CS 7172
Parallel and Distributed Computation

Message Passing Interface (MPI)

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https://kevinsuo.github.io/

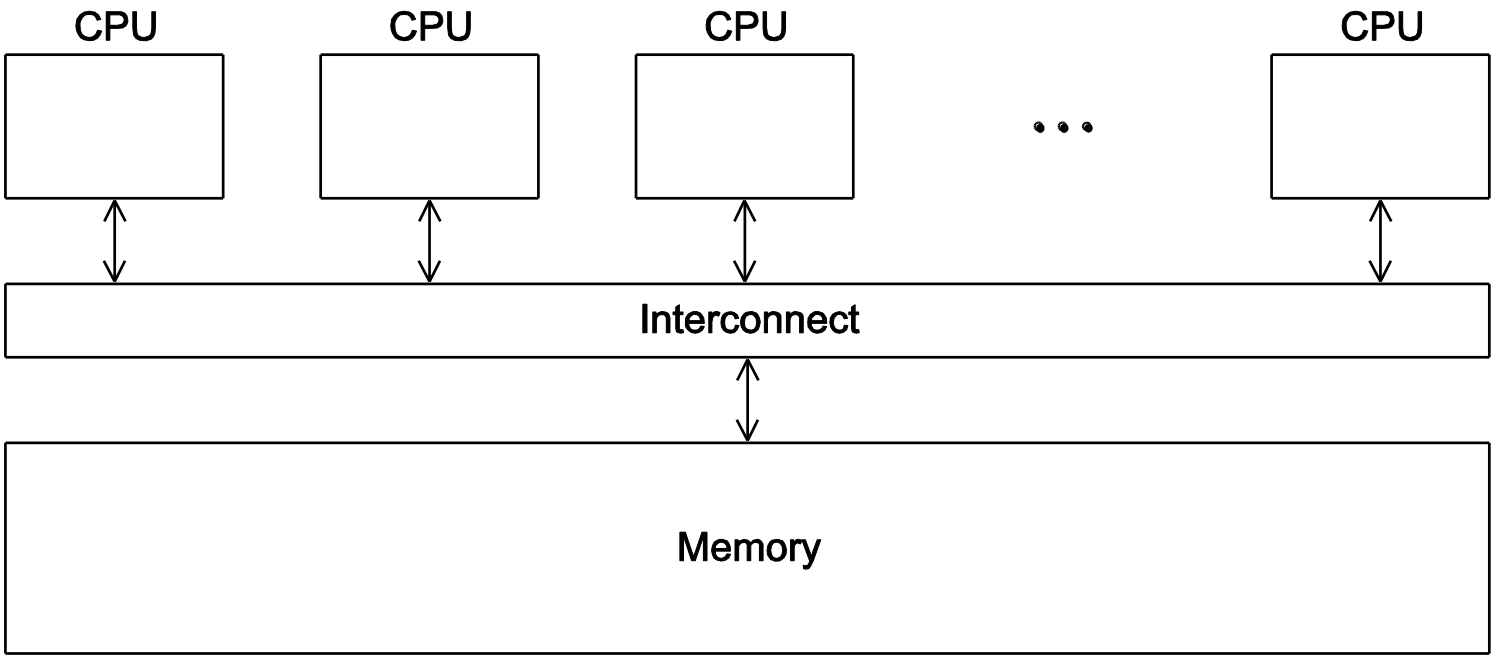
Outline

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

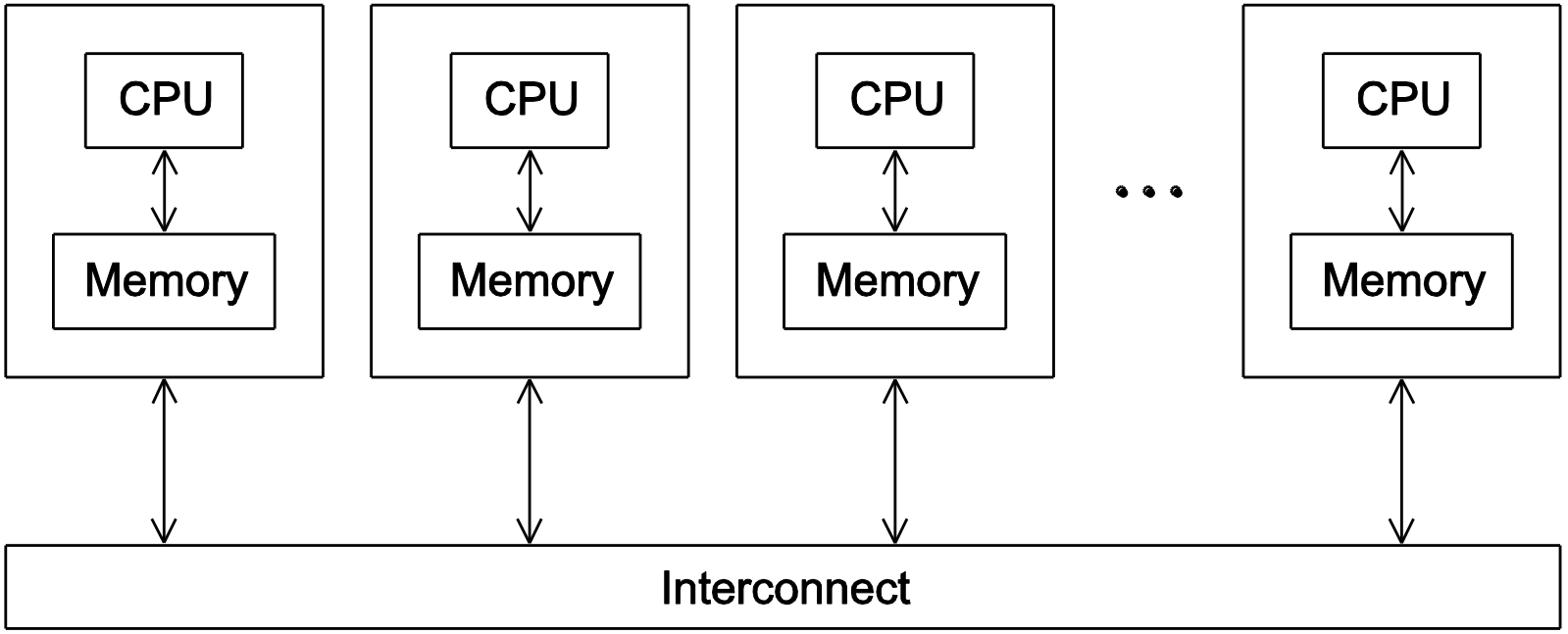
What is MPI?

