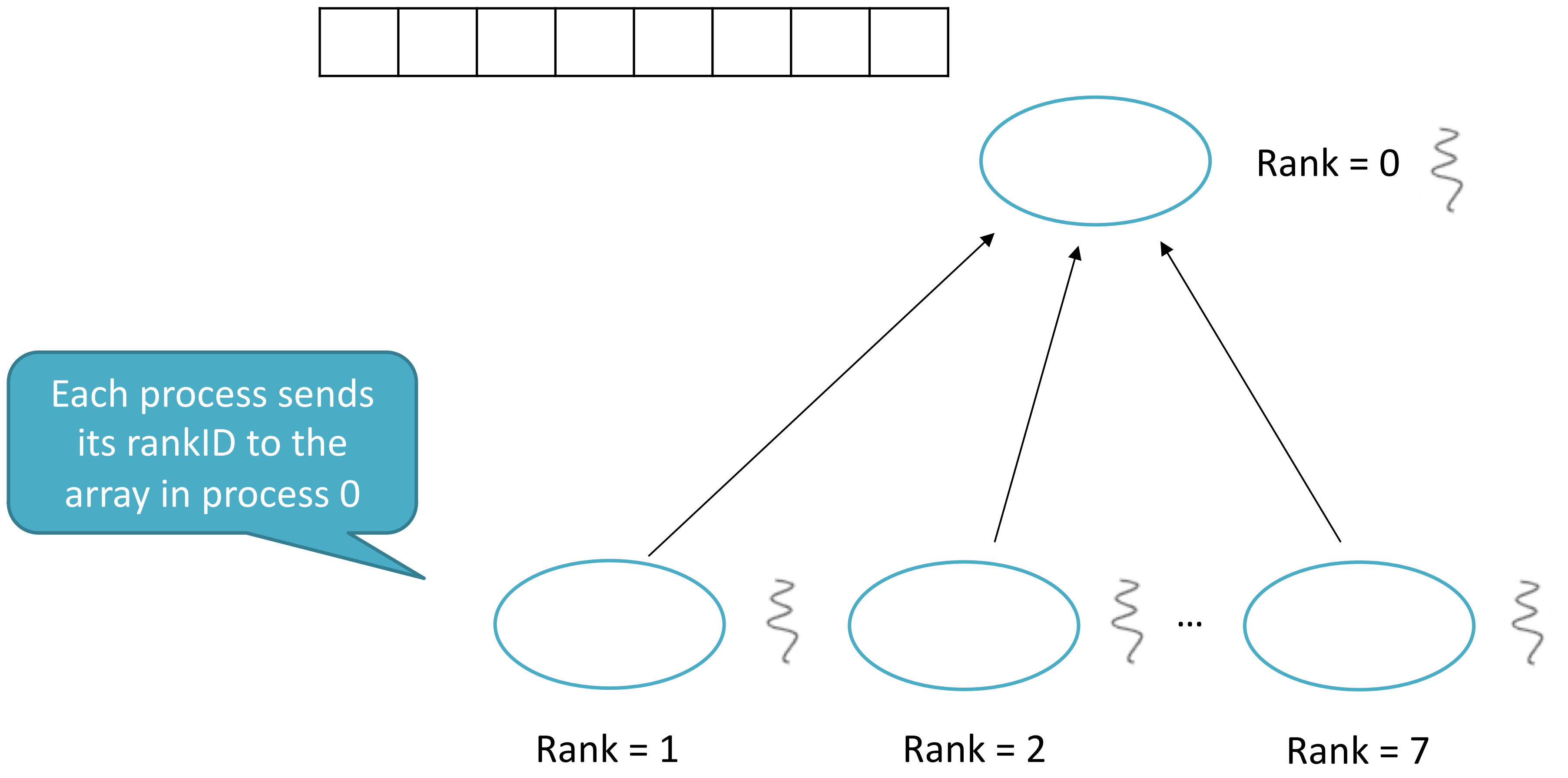
```
int MPI_Gather(
      void*          send_buf_p  /* in   */,
      int            send_count  /* in   */,
      MPI_Datatype   send_type   /* in   */,
      void*          recv_buf_p  /* out  */,
      int            recv_count  /* in   */,
      MPI_Datatype   recv_type   /* in   */,
      int 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

Send data

Receiver ID



Example of MPI_Gather

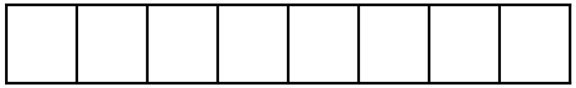


Each process sends its rankID to the array in process 0

Example of MPI_Gather

```
int main(int argc, char* argv[])
{
    blog3 test;

    test.TestForMPI_Gather(argc, argv);

    return 0;
}
void blog3::TestForMPI_Gather(int argc, char* argv[])
{
    int rankID, totalNumTasks;

    MPI_Init(&argc, &argv);
    MPI_Barrier(MPI_COMM_WORLD);
    double elapsed_time = -MPI_Wtime();

