Parallel Computing

OpenMP - I

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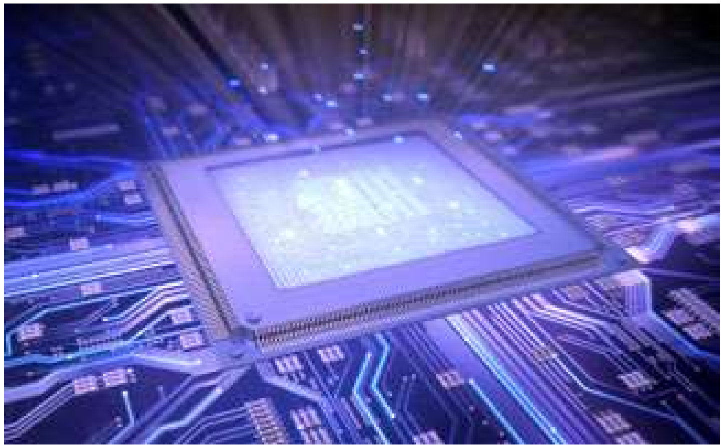


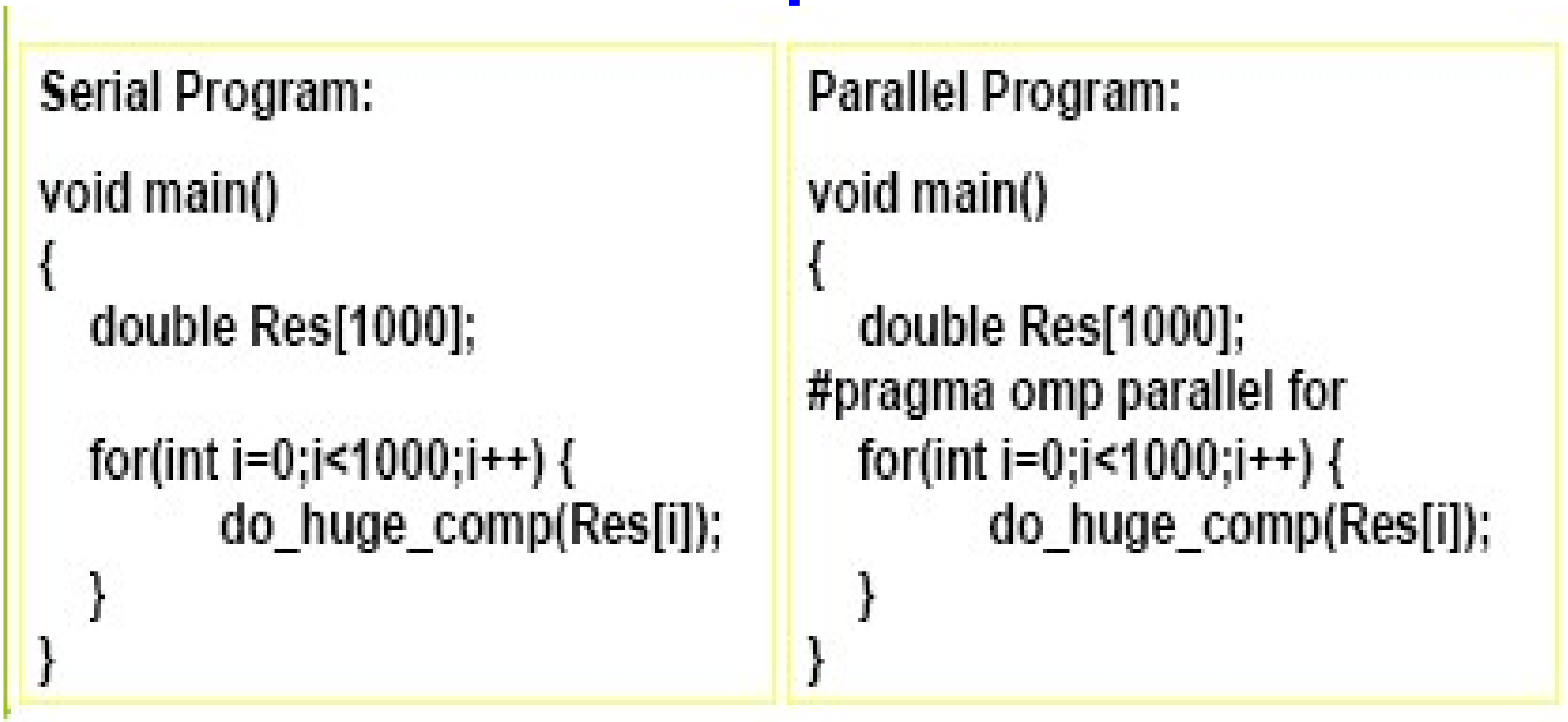
Small and Easy Motivation

```
 #include <stdio.h>
 #include <stdlib.h>


int main() {



  // Do this part in parallel


  printf( "Hello, World!\n" );


  return 0;
}
```