- 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
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}
```

- 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 */);
```

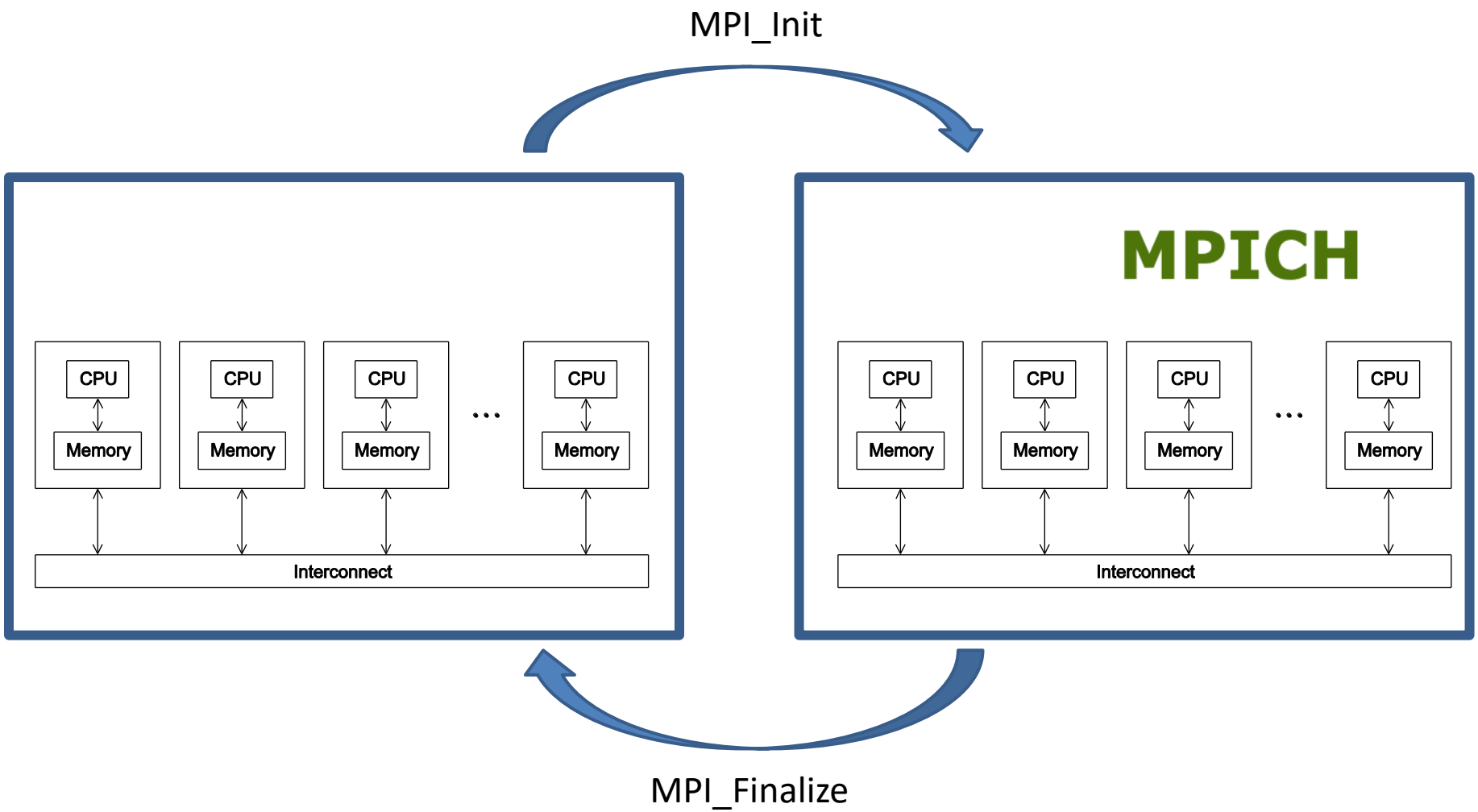
- MPI_Finalize
  - Tells MPI we're done, so clean up anything allocated for this program.

```
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