    MPI_Comm_rank(MPI_COMM_WORLD, &rankID);
    MPI_Comm_size(MPI_COMM_WORLD, &totalNumTasks);
```

Example of MPI_Gather



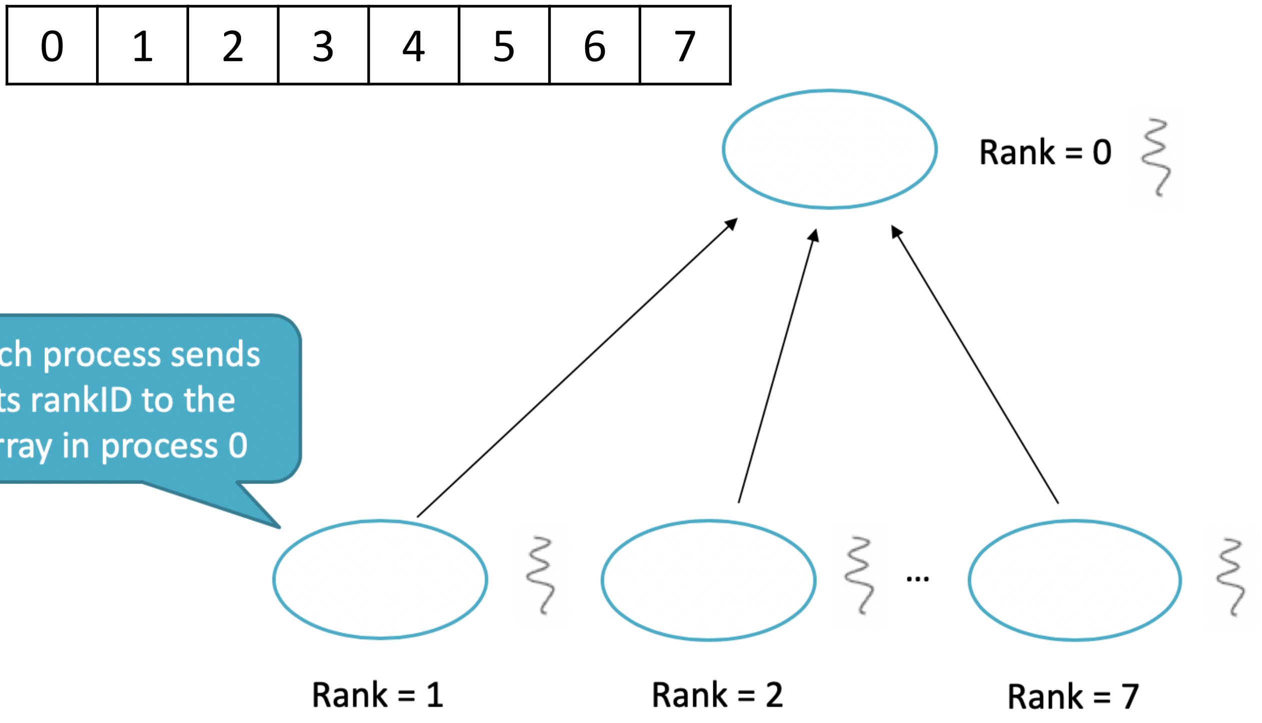
```c
int* gatherBuf = (int *)malloc(sizeof(int) * totalNumTasks);
if (gatherBuf == NULL) {
    printf("malloc error!");
    exit(-1);
    MPI_Finalize();
}

int sendBuf = rankID; //for each process, its rankID will be sent out

int sendCount = 1;
int recvCount = 1;
int root = 0;
MPI_Gather(&sendBuf, sendCount, MPI_INT, gatherBuf, recvCount, MPI_INT, root, MPI_COMM_WORLD);

elapsed_time += MPI_Wtime();
if (!rankID) {
    int i;
    for (i = 0; i < totalNumTasks; i++) {
        printf("gatherBuf[%d] = %d, ", i, gatherBuf[i]);
    }
    putchar('\n');
    printf("total elapsed time = %10.6f\n", elapsed_time);
}

