CS 4504
Parallel and Distributed Computation

Message Passing Interface (MPI)

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https://kevinsuo.github.io/

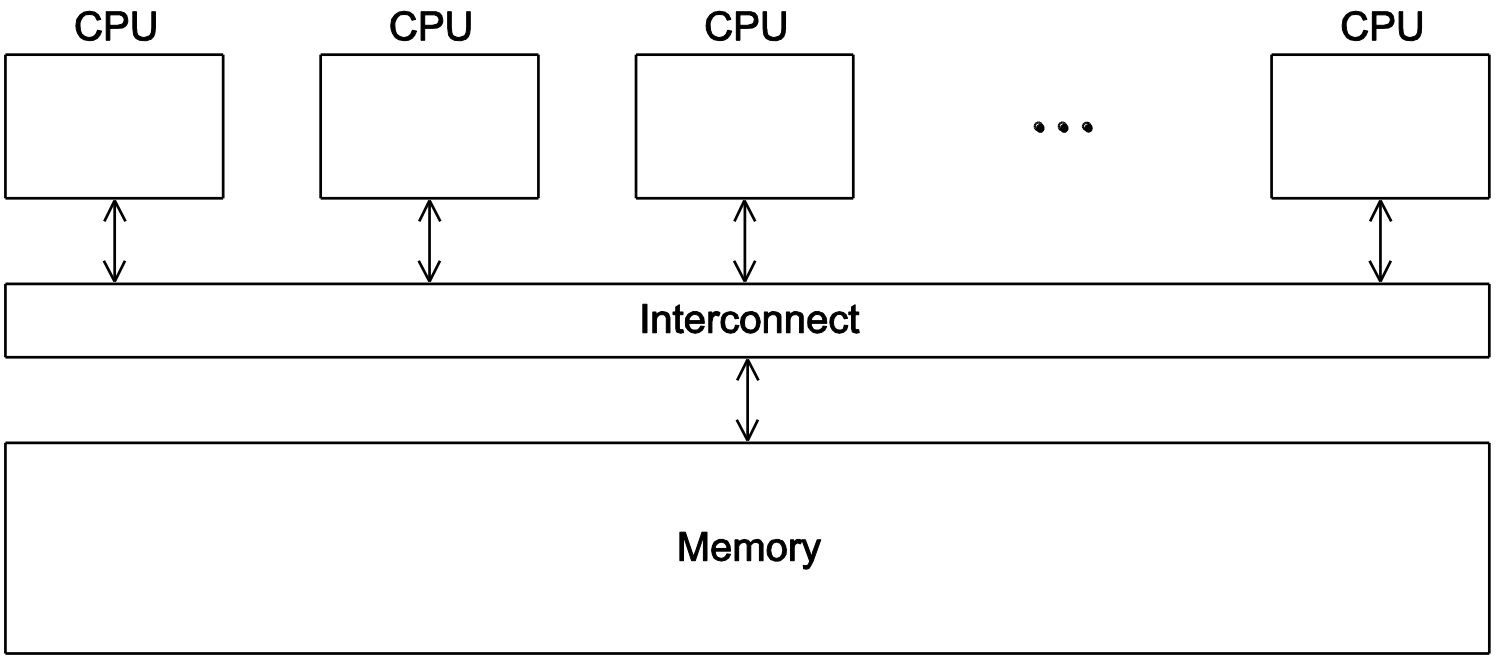
Outline

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

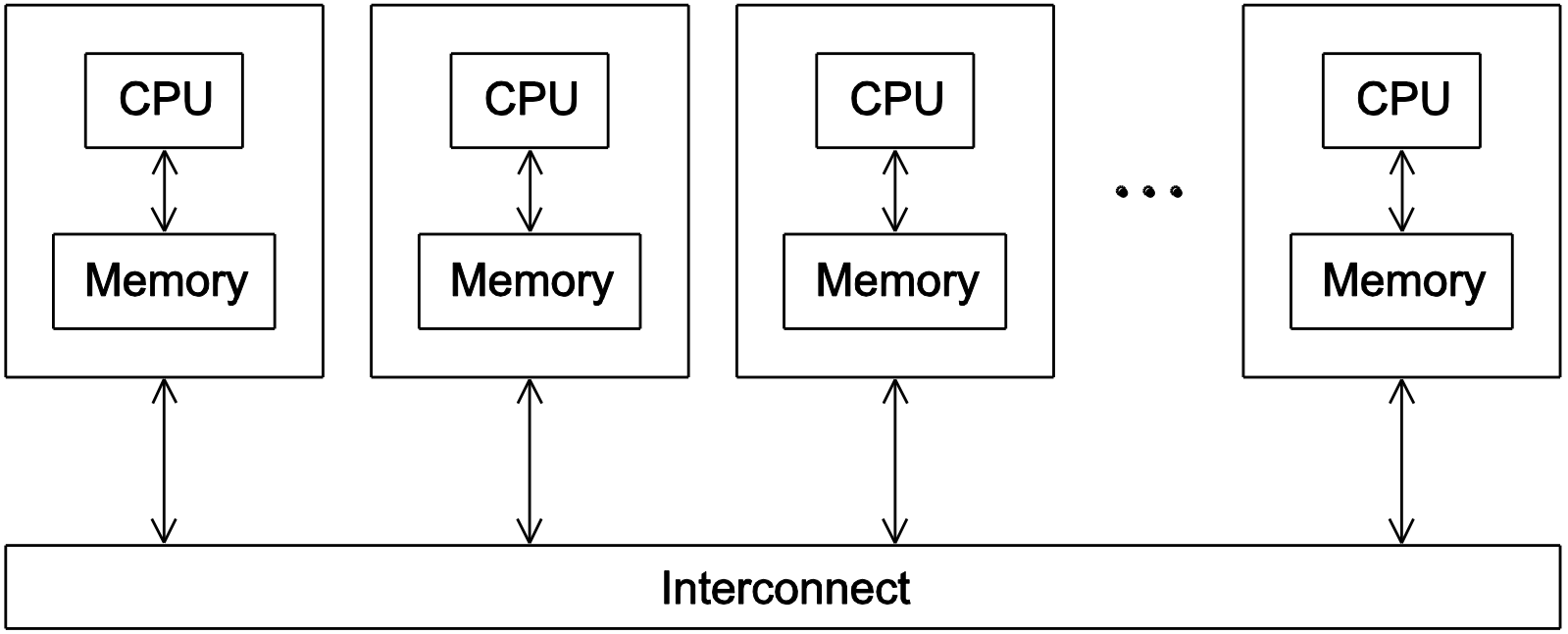
What is MPI?

- Message Passing Interface (MPI) is a standardized library for parallel computing

A shared memory system



A distributed memory system



Hello World!

```
#include <stdio.h>

int main(void) {
    printf("hello, world\n");

    return 0;
}
```

helloworld-mpi.c

https://github.com/kevinsuo/CS7172/blob/master/helloworld-mpi.c

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

int main(int argc, char** argv) {
    // Initialize the MPI environment
    MPI_Init(NULL, NULL);

    // Get the number of processes
    int world_size;
    MPI_Comm_size(MPI_COMM_WORLD, &world_size);

    // Get the rank of the process
    int world_rank;
    MPI_Comm_rank(MPI_COMM_WORLD, &world_rank);

    // Get the name of the processor
    char processor_name[MPI_MAX_PROCESSOR_NAME];
    int name_len;
    MPI_Get_processor_name(processor_name, &name_len);

    // Print off a hello world message
    printf("Hello world from processor %s, rank %d out of %d processors\n",
           processor_name, world_rank, world_size);

    // Finalize the MPI environment.
    MPI_Finalize();
}
```

MPI Programs

- Written in C.
  - Has main.
  - Uses stdio.h, string.h, etc.
- Need to add mpi.h header file.

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

int main(int argc, char** argv) {
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    MPI_Init(NULL, NULL);

    // Get the number of processes
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    // Print off a hello world message
    printf("Hello world from processor %s, rank %d out of %d processors\n",
           processor_name, world_rank, world_size);

    // Finalize the MPI environment.
    MPI_Finalize();
}
```

- Identifiers defined by MPI start with “MPI_”.
- First letter following underscore is uppercase (e.g., MPI_Init).
  - For function names and MPI-defined types.
  - Helps to avoid confusion.