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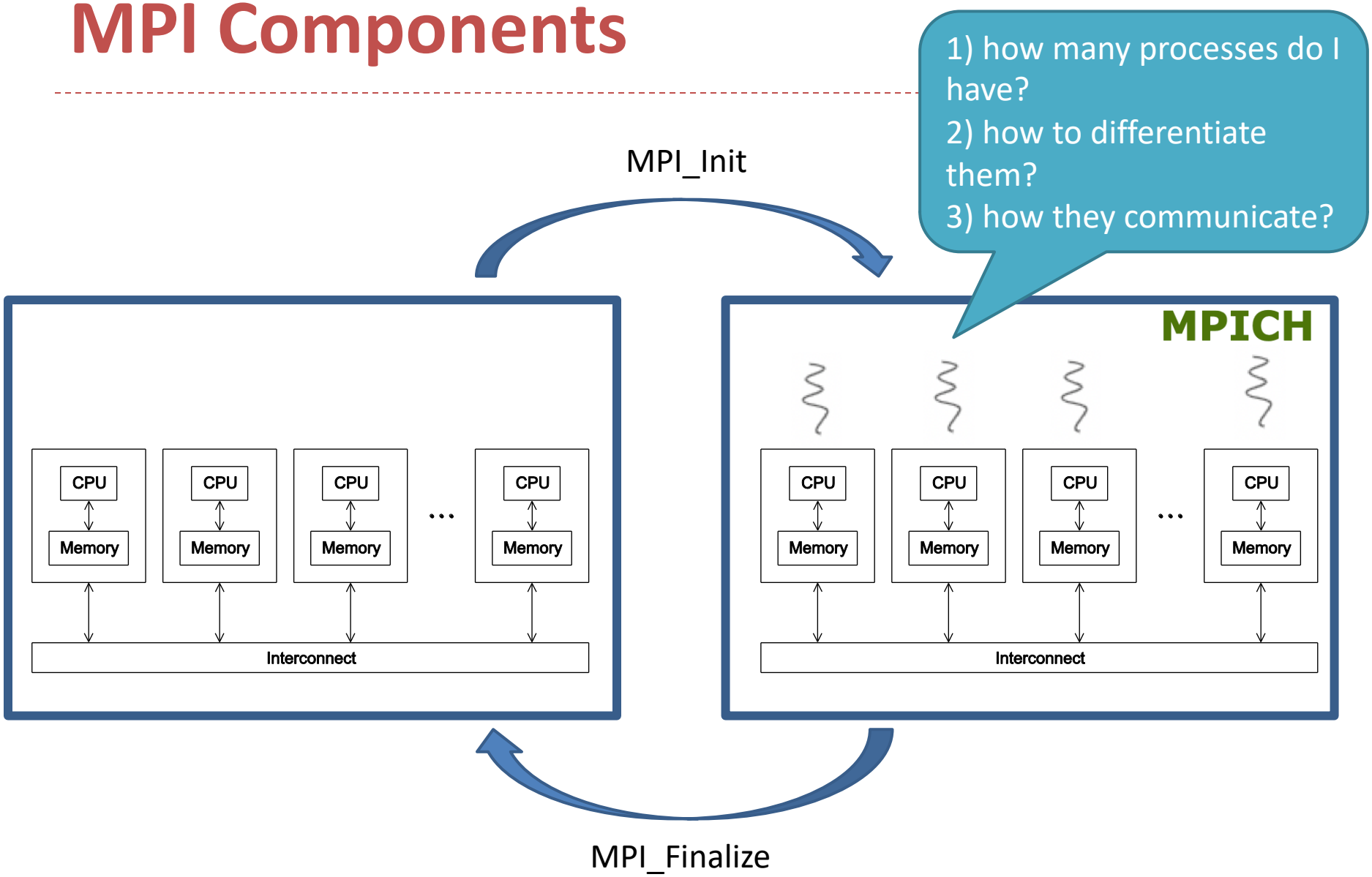
MPI Components



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.

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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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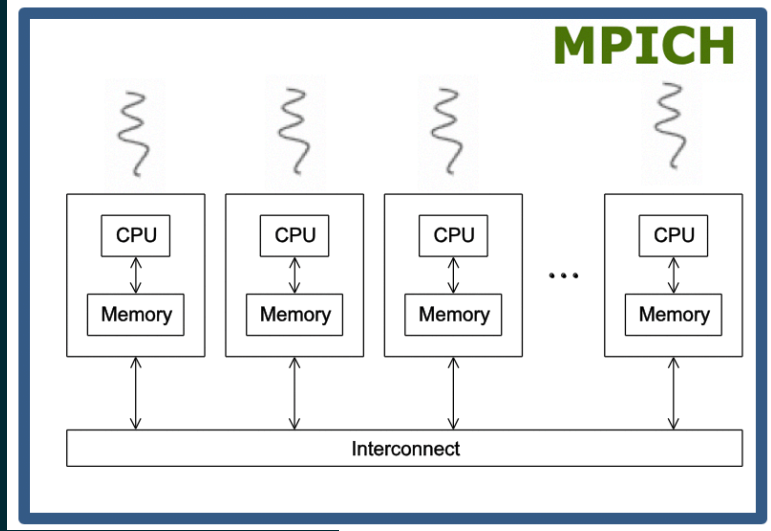