MPI_Finalize();
```

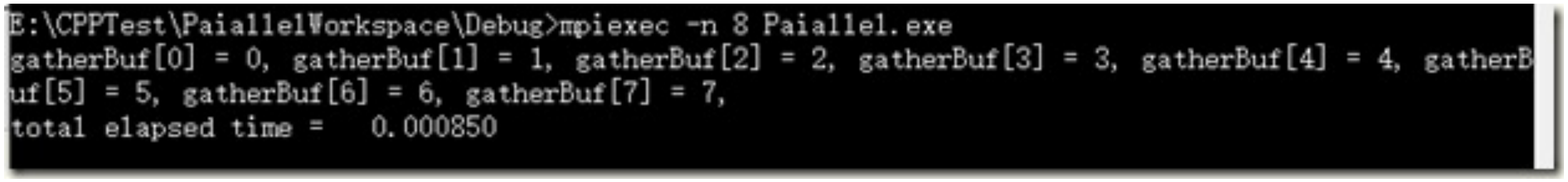
The sent content is the rankID

Data size is 1

Receiver is process 0

Example of MPI_Gather

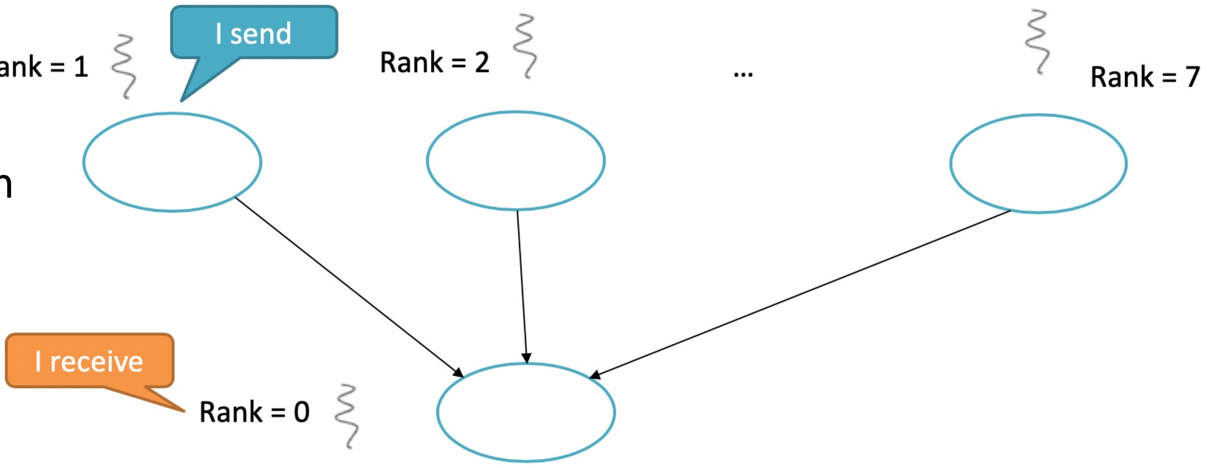




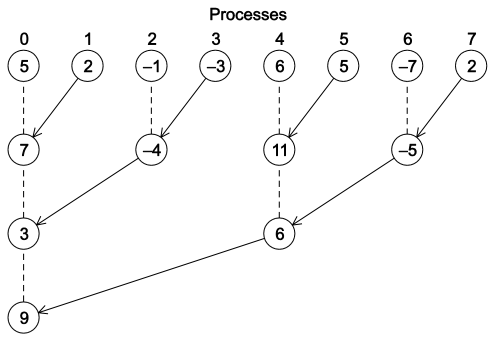
```
E:\CPPTest\PaiallelWorkspace\Debug>mpiexec -n 8 Paiallel.exe
gatherBuf[0] = 0, gatherBuf[1] = 1, gatherBuf[2] = 2, gatherBuf[3] = 3, gatherBuf[4] = 4, gatherB
uf[5] = 5, gatherBuf[6] = 6, gatherBuf[7] = 7,
total elapsed time =    0.000850
```

Conclusion

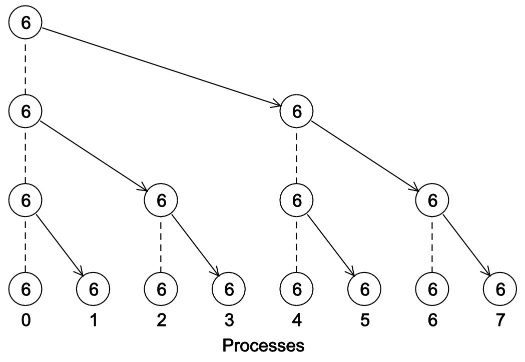
Point-to-Point communication