MPI Components

- MPI_Init
  - Tells MPI to do all the necessary setup.

```
int MPI_Init(
      int*      argc_p  /* in/out */,
      char***   argv_p  /* in/out */);
```

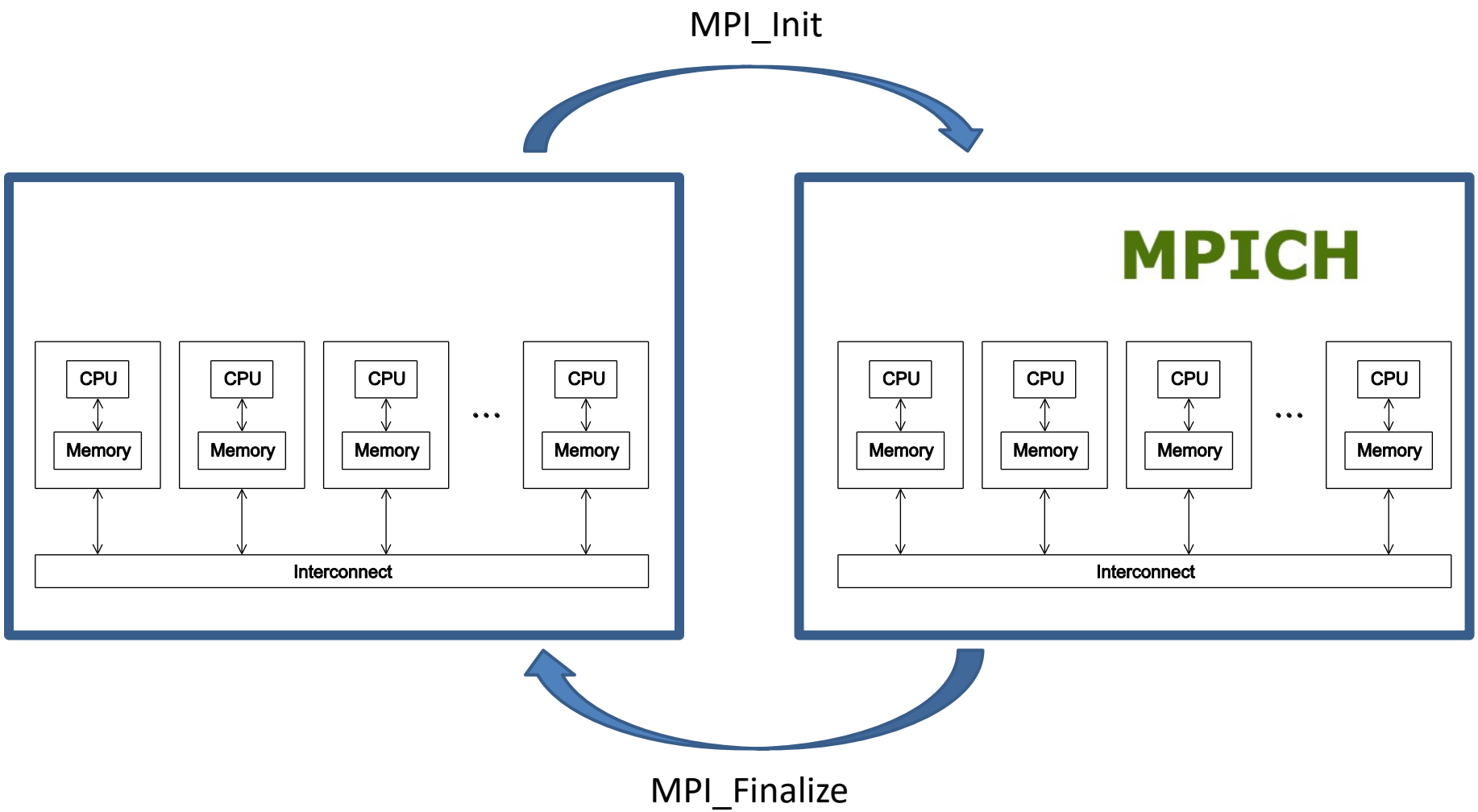
- MPI_Finalize
  - Tells MPI we're done, so clean up anything allocated for this program.

```
int MPI_Finalize(void);
```

Basic Outline

```
. . .
#include <mpi.h>
. . .
int main(int argc, char* argv[]) {
   . . .
   /* No MPI calls before this */
   MPI_Init(&argc, &argv);
   . . .
   MPI_Finalize();
   /* No MPI calls after this */
   . . .
   return 0;
}
```

MPI Components



helloworld-mpi.c

https://github.com/kevinsuo/CS7172/blob/master/helloworld-mpi.c

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int main(int argc, char** argv) {
    // Initialize the MPI environment
    MPI_Init(NULL, NULL);

    // Get the number of processes
    int world_size;
    MPI_Comm_size(MPI_COMM_WORLD, &world_size);

    // Get the rank of the process
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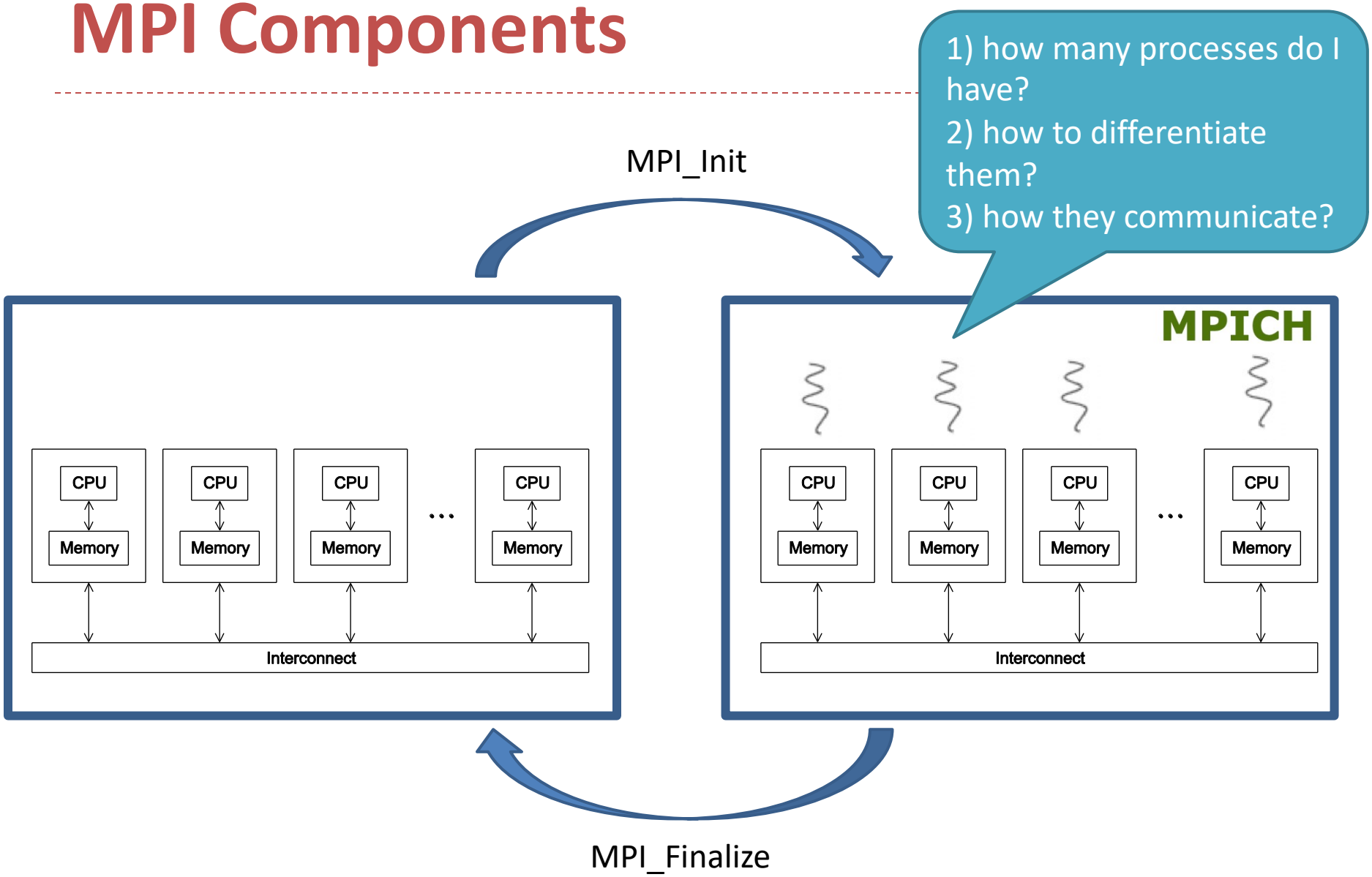
    // Get the name of the processor
    char processor_name[MPI_MAX_PROCESSOR_NAME];
    int name_len;
    MPI_Get_processor_name(processor_name, &name_len);

    // Print off a hello world message
    printf("Hello world from processor %s, rank %d out of %d processors\n",
           processor_name, world_rank, world_size);

    // Finalize the MPI environment.
    MPI_Finalize();
}
```

MPI Components



Communicators

- A collection of processes that can send messages to each other.

- MPI_Init defines a communicator that consists of all the processes created when the program is started (defined by user).

- Called MPI_COMM_WORLD. → Number of process

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}
```

Communicators

```
int MPI_Comm_size(
      MPI_Comm   comm          /* in  */,
      int*       comm_sz_p     /* out */);
```

number of processes in the communicator

```
int MPI_Comm_rank(
      MPI_Comm   comm          /* in  */,
      int*       my_rank_p     /* out */);
```

my rank
(the process making this call)