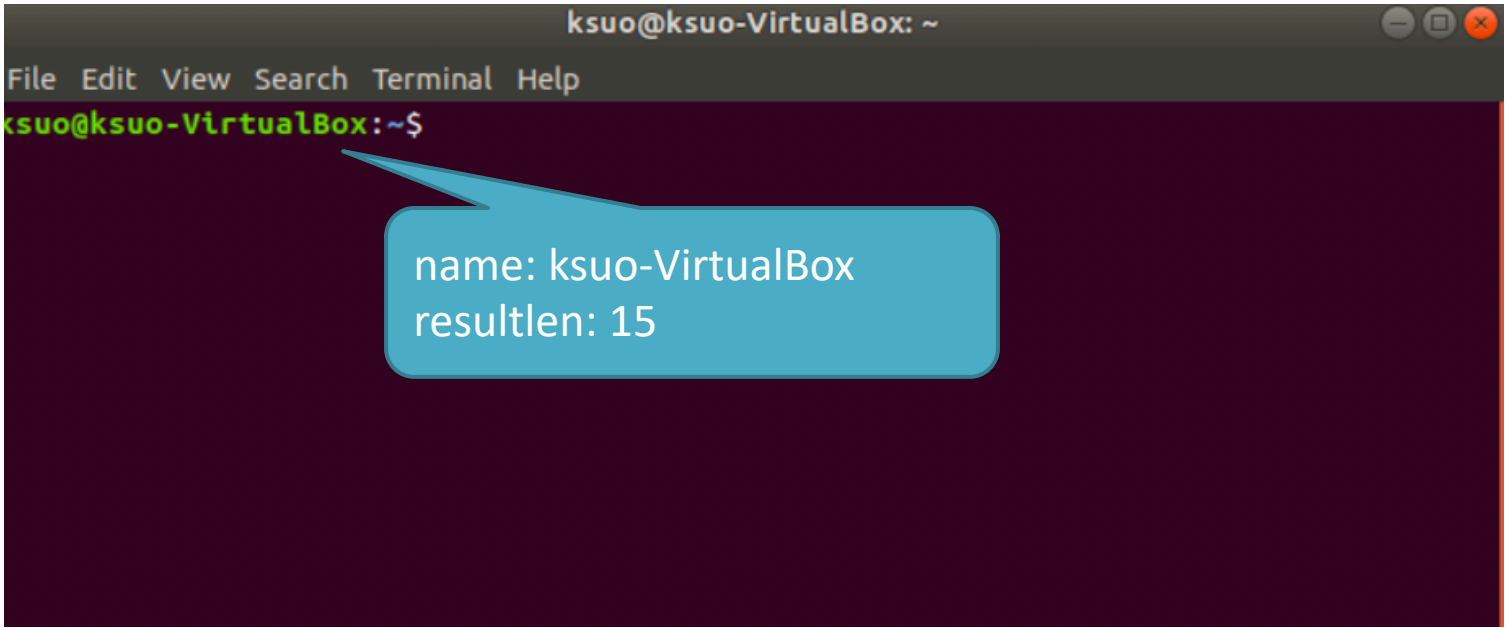


MPI_Get_processor_name(char *name,int *resultlen)

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



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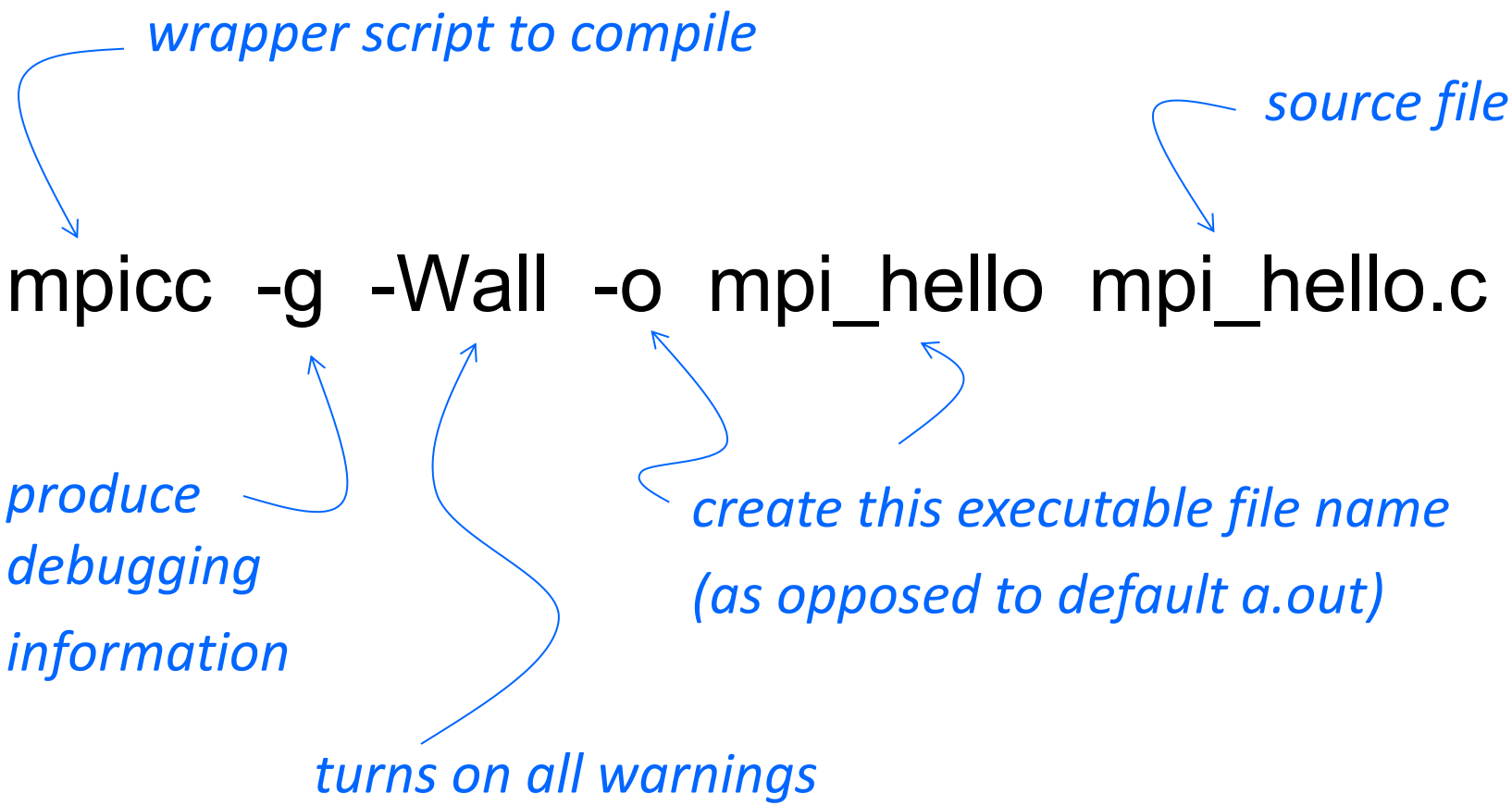
Compile


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

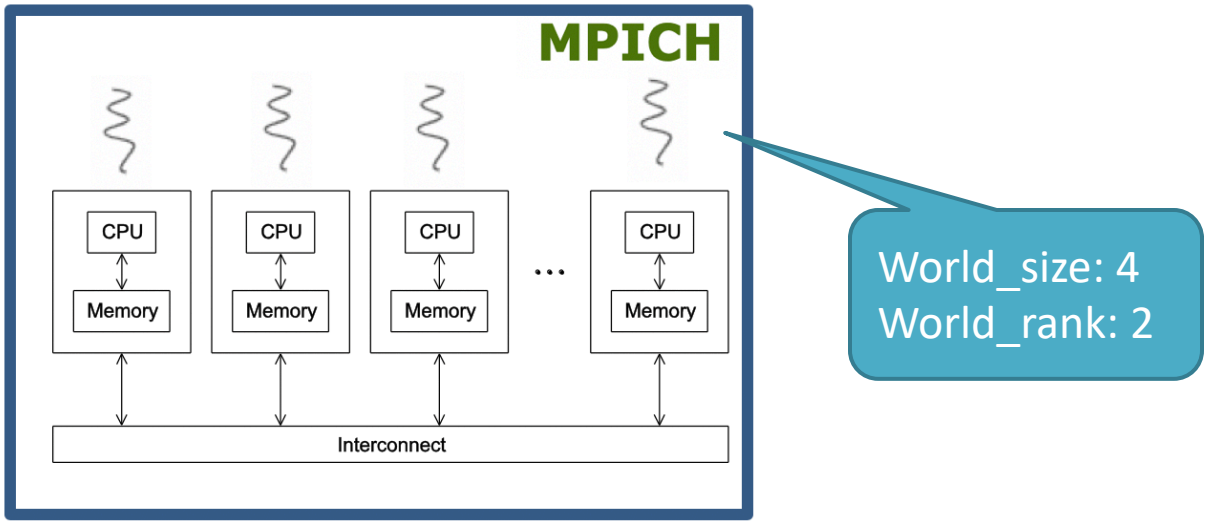
```
mpiexec  -n  1  ./mpi_hello