MPI_Send
MPI_Receive



MPI_Reduce

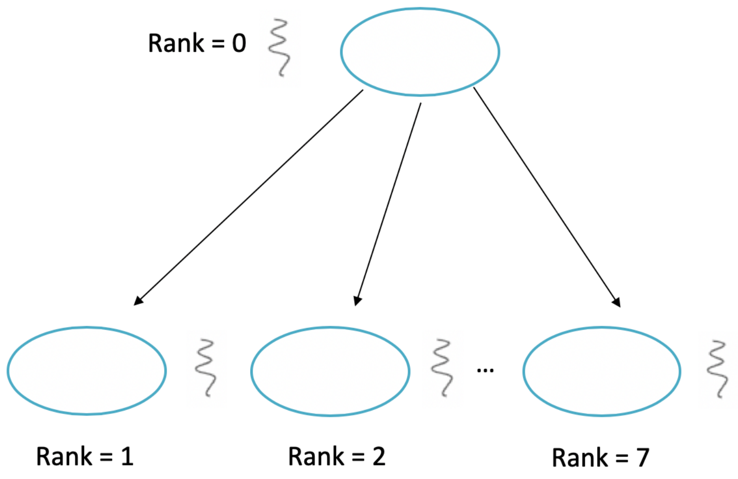


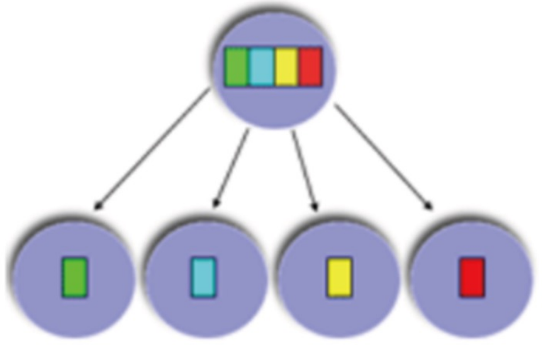
MPI_Bcast



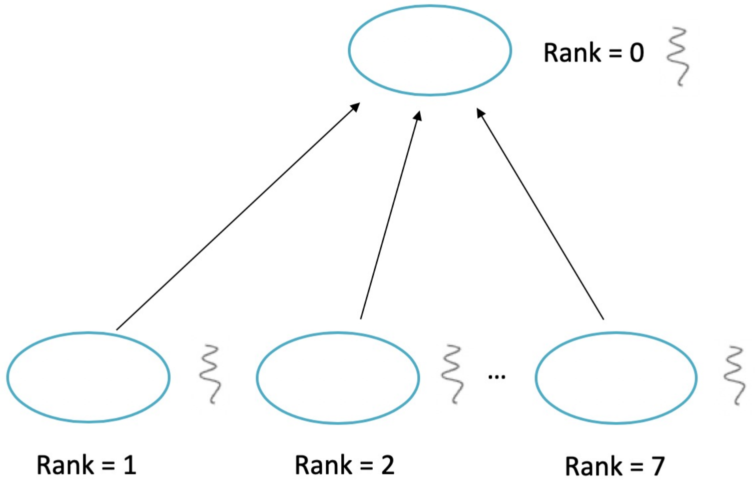
Conclusion

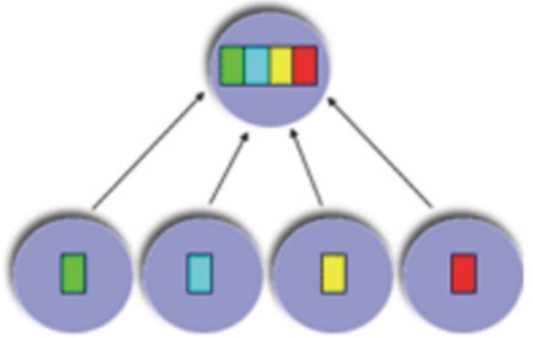
MPI_Scatter





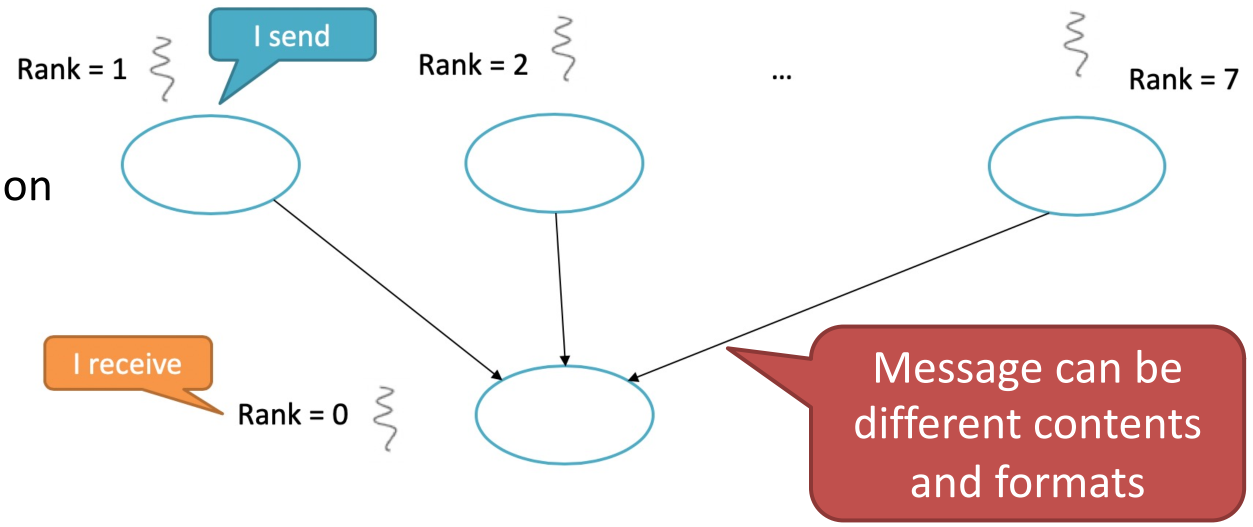
MPI_Gather



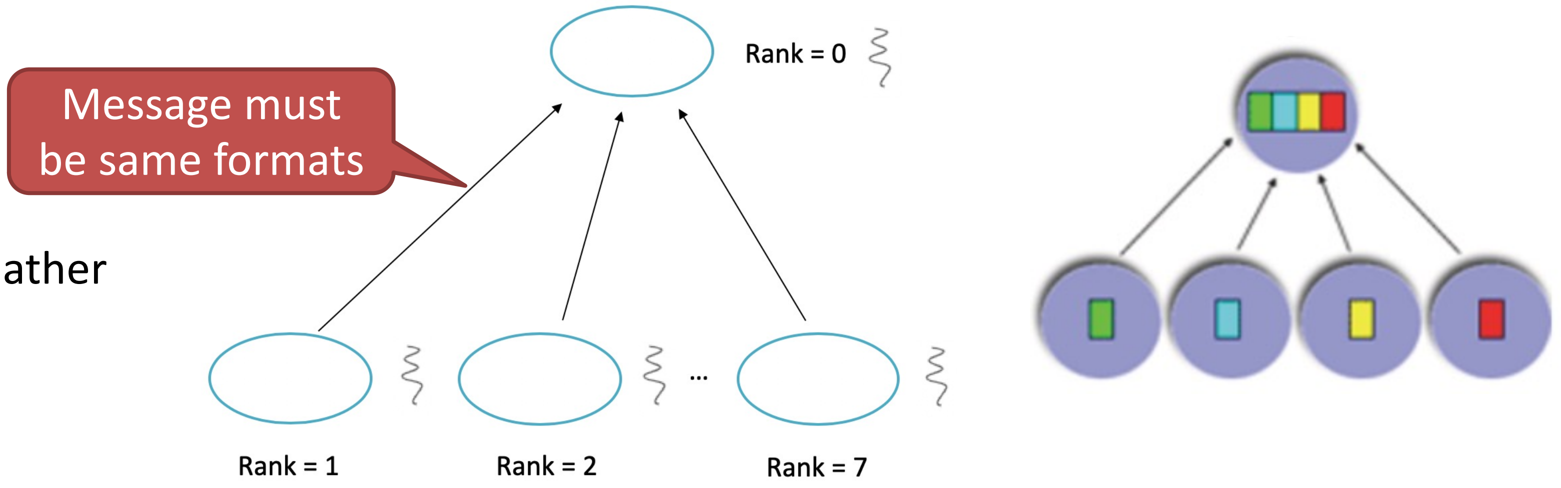


What is the Difference between Point-to-Point communication and MPI_Gather?

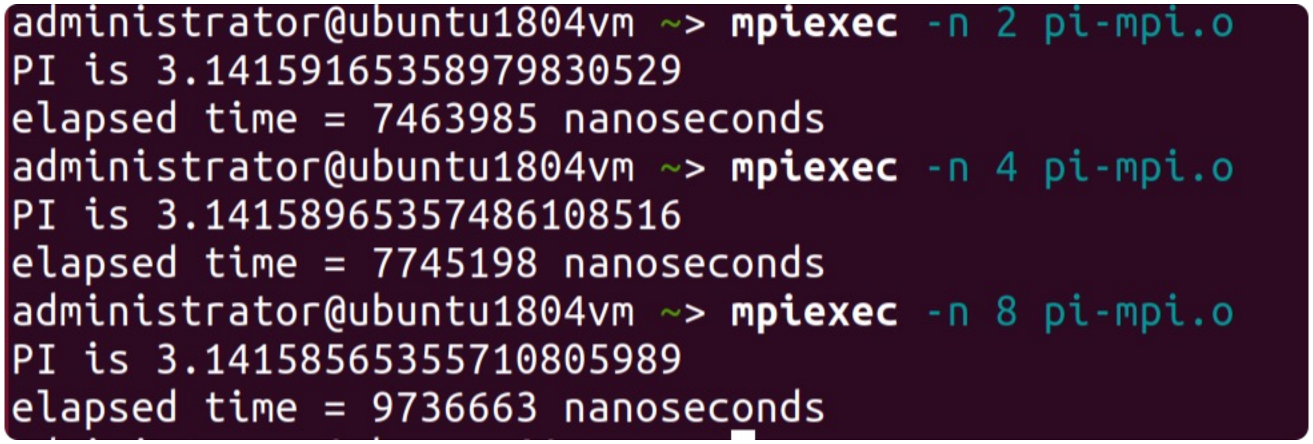
Point-to-Point communication
MPI_Send
MPI_Receive



MPI_Gather



Hint of Project