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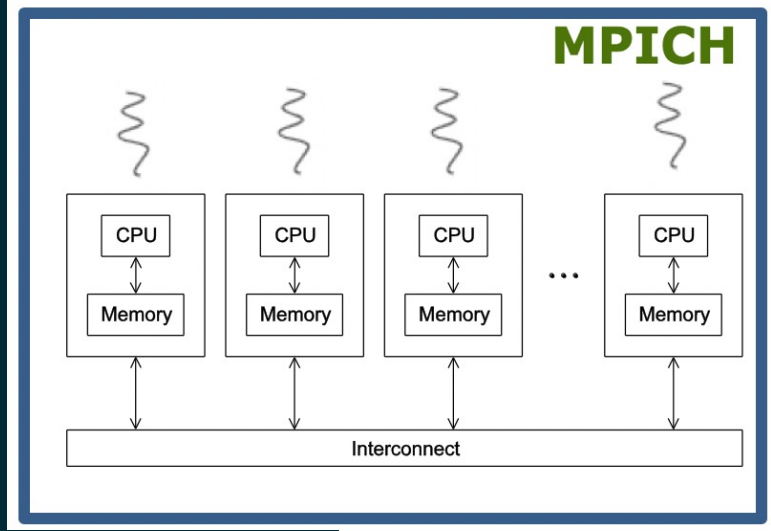
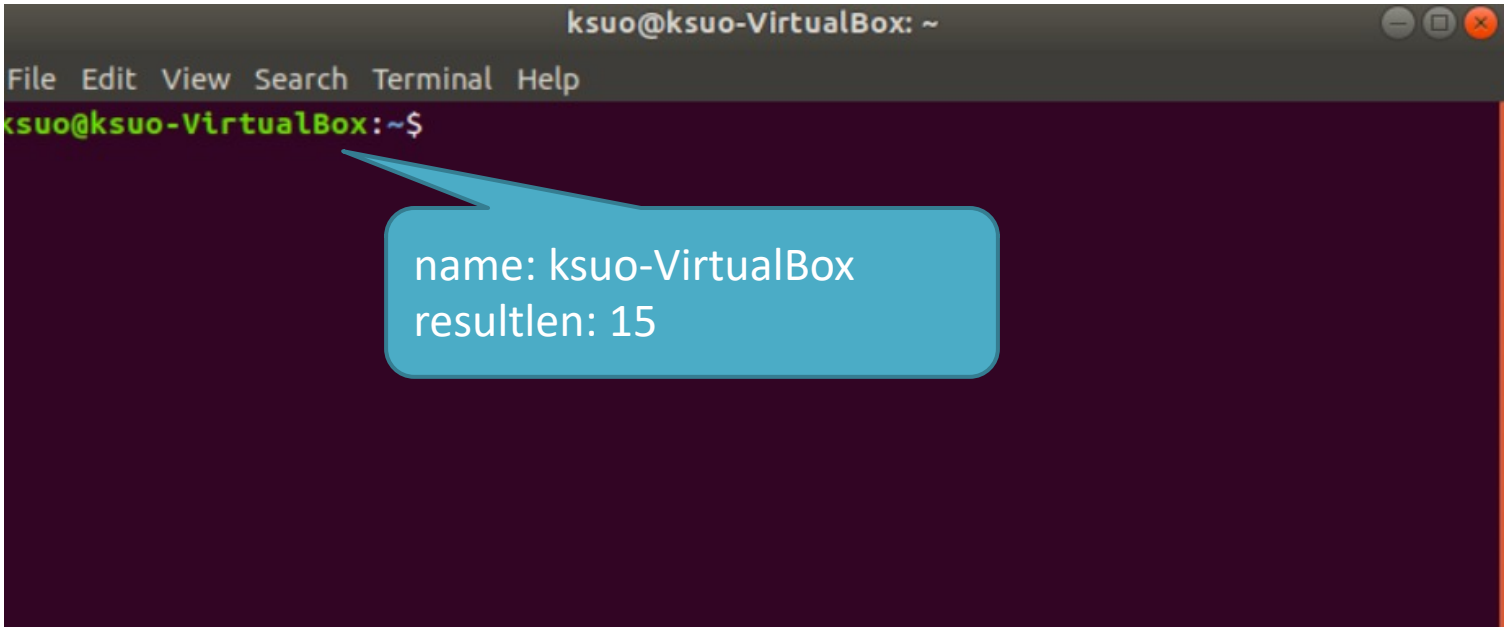
```



MPI_Get_processor_name(char *name,int *resultlen)

- name: your machine name string
- resultlen: your machine name string length



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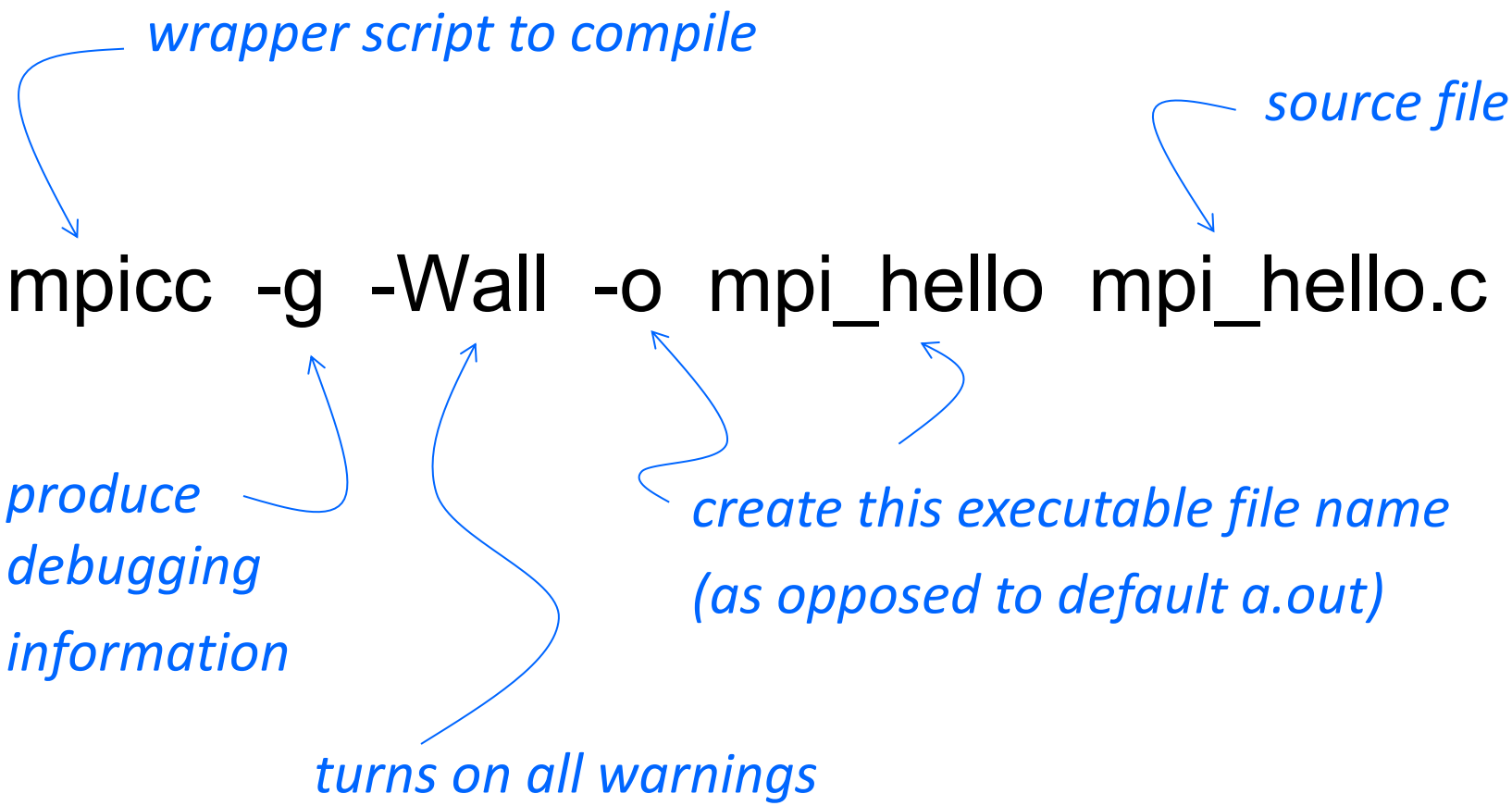
```

Compile


wrapper script to compile
source file
mpicc -g -Wall -o mpi_hello mpi_hello.c
produce debugging information
turns on all warnings
create this executable file name (as opposed to default a.out)

Execution

mpiexec -n <number of processes> <executable>

---

mpiexec -n 1 ./mpi_hello

mpiexec -n 4 ./mpi_hello

Execution

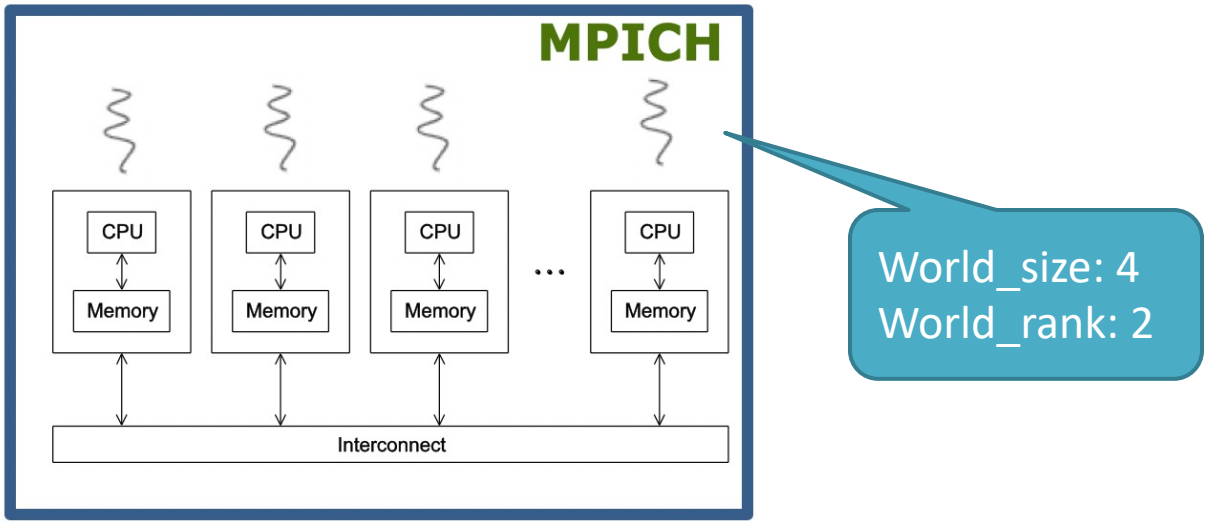
```
mpiexec  -n  1  ./mpi_hello

    Greetings from process 0 of 1 !
```

```
mpiexec  -n  4  ./mpi_hello

    Greetings from process 0 of 4 !
    Greetings from process 1 of 4 !
    Greetings from process 2 of 4 !
    Greetings from process 3 of 4 !
```

```
ksuo@ksuo-VirtualBox ~/cs7172> mpiexec -n 4 ./helloworld-mpi.o
Hello world from processor ksuo-VirtualBox, rank 0 out of 4 processors
Hello world from processor ksuo-VirtualBox, rank 1 out of 4 processors
Hello world from processor ksuo-VirtualBox, rank 2 out of 4 processors
Hello world from processor ksuo-VirtualBox, rank 3 out of 4 processors
ksuo@ksuo-VirtualBox ~/cs7172> mpiexec -n 2 ./helloworld-mpi.o
Hello world from processor ksuo-VirtualBox, rank 1 out of 2 processors
Hello world from processor ksuo-VirtualBox, rank 0 out of 2 processors
ksuo@ksuo-VirtualBox ~/cs7172> mpiexec -n 1 ./helloworld-mpi.o
Hello world from processor ksuo-VirtualBox, rank 0 out of 1 processors
```