    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
```



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```
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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);
```

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);
```

Elapsed serial time in nanoseconds

```
#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);

}
```

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)

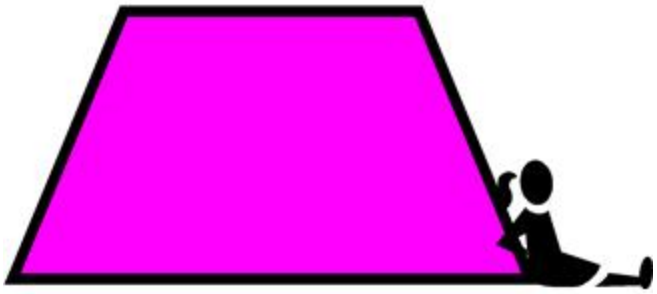
Speedup

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

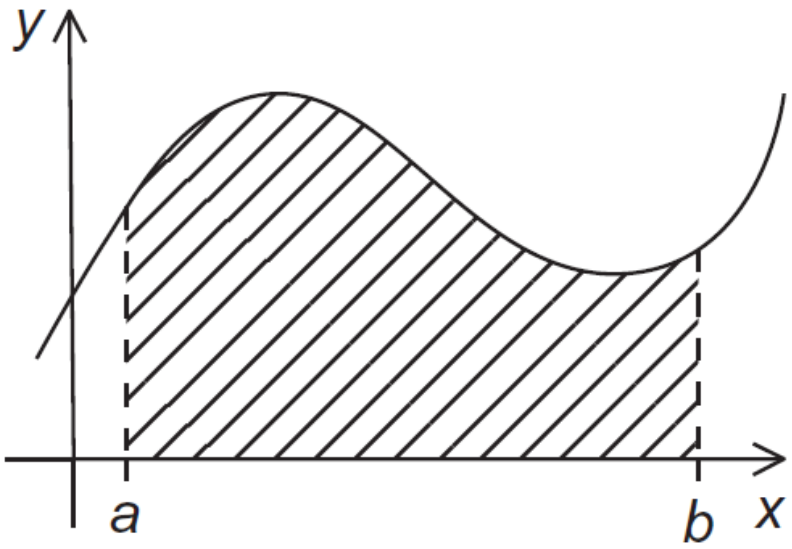
Speedups of Parallel Matrix-Vector Multiplication

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

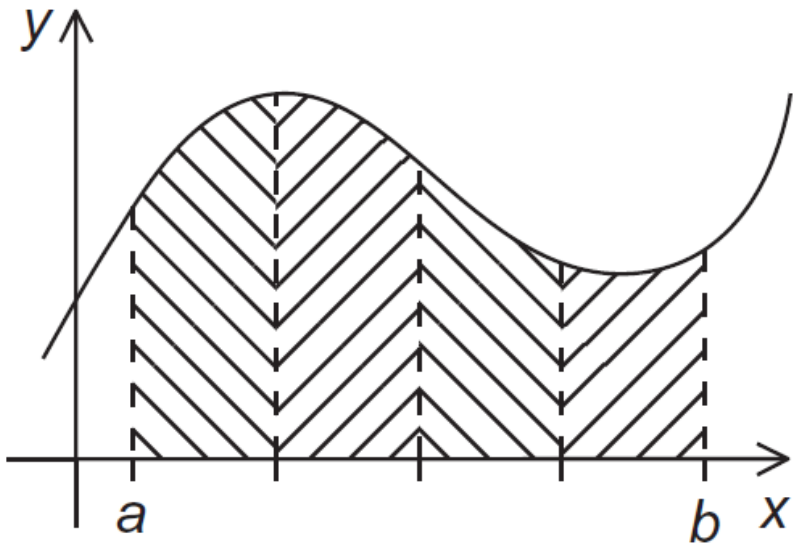
Trapezoidal rule in mpi



The Trapezoidal Rule

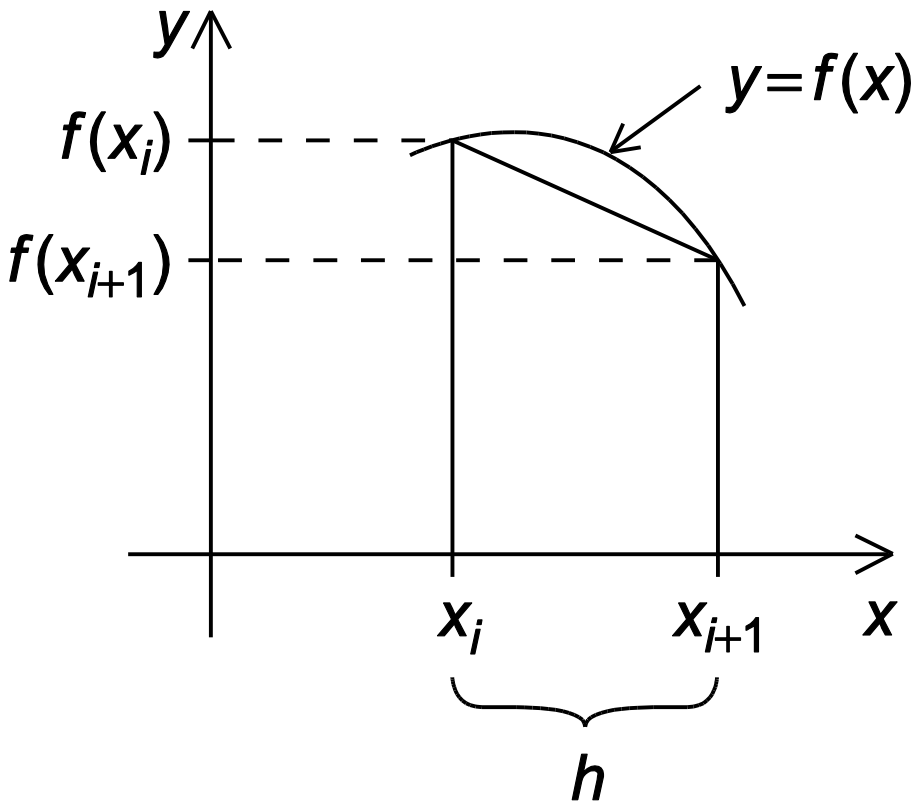


(a)



(b)