```
administrator@ubuntu1804vm ~> mpiexec -n 2 pi-mpi.o
PI is 3.14159165358979830529
elapsed time = 7463985 nanoseconds
administrator@ubuntu1804vm ~> mpiexec -n 4 pi-mpi.o
PI is 3.14158965357486108516
elapsed time = 7745198 nanoseconds
administrator@ubuntu1804vm ~> mpiexec -n 8 pi-mpi.o
PI is 3.14158565355710805989
elapsed time = 9736663 nanoseconds
```

Result in a.aa:

2 digits

$$3.332 \approx 3.33 + 1.999 = 5.329 \approx 5.33$$

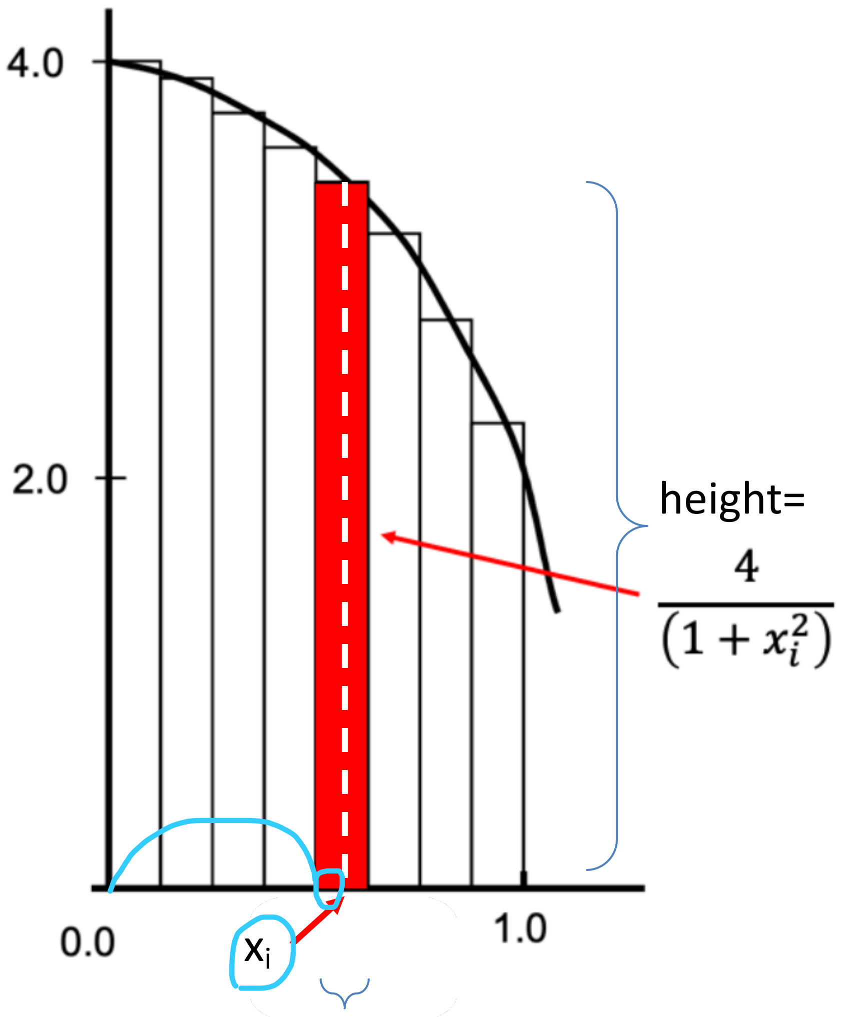
$$\overbrace{1.555 + 1.777} + 1.999 = ?$$

$$1.555 + \underbrace{1.777 + 1.999}$$

$$3.776 \approx 3.78 + 1.555 = 5.335 \approx 5.34$$

Hint of Project

$$y = \frac{4}{(1+x^2)}$$



width=step

Hint of Project

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

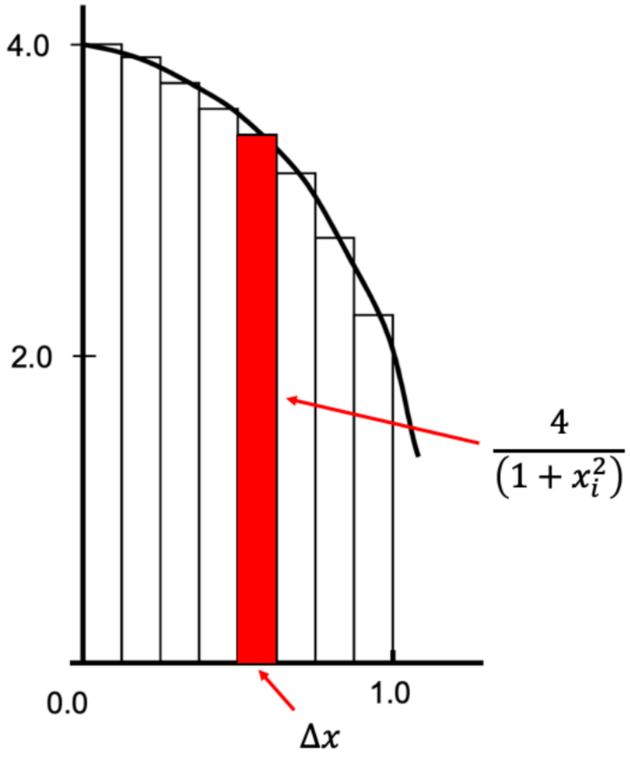
```
#define NUMSTEPS 1000000