helloworld-mpi.c

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    // Get the rank of the process
    int world_rank;
    MPI_Comm_rank(MPI_COMM_WORLD, &world_rank);

    // Get the name of the processor
    char processor_name[MPI_MAX_PROCESSOR_NAME];
    int name_len;
    MPI_Get_processor_name(processor_name, &name_len);

    // Print off a hello world message
    printf("Hello world from processor %s, rank %d out of %d processors\n",
           processor_name, world_rank, world_size);

    // Finalize the MPI environment.
    MPI_Finalize();
}
```

```
ksuo@ksuo-VirtualBox ~/cs7172> mpiexec -n 4 ./helloworld-mpi.o
Hello world from processor ksuo-VirtualBox, rank 0 out of 4 processors
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Hello world from processor ksuo-VirtualBox, rank 3 out of 4 processors
ksuo@ksuo-VirtualBox ~/cs7172> mpiexec -n 2 ./helloworld-mpi.o
Hello world from processor ksuo-VirtualBox, rank 1 out of 2 processors
Hello world from processor ksuo-VirtualBox, rank 0 out of 2 processors
ksuo@ksuo-VirtualBox ~/cs7172> mpiexec -n 1 ./helloworld-mpi.o
Hello world from processor ksuo-VirtualBox, rank 0 out of 1 processors
```

Performance evaluation

Elapsed parallel time

- 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);
```

Example

https://raw.githubusercontent.com/kevinsuo/CS7172/master/time_sample.c

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

int main( int argc, char *argv[] )
{
        double t1, t2 = 0;

        MPI_Init( 0, 0 );
        sleep(10);
        printf("MPI_Wtime measured a 1 second sleep to be: %1.2f\n", t2-t1);fflush(stdout);
        MPI_Finalize( );
        return 0;
}
```

Example

https://raw.githubusercontent.com/kevinsuo/CS7172/master/time_sample.c

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

int main( int argc, char *argv[] )
{
        double t1, t2;

        MPI_Init( 0, 0 );
        t1 = MPI_Wtime();
        sleep(10);
        t2 = MPI_Wtime();
        printf("MPI_Wtime measured a 1 second sleep to be: %1.2f\n", t2-t1);fflush(stdout);
        MPI_Finalize( );
        return 0;
}
```

Elapsed serial time

- In this case, you don't need to link in the MPI libraries.

- Returns time in **microseconds** elapsed from some point in the past.

```
#include "timer.h"
. . .
double now;
. . .
GET_TIME(now);
```

Elapsed serial 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);
```

Example

https://raw.githubusercontent.com/kevinsuo/CS7172/master/time_sample2.c

```c
#include "mpi.h"
#include <stdio.h>
#include <sys/time.h>

#define GET_TIME(now) { \
   struct timeval t; \
   gettimeofday(&t, NULL); \
   now = t.tv_sec + t.tv_usec/1000000.0; \
}

int main( int argc, char *argv[] )
{
        double t1, t2 = 0;

        MPI_Init( 0, 0 );
        sleep(10);
        printf("Elapsed time = %e\n", t2-t1);fflush(stdout);
        MPI_Finalize( );
        return 0;
}
```

Example

https://raw.githubusercontent.com/kevinsuo/CS7172/master/time_sample2.c

```c
#include "mpi.h"
#include <stdio.h>
#include <sys/time.h>

#define GET_TIME(now) { \
   struct timeval t; \
   gettimeofday(&t, NULL); \
   now = t.tv_sec + t.tv_usec/1000000.0; \
}

int main( int argc, char *argv[] )
{
        double t1, t2;

        MPI_Init( 0, 0 );
        GET_TIME(t1);
        sleep(10);
        GET_TIME(t2);
        printf("Elapsed time = %e\n", t2-t1);fflush(stdout);
        MPI_Finalize( );
        return 0;
}
```

Elapsed serial time in nanoseconds

```c
#include <time.h>

{
        struct timespec start, end;

        clock_gettime(CLOCK_MONOTONIC, &start);

        //... do something

        clock_gettime(CLOCK_MONOTONIC, &end);

        u_int64_t diff = 1000000000L * (end.tv_sec - start.tv_sec) + end.tv_nsec - start.tv_nsec;

        printf("elapsed time = %llu nanoseconds\n", (long long unsigned int) diff);

}
```

Example

https://github.com/kevinsuo/CS7172/blob/master/time_sample3.c

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

int main( int argc, char *argv[] )
{
        struct timespec t1, t2;

        MPI_Init( 0, 0 );
        sleep(10);

        double diff = 0;

        printf("Time = %llu nanoseconds\n", (long long unsigned int)diff) ; fflush(stdout);
        MPI_Finalize( );
        return 0;
}
```

Example

https://github.com/kevinsuo/CS7172/blob/master/time_sample3.c

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

int main( int argc, char *argv[] )
{
        struct timespec t1, t2;

        MPI_Init( 0, 0 );
        clock_gettime(CLOCK_MONOTONIC, &t1);

        sleep(10);

        clock_gettime(CLOCK_MONOTONIC, &t2);

        double diff = 1000000000L * (t2.tv_sec - t1.tv_sec) + t2.tv_nsec - t1.tv_nsec;