One trapezoid



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

The Trapezoidal Rule

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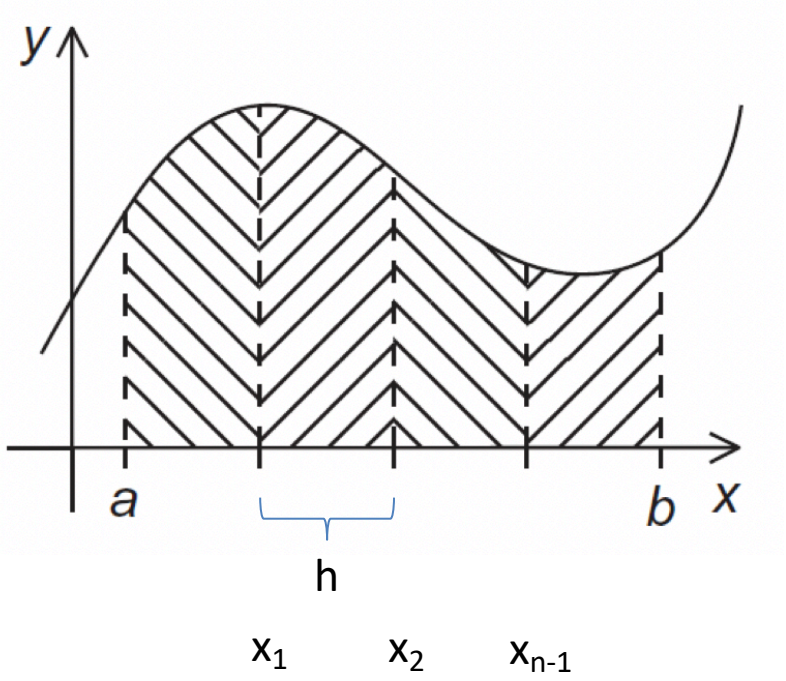


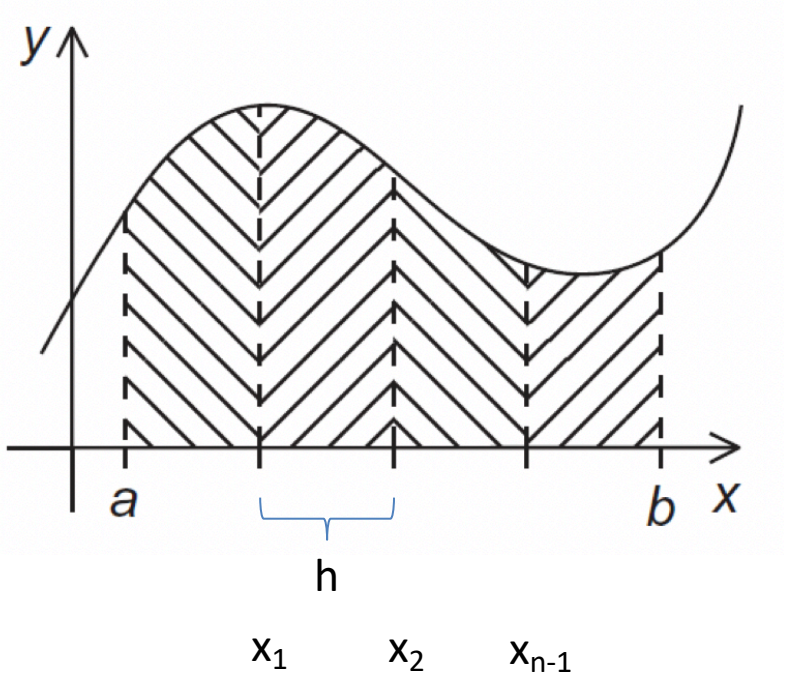
$$h = \frac{b-a}{n}$$

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

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

The Trapezoidal Rule

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



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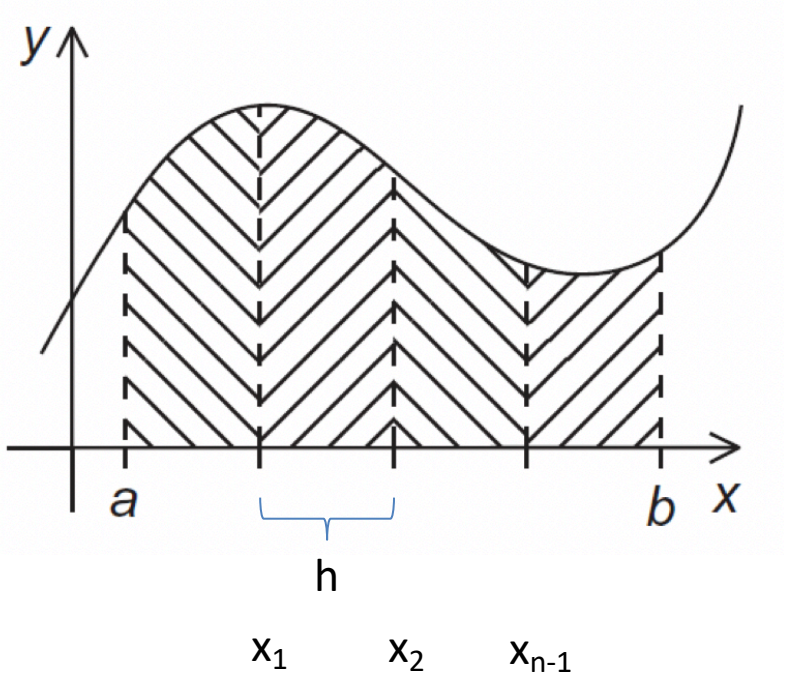
$$S = h\left[\frac{f(a)}{2} + \frac{f(x_1)}{2} + \frac{f(x_1)}{2} + \frac{f(x_2)}{2}\right]$$

The Trapezoidal Rule

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



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The Trapezoidal Rule

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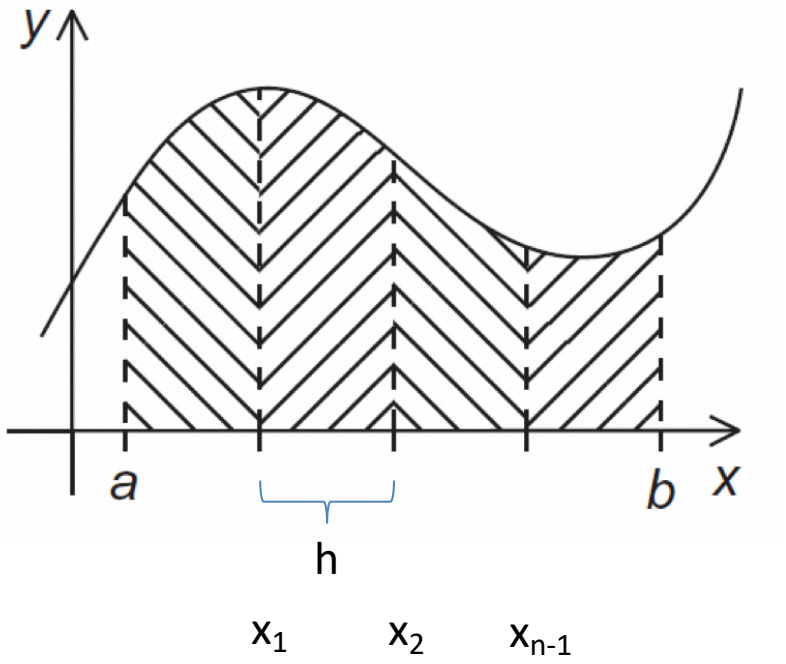