Small and Easy Motivation

```
 #include <stdio.h>
 #include <stdlib.h>
 #include <omp.h>

int main() {

  omp_set_num_threads(16);

  // Do this part in parallel
  #pragma omp parallel
  {
    printf( "Hello, World!\n" );
  }

  return 0;
}
```

Simple!



Serial Program:

```
void main()
{
   double Res[1000];

   for(int i=0;i<1000;i++) {
          do_huge_comp(Res[i]);
   }
}
```

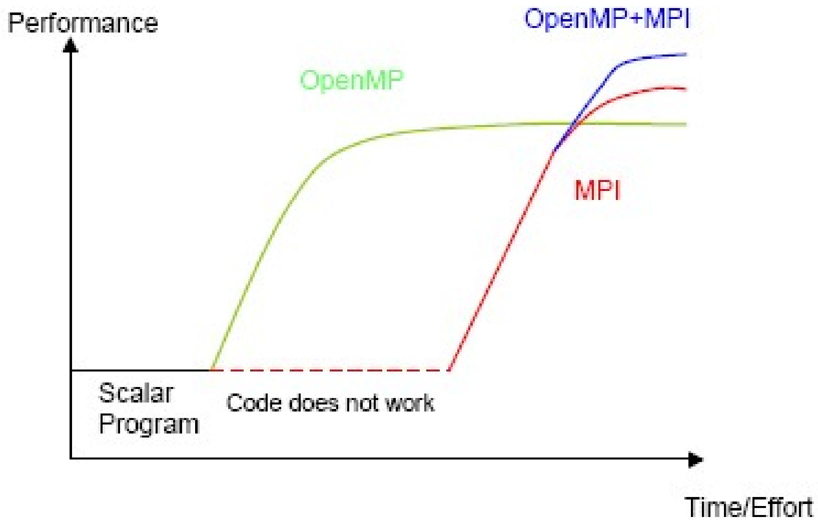
Parallel Program:

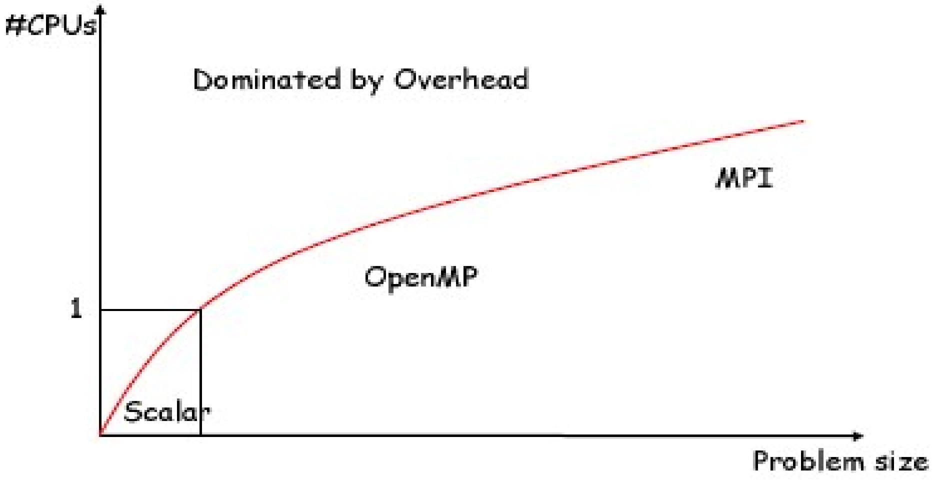
```
void main()
{
   double Res[1000];
#pragma omp parallel for
   for(int i=0;i<1000;i++) {
          do_huge_comp(Res[i]);
   }
}
```