int main() {
        int i;
        double x, pi, sum = 0.0;
        struct timespec start, end;

        clock_gettime(CLOCK_MONOTONIC, &start);
        double step = 1.0/(double) NUMSTEPS;
        x = 0.5 * step;

        for (i=0;i<= NUMSTEPS; i++){
                x+=step;
                sum += 4.0/(1.0+x*x);
        }
        pi = step * sum;
        clock_gettime(CLOCK_MONOTONIC, &end);
        u_int64_t diff = 1000000000L * (end.tv_sec - start.tv_sec) + end.tv_nsec -
start.tv_nsec;

        printf("PI is %.20f\n",pi);
        printf("elapsed time = %llu nanoseconds\n", (long long unsigned int) diff);

        return 0;
}
```

Δx

y

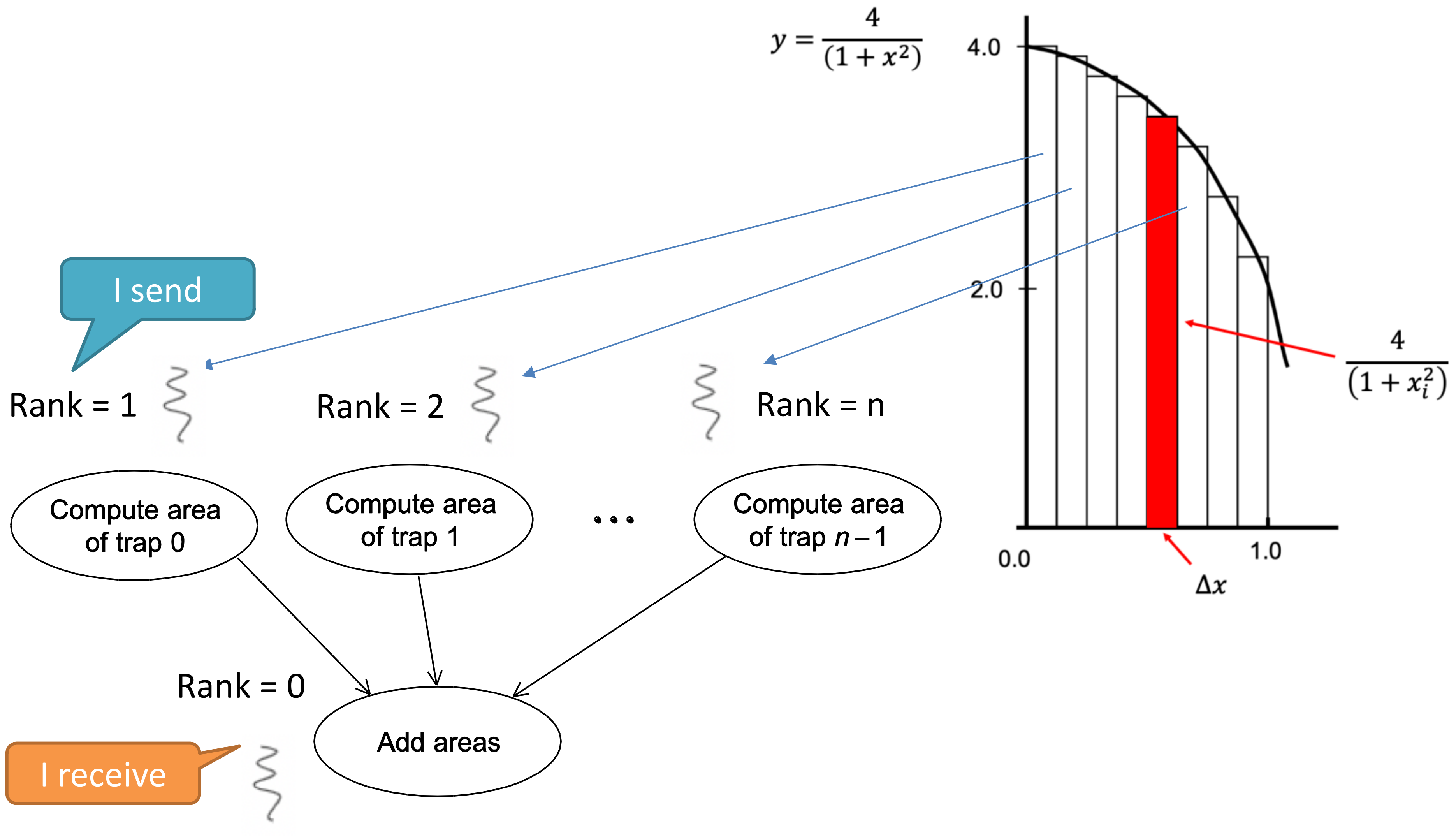
size of rectangle

$$y = \frac{4}{(1+x^2)}$$



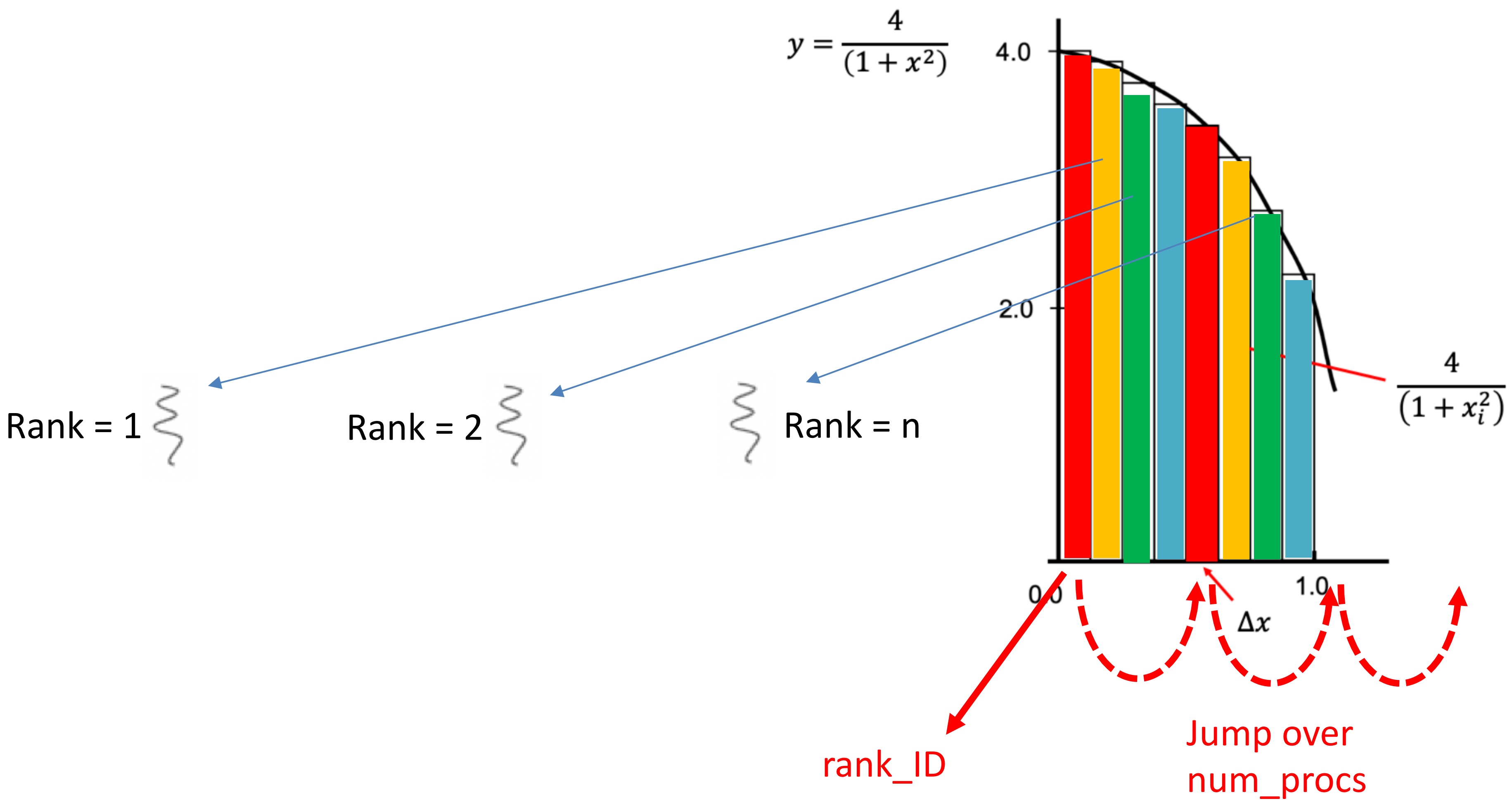
Hint of Project

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



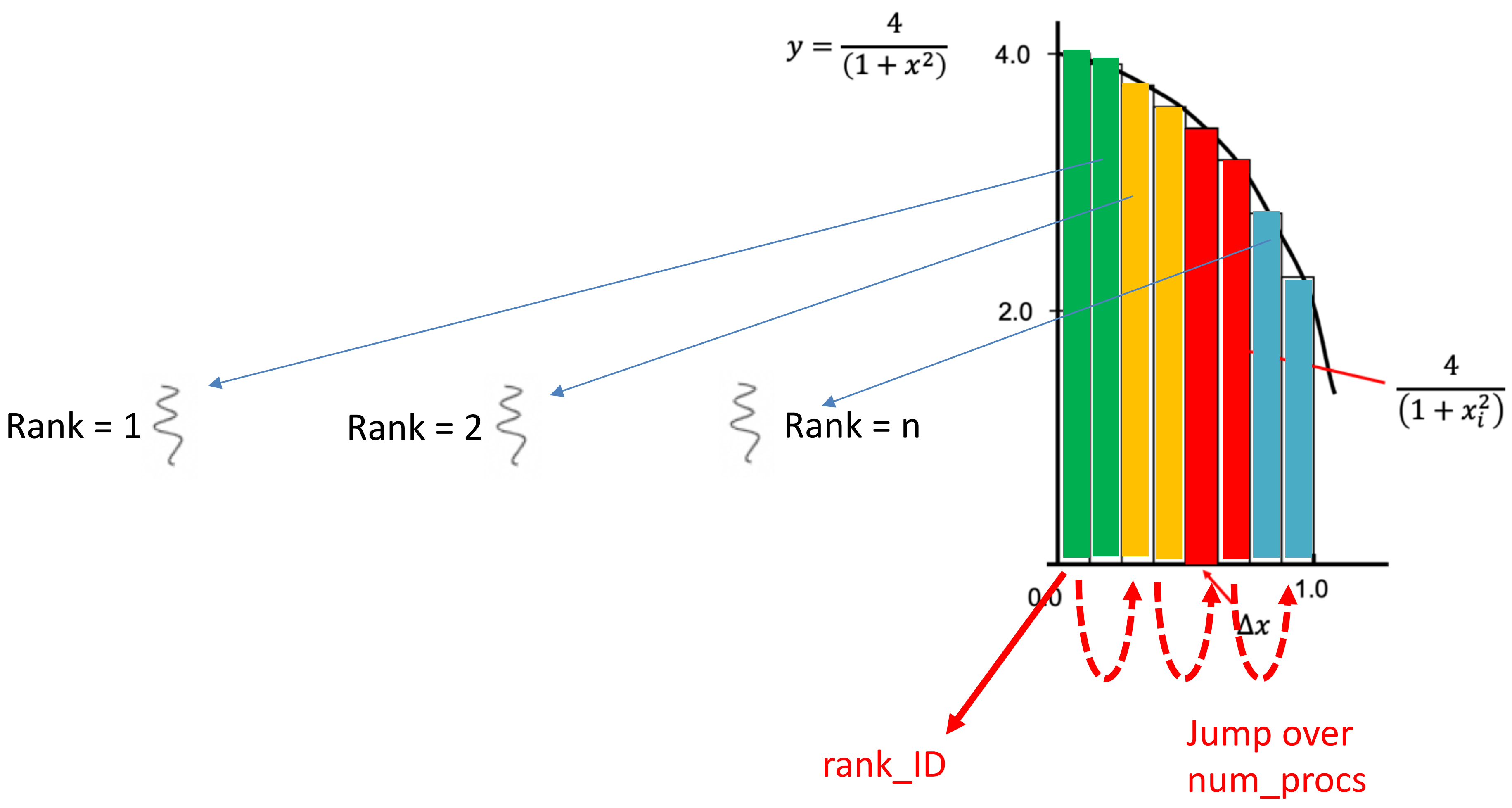
Hint of Project

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



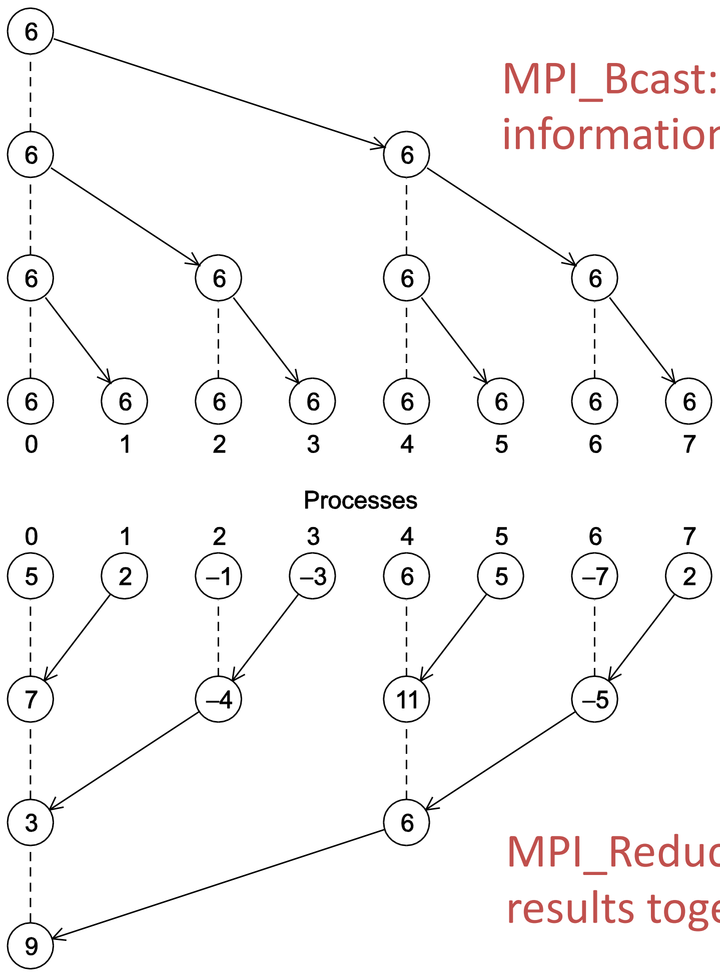
Hint of Project

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