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$$x_0 = a,\ x_1 = a+h,\ x_2 = a+2h,\ \ldots,\ x_{n-1} = a+(n-1)h,\ x_n = b$$

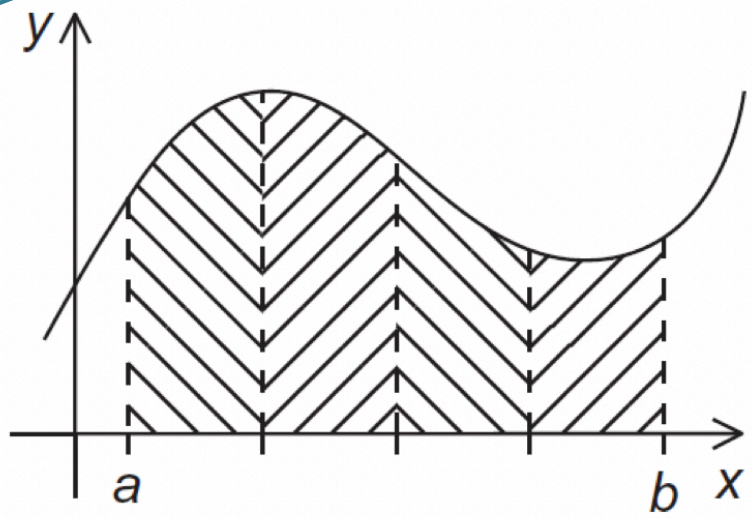
$$\text{Sum of trapezoid areas} = h[f(x_0)/2 + f(x_1) + f(x_2) + \cdots + f(x_{n-1}) + f(x_n)/2]$$

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

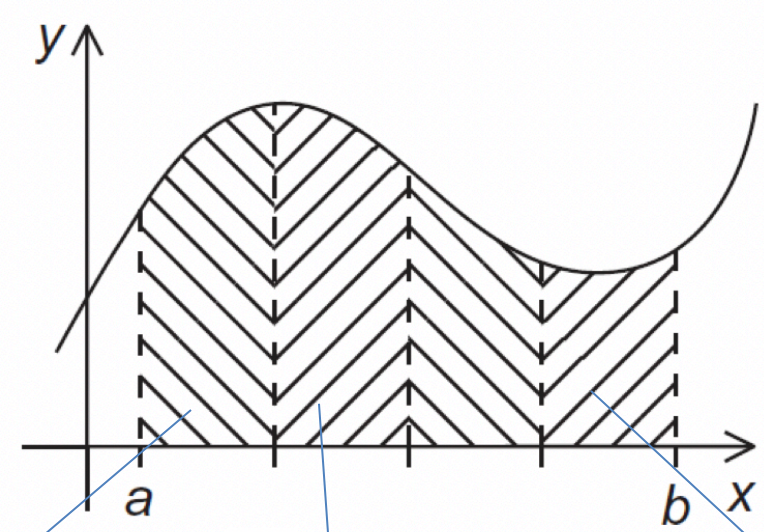
1. Partition problem solution into tasks.

2. Identify communication channels between tasks.

3. Aggregate tasks into composite tasks.

4. Map composite tasks to cores.

Tasks and communications for Trapezoidal Rule



I send

Rank = 1

Rank = 2

I send

Rank = n

Compute area of trap 0

Compute area of trap 1

...

Compute area of trap $n-1$

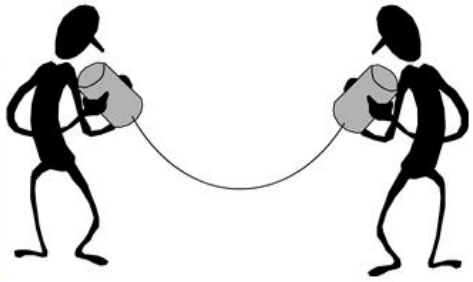
I receive

Rank = 0

Add areas

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 */);
```