        printf("Time = %llu nanoseconds\n", (long long unsigned int)diff) ; fflush(stdout);
        MPI_Finalize( );
        return 0;
}
```

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)

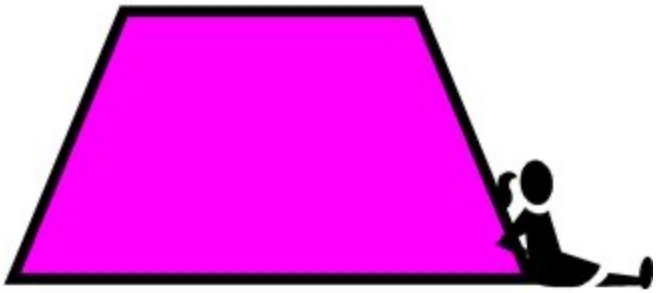
Speedup

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

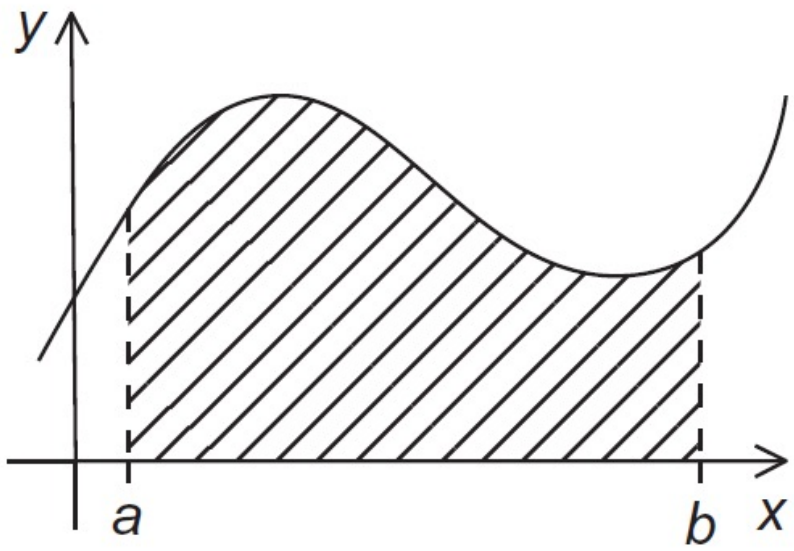
Speedups of Parallel Matrix-Vector Multiplication

comm_sz	Order of Matrix				
	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

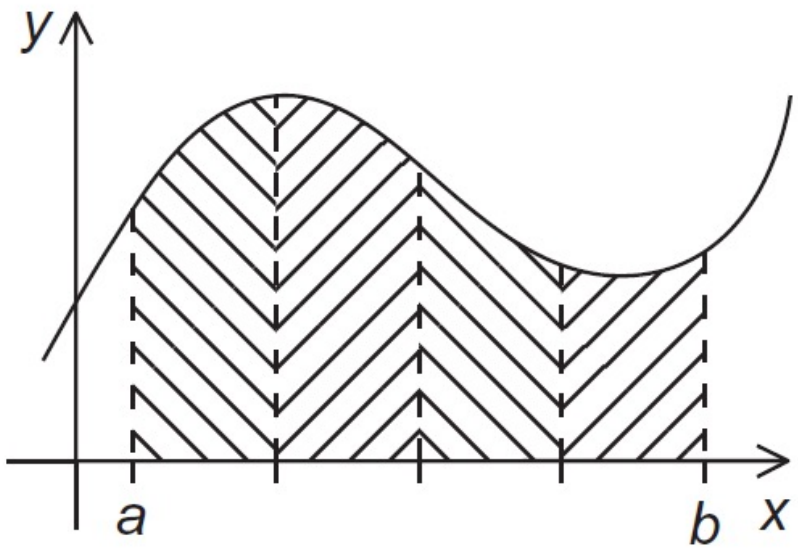
Trapezoidal rule in mpi



The Trapezoidal Rule

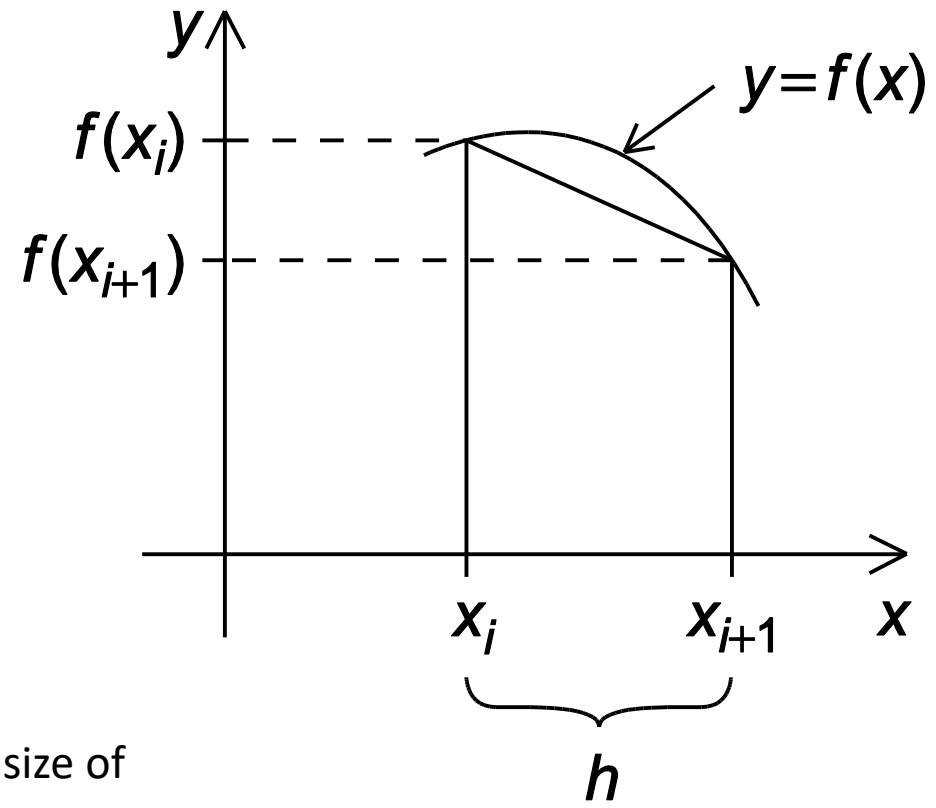


(a)



(b)

One trapezoid

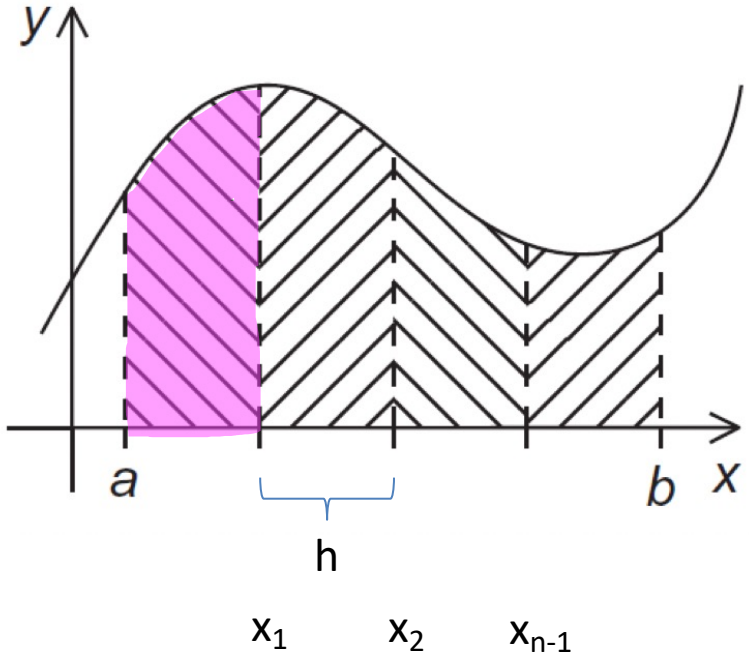


How to get the size of one trapezoid?

$$\text{Area of one trapezoid} = \frac{h}{2}[f(x_i) + f(x_{i+1})]$$

The Trapezoidal Rule

$$\text{Area of one trapezoid} = \frac{h}{2}[f(x_i) + f(x_{i+1})]$$



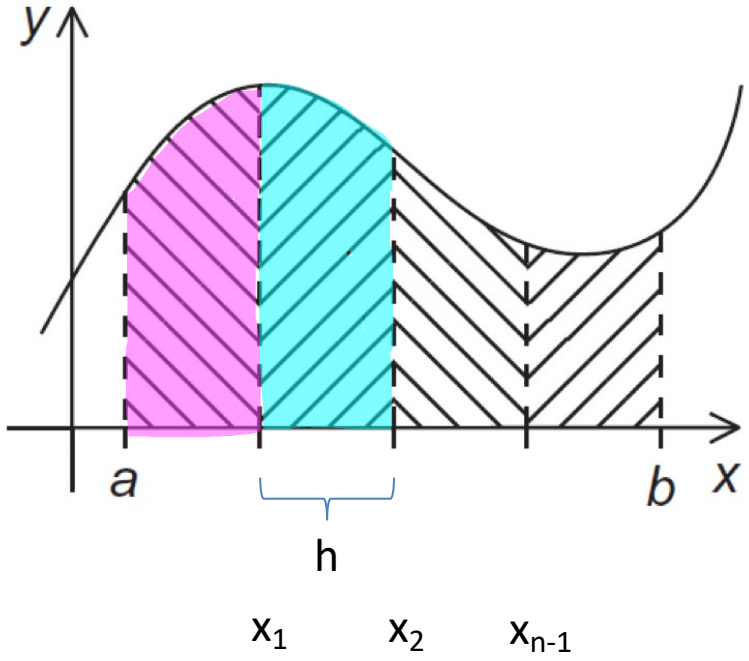
$$h = \frac{b-a}{n}$$

$$x_0 = a,\ x_1 = a+h,\ x_2 = a+2h,\ \ldots,\ x_{n-1} = a+(n-1)h,\ x_n = b$$

$$\frac{h}{2}[f(a) + f(x_1)] = h\left[\frac{f(a)}{2} + \frac{f(x_1)}{2}\right]$$

The Trapezoidal Rule

$$\text{Area of one trapezoid} = \frac{h}{2}[f(x_i) + f(x_{i+1})]$$



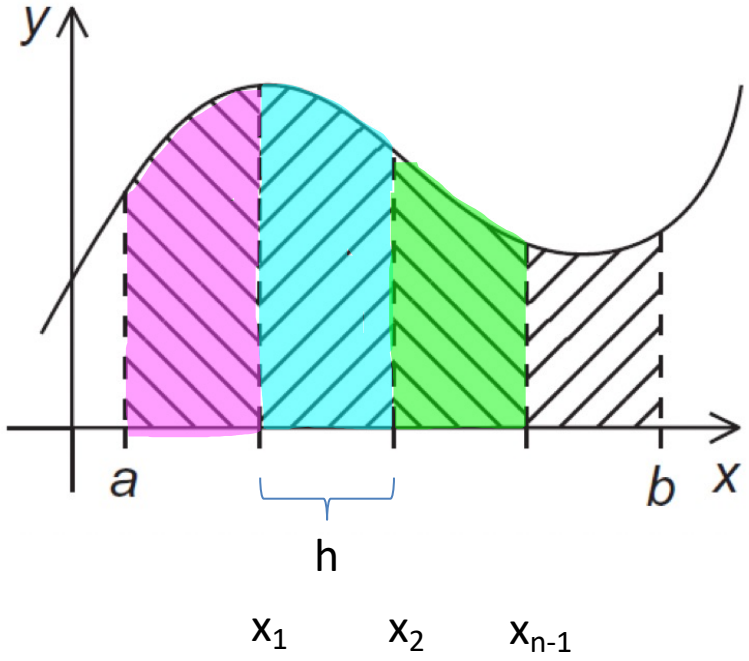
$$h = \frac{b-a}{n}$$

$$x_0 = a,\ x_1 = a+h,\ x_2 = a+2h,\ \ldots,\ x_{n-1} = a+(n-1)h,\ x_n = b$$

$$S = h\left[\frac{f(a)}{2} + \frac{f(x_1)}{2} + \frac{f(x_1)}{2} + \frac{f(x_2)}{2}\right]$$

The Trapezoidal Rule

$$\text{Area of one trapezoid} = \frac{h}{2}[f(x_i) + f(x_{i+1})]$$



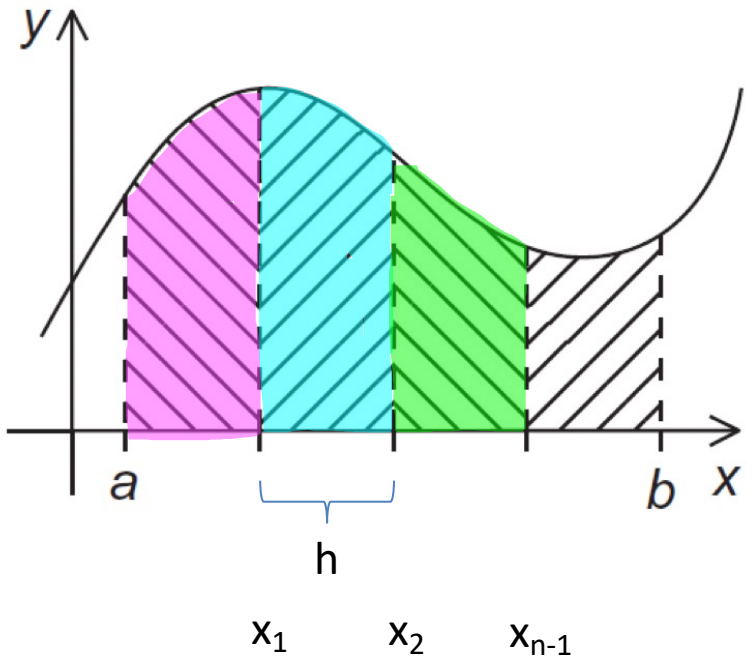
$$h = \frac{b-a}{n}$$

$$x_0 = a,\ x_1 = a+h,\ x_2 = a+2h,\ \ldots,\ x_{n-1} = a+(n-1)h,\ x_n = b$$

$$S = h\left[\frac{f(a)}{2} + \frac{f(x_1)}{2} + \frac{f(x_1)}{2} + \frac{f(x_2)}{2} + \frac{f(x_2)}{2} + \frac{f(x_3)}{2}\right]$$

The Trapezoidal Rule

$$\text{Area of one trapezoid} = \frac{h}{2}[f(x_i) + f(x_{i+1})]$$



$$h = \frac{b-a}{n}$$

$$x_0 = a,\ x_1 = a+h,\ x_2 = a+2h,\ \ldots,\ x_{n-1} = a+(n-1)h,\ x_n = b$$

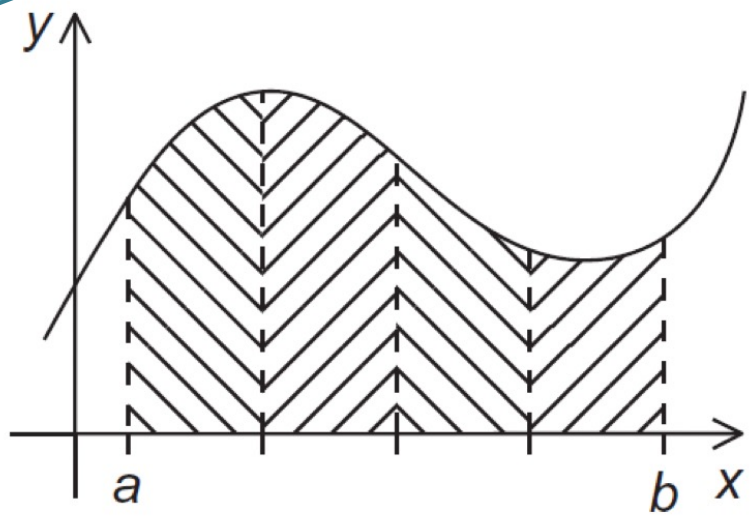
$$\text{Sum of trapezoid areas} = h[f(x_0)/2 + f(x_1) + f(x_2) + \cdots + f(x_{n-1}) + f(x_n)/2]$$

Pseudo-code for a serial program

$$\text{Sum of trapezoid areas} = h[f(x_0)/2 + f(x_1) + f(x_2) + \cdots + f(x_{n-1}) + f(x_n)/2]$$

(f(a) + f(b))/2
= (f(x_0) + f(x_n))/2