OpenMP can parallelize many serial programs with relatively few annotations that specify parallelism and independence

OpenMP is a small API that hides cumbersome threading calls with simpler *directives*

Interesting Insights About OpenMP





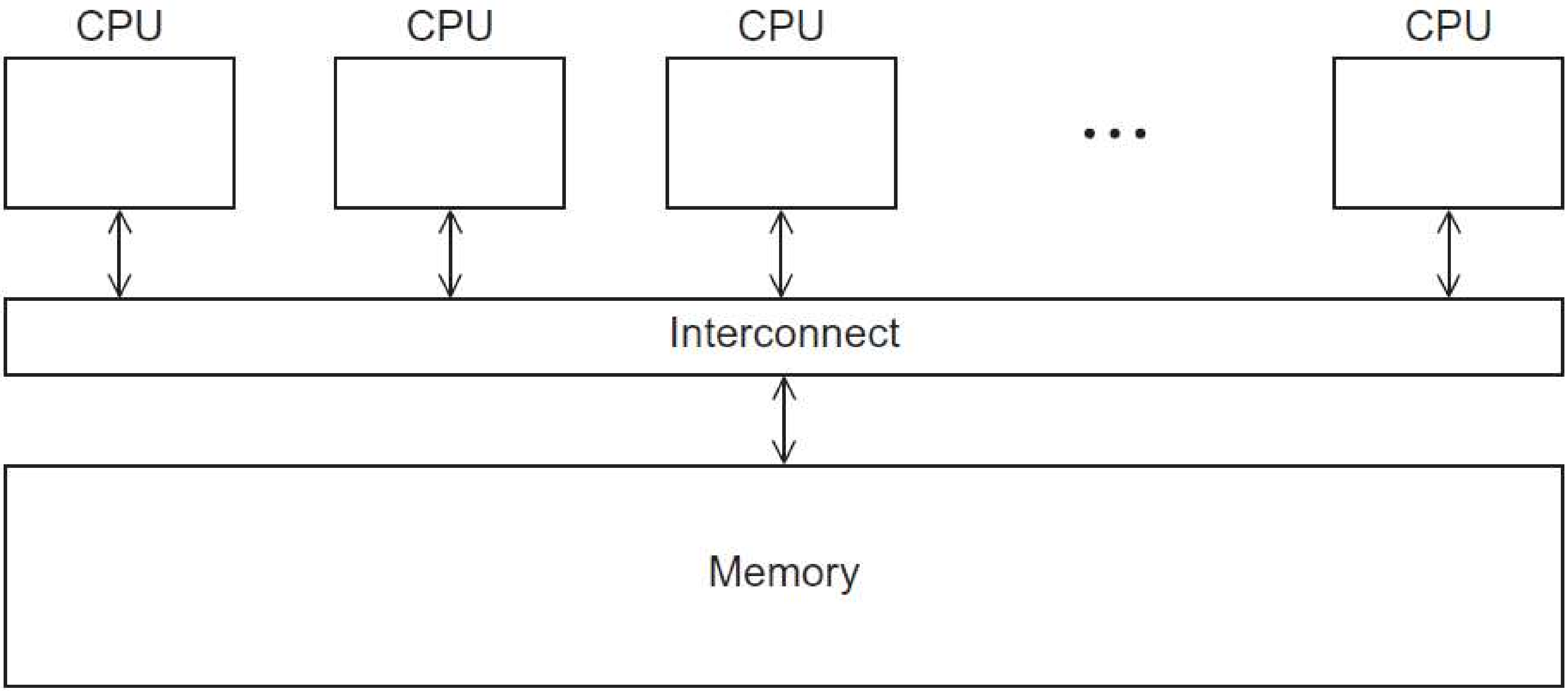
These insights are coming from HPC folks though!