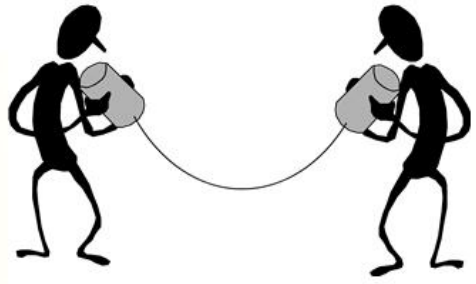


Data types

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

```
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 matching

```
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

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;

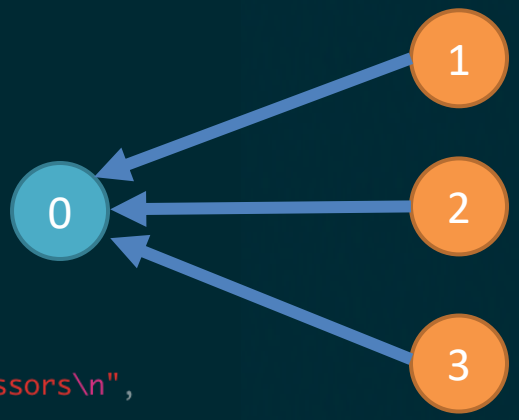
int main(int argc, char** argv) {
    char greeting[MAX_STRING];
    int  comm_sz; //number of processes
    int  my_rank; //my process rank

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

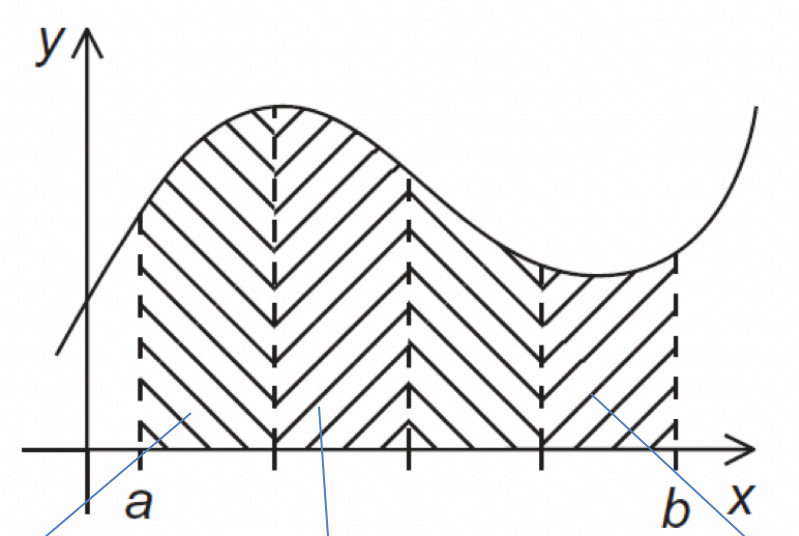
    // Get the name of the processor
    char processor_name[MPI_MAX_PROCESSOR_NAME];
    int name_len;
    MPI_Get_processor_name(processor_name, &name_len);

    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
```



Go back



I send

Rank = 1

Compute area of trap 0

Rank = 2

Compute area of trap 1

...

I send

Rank = n

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;
```

First version (1)

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 (2)

```
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  */
```

First version (3)

```
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  */
```

Conclusion

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