```
/* Input:  a, b, n */
h = (b-a)/n;
approx = (f(a) + f(b))/2.0;
for (i = 1; i <= n-1; i++) {
    x_i = a + i*h;
    approx += f(x_i);
}
approx = h*approx;
```



Parallelizing the Trapezoidal Rule

1. Partition problem solution into tasks.

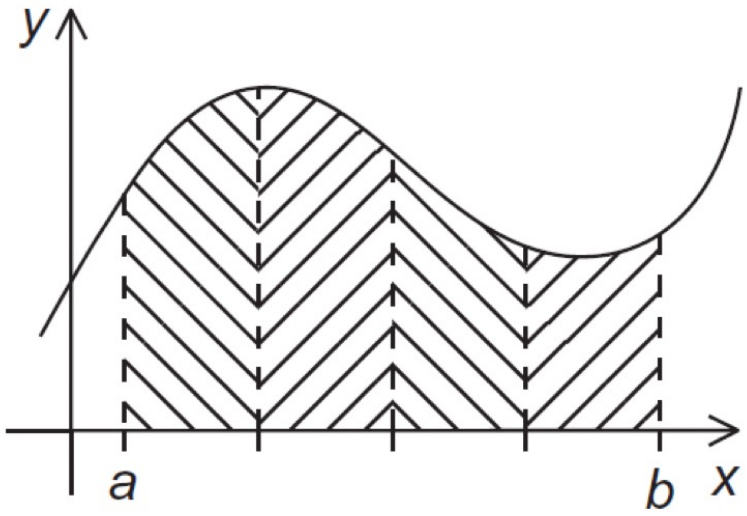
2. Identify communication channels between threads.

3. Aggregate tasks into composite tasks.

4. Map composite tasks to threads/cores.

Parallelizing the Trapezoidal Rule

1. Partition problem solution into tasks.

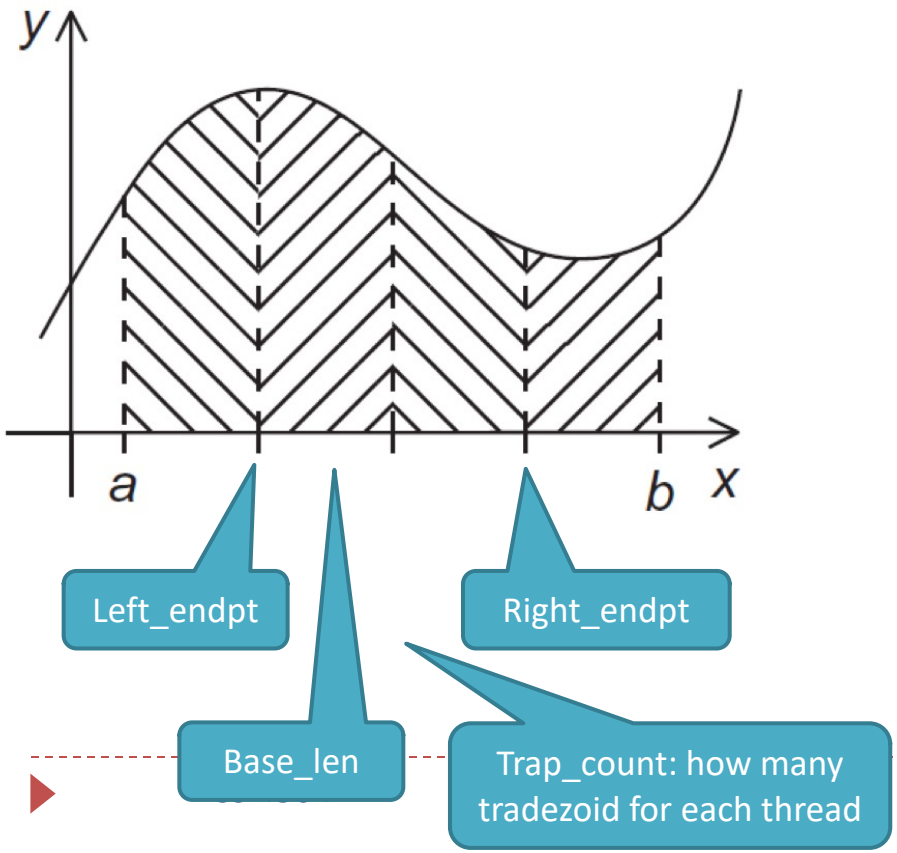


What is the problem?

What is the task?

Parallelizing the Trapezoidal Rule

1. Partition problem solution into tasks.



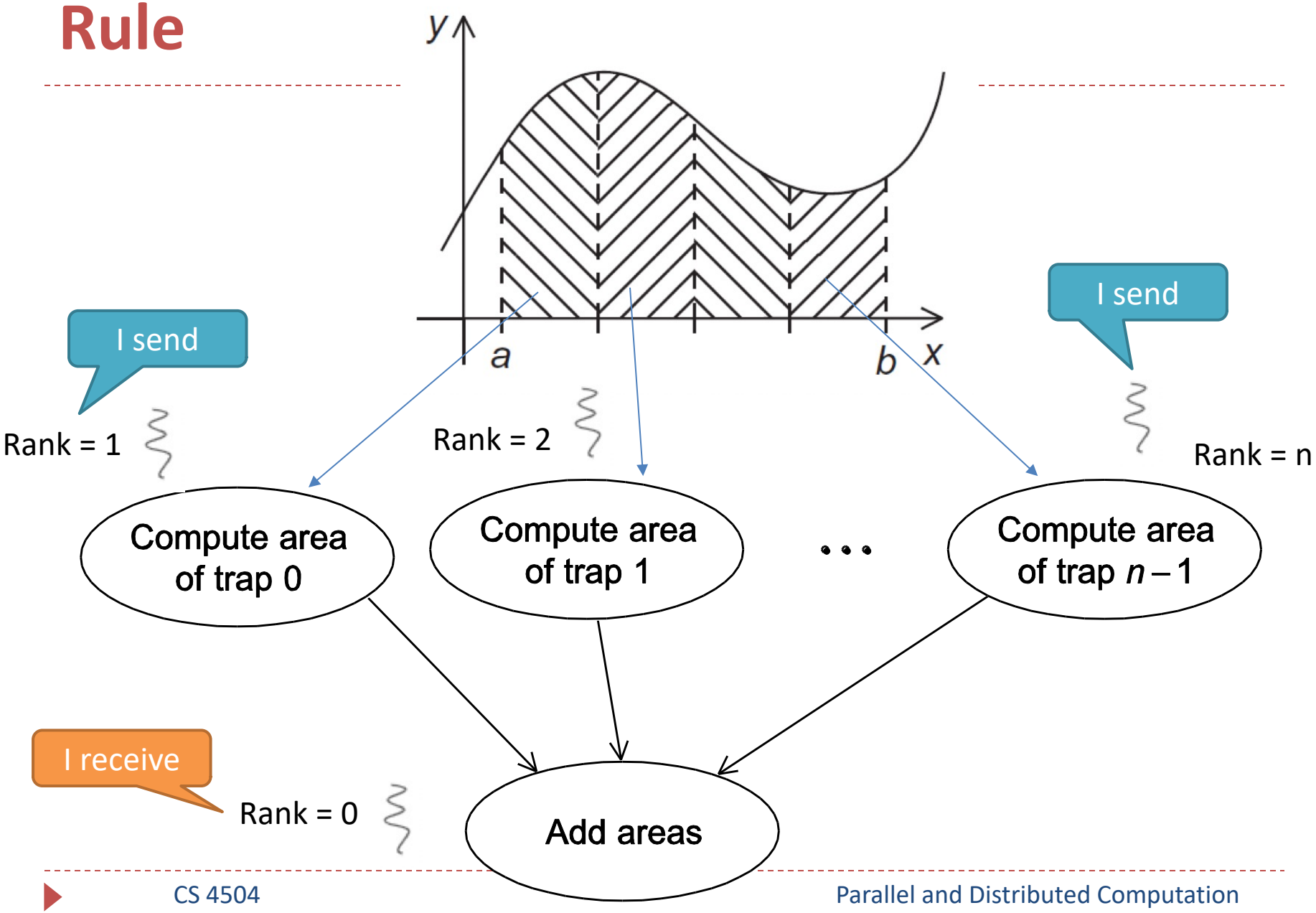