Source: www.sdsc.edu/~allans/cs260/lectures/OpenMP.ppt

OpenMP

- An API for shared-memory parallel programming.
- Designed for systems in which each thread can have access to all available memory.
- System is viewed as a collection of cores or CPU's, all of which have access to the same main memory → shared memory architecture

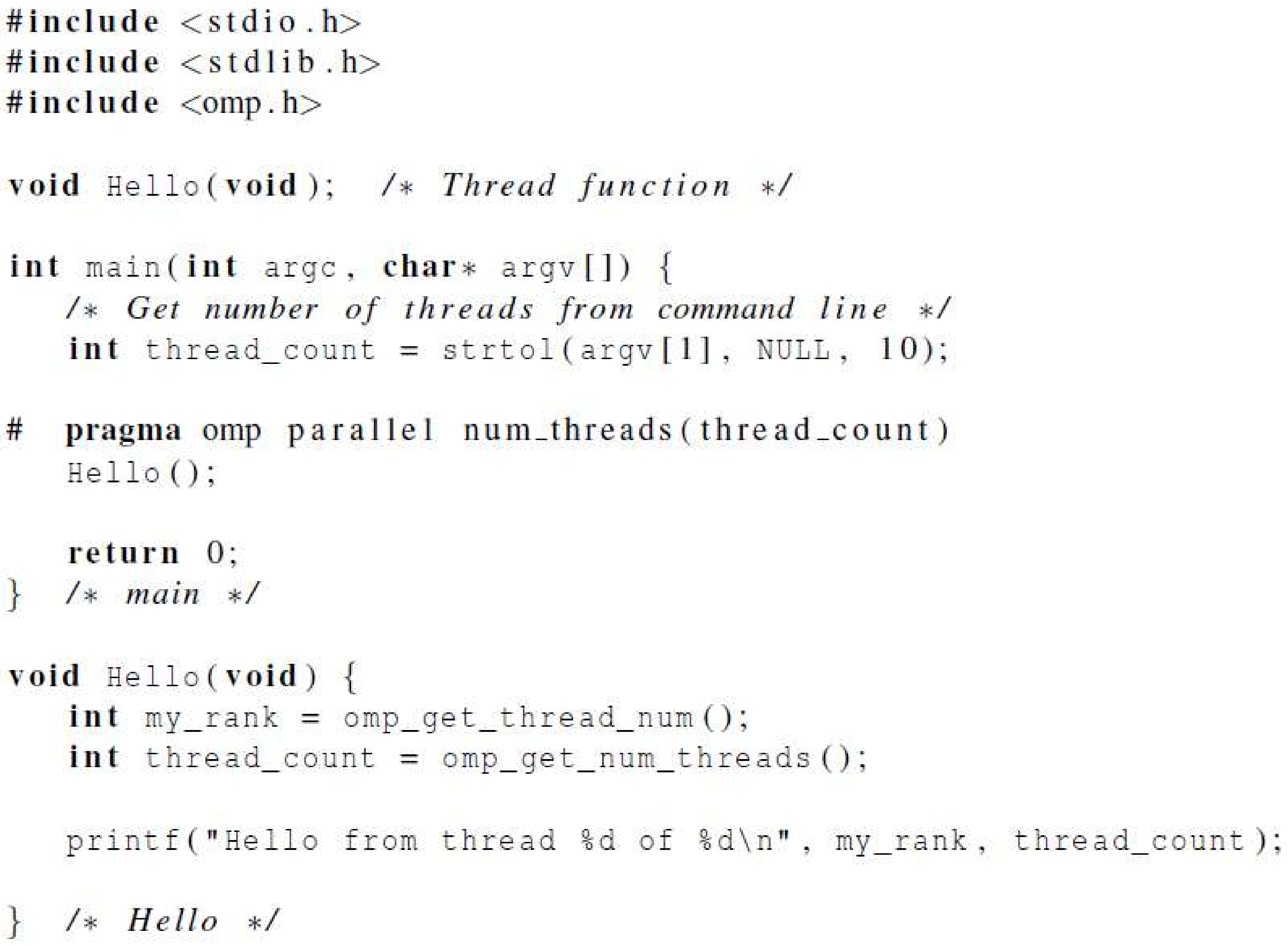
A shared memory system



Pragmas

- Special **preprocessor** instructions.
- specified by the C standard for providing additional information to the compiler, beyond what is conveyed in the language itself.
- Compilers that don't support the pragmas ignore them.

#pragma



```
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>

void Hello(void);  /* Thread function */

int main(int argc, char* argv[]) {
   /* Get number of threads from command line */
   int thread_count = strtol(argv[1], NULL, 10);