Hint of Project

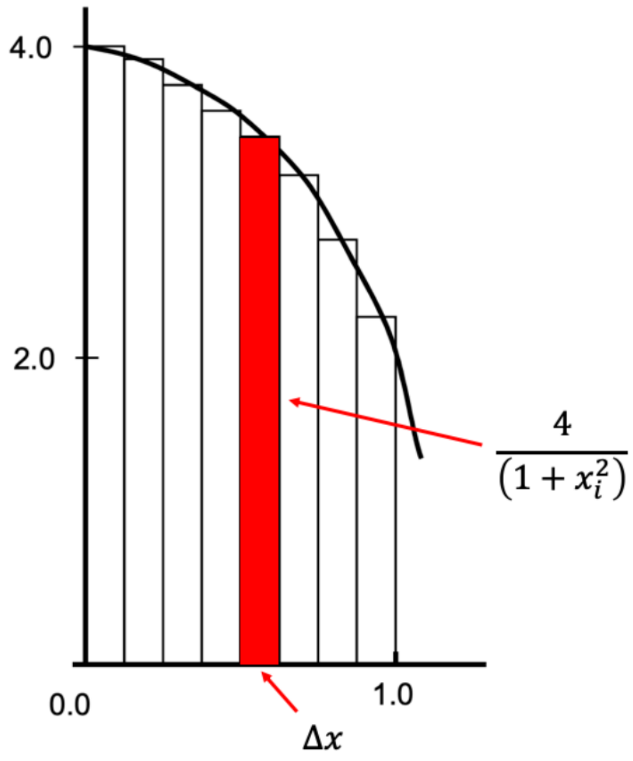
$$\int_0^1 \frac{4}{(1+x^2)}dx = \pi$$



MPI_Bcast: broadcast information to all threads

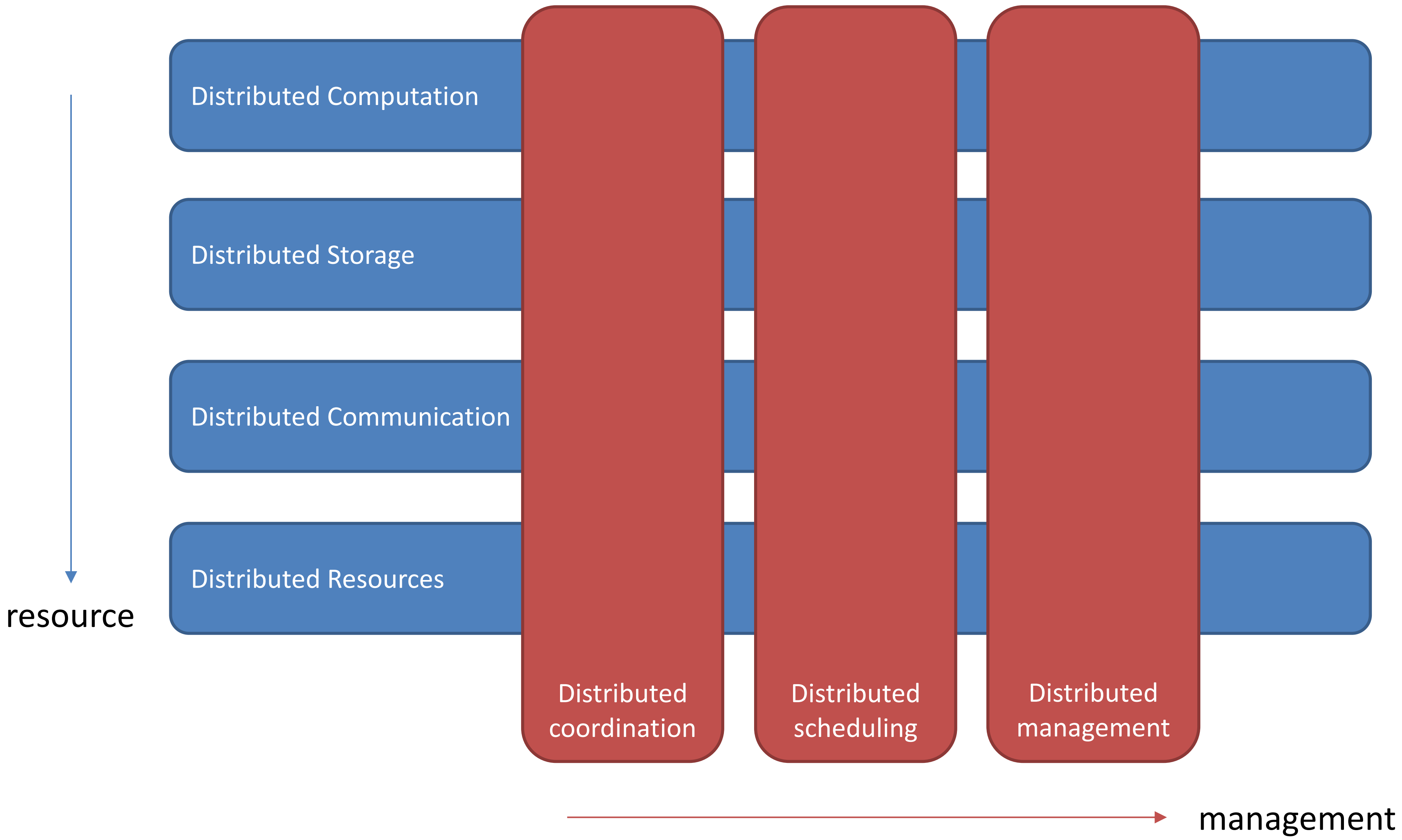
MPI_Reduce: sum up results together

$$y = \frac{4}{(1+x^2)}$$



Overview

Hadoop, zookeeper, Kafka, Dapper, MapReduce, GFS, Comet, Spanner, ...


Distributed Computation
Distributed Storage
Distributed Communication
Distributed Resources
resource
Distributed coordination
Distributed scheduling
Distributed management
management