```
double Trap(
      double left_endpt  /* in */,
      double right_endpt /* in */,
      int    trap_count  /* in */,
      double base_len    /* in */) {

   // function logic

   return estimate;
} /* Trap */
```

Parallelizing the Trapezoidal Rule

1. ~~Partition problem solution into tasks.~~

2. Identify communication channels between threads.

Tasks and communications for Trapezoidal Rule



Communication

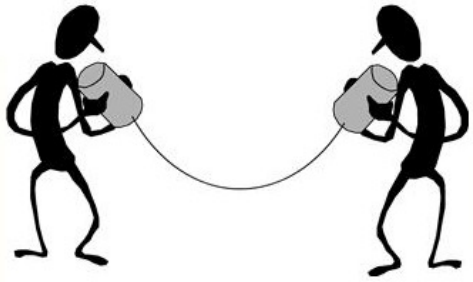
```
int MPI_Send(
    void*          msg_buf_p     /* in */,
    int            msg_size      /* in */,
    MPI_Datatype   msg_type      /* in */,
    int            dest          /* in */,
    int            tag           /* in */,
    MPI_Comm       communicator  /* in */);
```

Send what?

How many?

Type?

To where?



Data types

MPI datatype	C datatype
MPI_CHAR	signed **char**
MPI_SHORT	signed **short int**
MPI_INT	signed **int**
MPI_LONG	signed **long int**
MPI_LONG_LONG	signed **long long int**
MPI_UNSIGNED_CHAR	**unsigned char**
MPI_UNSIGNED_SHORT	**unsigned short int**
MPI_UNSIGNED	**unsigned int**
MPI_UNSIGNED_LONG	**unsigned long int**
MPI_FLOAT	**float**
MPI_DOUBLE	**double**
MPI_LONG_DOUBLE	**long double**
MPI_BYTE	
MPI_PACKED	

Communication

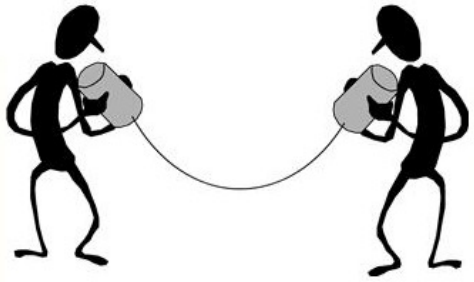
Recv what?

How many?

Type?

From where?

```
int MPI_Recv(
      void*          msg_buf_p     /* out */,
      int            buf_size      /* in  */
      MPI_Datatype   buf_type      /* in  */
      int            source        /* in  */,
      int            tag           /* in  */,
      MPI_Comm       communicator  /* in  */,
      MPI_Status*    status_p      /* out */);
```



Message Sent From q to r

```
MPI_Send(send_buf_p, send_buf_sz, send_type, dest, send_tag,
         send_comm);
```

r

MPI_Send

src = q

MPI_Recv

dest = r

```
MPI_Recv(recv_buf_p, recv_buf_sz, recv_type, src, recv_tag,
         recv_comm, &status);
```

q

Parallelizing the Trapezoidal Rule

1. ~~Partition problem solution into tasks.~~

2. ~~Identify communication channels between threads.~~

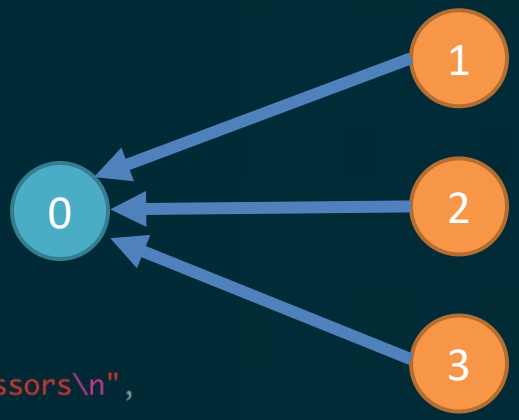
3. Aggregate tasks into composite tasks.

4. Map composite tasks to threads/cores.

Example: 1/2/3 send to 0 and 0 prints out messages

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

const int MAX_STRING = 100;

int main(int argc, char** argv) {
    char greeting[MAX_STRING];
    int  comm_sz; //number of processes
    int  my_rank; //my process rank

    // Initialize the MPI environment
    MPI_Init(NULL, NULL);
    MPI_Comm_size(MPI_COMM_WORLD, &comm_sz);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);

    // Get the name of the processor
    char processor_name[MPI_MAX_PROCESSOR_NAME];
    int name_len;
    MPI_Get_processor_name(processor_name, &name_len);

    if (my_rank != 0) {
            sprintf(greeting, "Greetings from processor %s, rank %d out of %d processors\n",
                    processor_name, my_rank, comm_sz);
            MPI_Send(greeting, strlen(greeting)+1, MPI_CHAR, 0, 0, MPI_COMM_WORLD);
    } else {
            printf("This is process: %d, Greetings from processor %s\n",
                    my_rank, processor_name);
            for (int q = 1; q < comm_sz; q++) {
                MPI_Recv(greeting, MAX_STRING, MPI_CHAR, q, 0, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
                printf("%s", greeting);
            }
    }
    // Finalize the MPI environment.
    MPI_Finalize();
}
```

```
ksuo@ksuo-VirtualBox ~/cs7172> mpiexec -n 4 ./helloworld-mpi.o
This is process: 0, Greetings from processor ksuo-VirtualBox
Greetings from processor ksuo-VirtualBox, rank 1 out of 4 processors
Greetings from processor ksuo-VirtualBox, rank 2 out of 4 processors
Greetings from processor ksuo-VirtualBox, rank 3 out of 4 processors
```

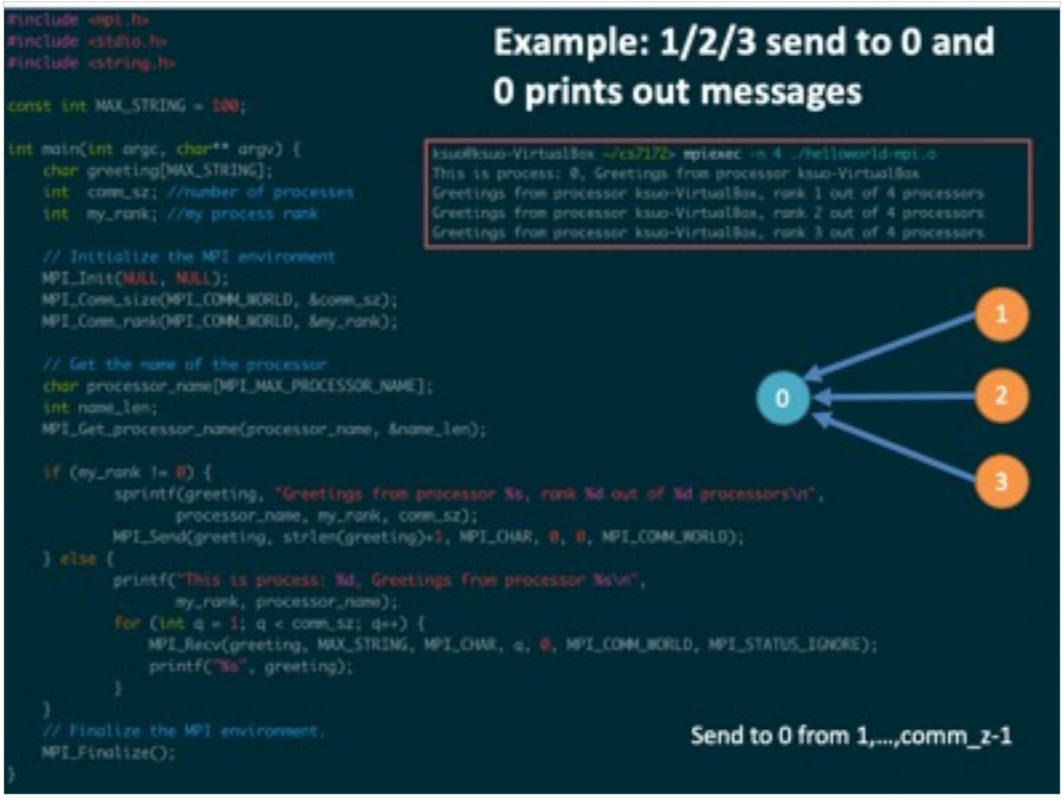


Send to 0 from 1,…,comm_z-1

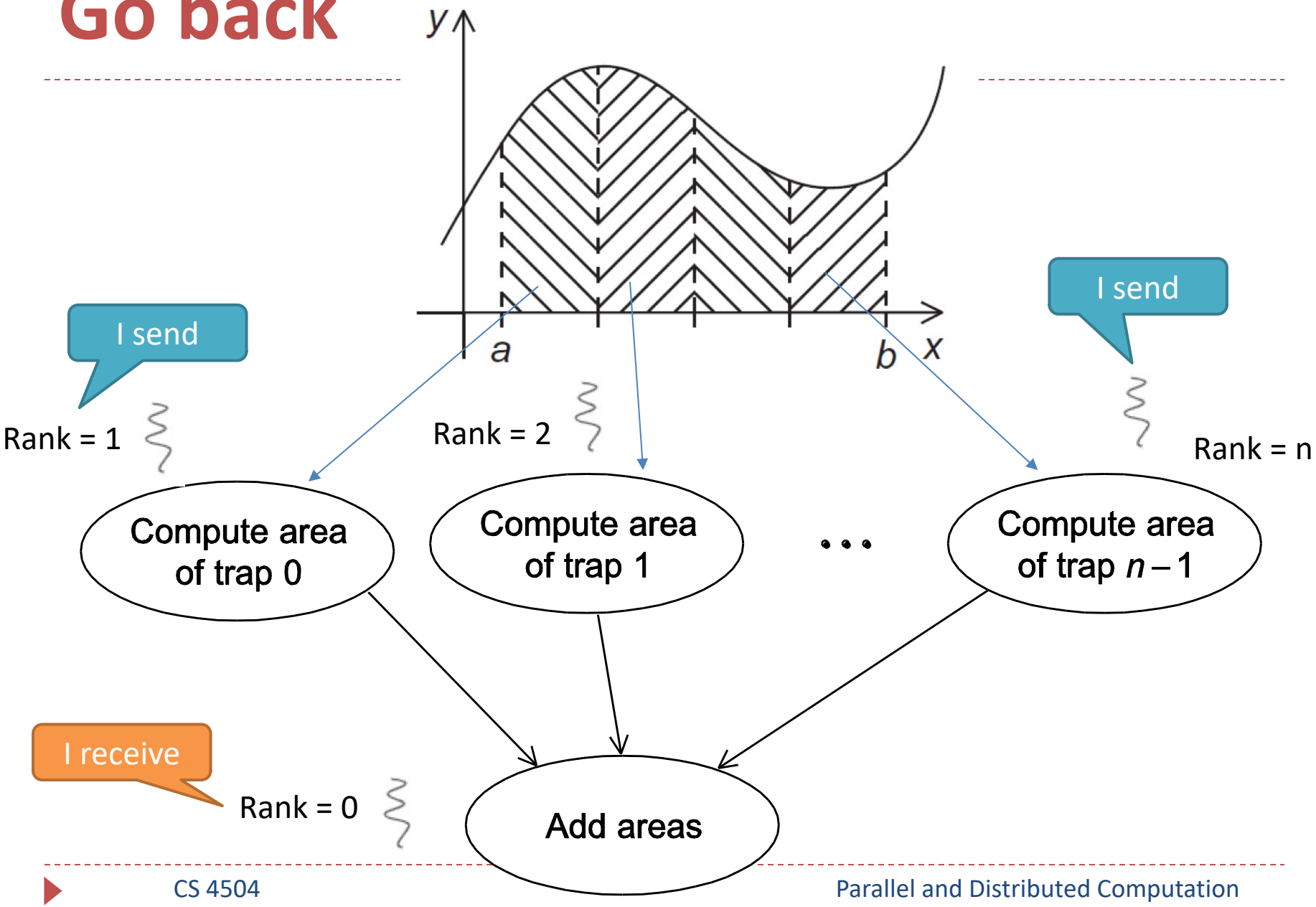
Sample code:

```
ksuo@ksuo-VirtualBox ~/cs7172> mpiexec -n 4 ./helloworld-mpi.o
This is process: 0, Greetings from processor ksuo-VirtualBox
Greetings from processor ksuo-VirtualBox, rank 1 out of 4 processors
Greetings from processor ksuo-VirtualBox, rank 2 out of 4 processors
Greetings from processor ksuo-VirtualBox, rank 3 out of 4 processors
```

https://github.com/kevinsuo/CS7172/blob/master/helloworld-mpi-sample.c



Go back


y
a
b
x
I send
Rank = 1
Rank = 2
I send
Rank = n
Compute area of trap 0
Compute area of trap 1
...
Compute area of trap n – 1
I receive
Rank = 0
Add areas

Parallel pseudo-code

```
1     Get a, b, n;
2     h = (b-a)/n;
3     local_n = n/comm_sz;
4     local_a = a + my_rank*local_n*h;
5     local_b = local_a + local_n*h;
6     local_integral = Trap(local_a, local_b, local_n, h);
7     if (my_rank != 0)
8        Send local_integral to process 0;
9     else /* my_rank == 0 */
10       total_integral = local_integral;
11       for (proc = 1; proc < comm_sz; proc++) {
12          Receive local_integral from proc;
13          total_integral += local_integral;
14       }
15    }
16    if (my_rank == 0)
17       print result;
```

Task

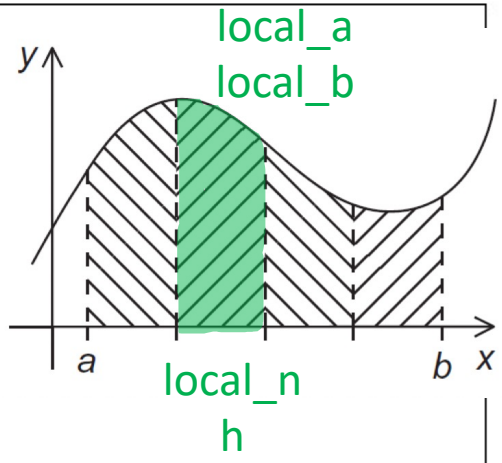
First version (1)

```
1  double Trap(
2        double left_endpt  /* in */,
3        double right_endpt /* in */,
4        int    trap_count  /* in */,
5        double base_len    /* in */) {
6     double estimate, x;
7     int i;
8
9     estimate = (f(left_endpt) + f(right_endpt))/2.0;
10    for (i = 1; i <= trap_count-1; i++) {
11       x = left_endpt + i*base_len;
12       estimate += f(x);
13    }
14    estimate = estimate*base_len;
15
16    return estimate;
17 } /*  Trap  */
```

First version (2)

Please read the code by yourself based on the pseudo-code

```
1  int main(void) {
2     int my_rank, comm_sz, n = 1024, local_n;
3     double a = 0.0, b = 3.0, h, local_a, local_b;
4     double local_int, total_int;
5     int source;
6
7     MPI_Init(NULL, NULL);
8     MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);
9     MPI_Comm_size(MPI_COMM_WORLD, &comm_sz);
10
11    h = (b-a)/n;            /* h is the same for all processes */
12    local_n = n/comm_sz;    /* So is the number of trapezoids  */
13
14    local_a = a + my_rank*local_n*h;
15    local_b = local_a + local_n*h;
16    local_int = Trap(local_a, local_b, local_n, h);
17
18    if (my_rank != 0) {
19       MPI_Send(&local_int, 1, MPI_DOUBLE, 0, 0,
20             MPI_COMM_WORLD);
```



First version (3)

```
21      } else {
22         total_int = local_int;
23         for (source = 1; source < comm_sz; source++) {
24            MPI_Recv(&local_int, 1, MPI_DOUBLE, source, 0,
25                  MPI_COMM_WORLD, MPI_STATUS_IGNORE);
26            total_int += local_int;
27         }
28      }
29
30      if (my_rank == 0) {
31         printf("With n = %d trapezoids, our estimate\n", n);
32         printf("of the integral from %f to %f = %.15e\n",
33             a, b, total_int);
34      }
35      MPI_Finalize();
36      return 0;
37   } /*  main  */
```

Conclusion

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