#  pragma omp parallel num_threads(thread_count)
   Hello();

   return 0;
}  /* main */

void Hello(void) {
   int my_rank = omp_get_thread_num();
   int thread_count = omp_get_num_threads();

   printf("Hello from thread %d of %d\n", my_rank, thread_count);

}  /* Hello */
```

```
gcc −g −Wall −fopenmp −o omp_hello omp_hello . c
```

```
. /omp_hello 4
```

running with 4 threads

possible outcomes

```
Hello from thread 0 of 4
Hello from thread 1 of 4
Hello from thread 2 of 4
Hello from thread 3 of 4
```

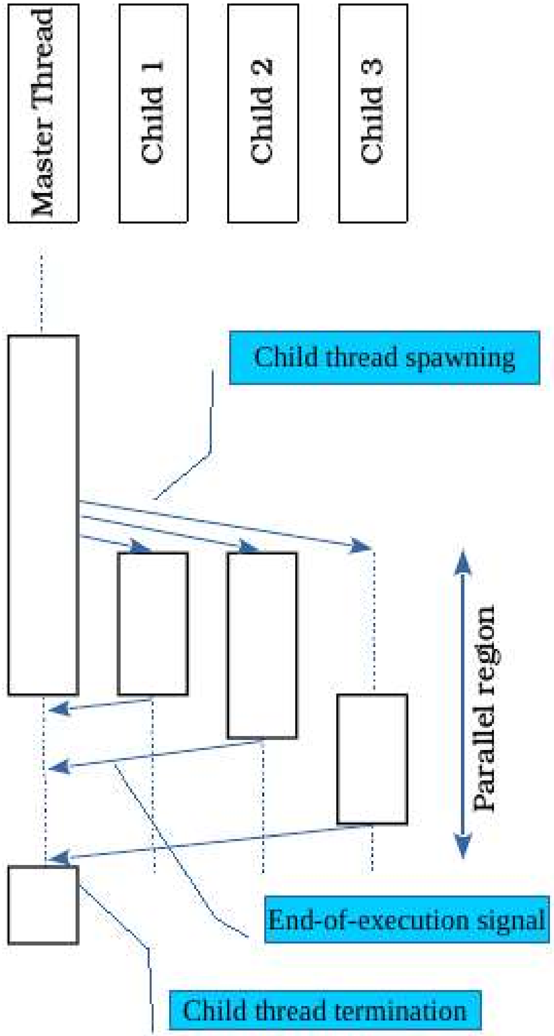
```
Hello from thread 1 of 4
Hello from thread 2 of 4
Hello from thread 0 of 4
Hello from thread 3 of 4
```

```
Hello from thread 3 of 4
Hello from thread 1 of 4
Hello from thread 2 of 4
Hello from thread 0 of 4
```

Another *Hello World*

- One of the possible execution sequences:

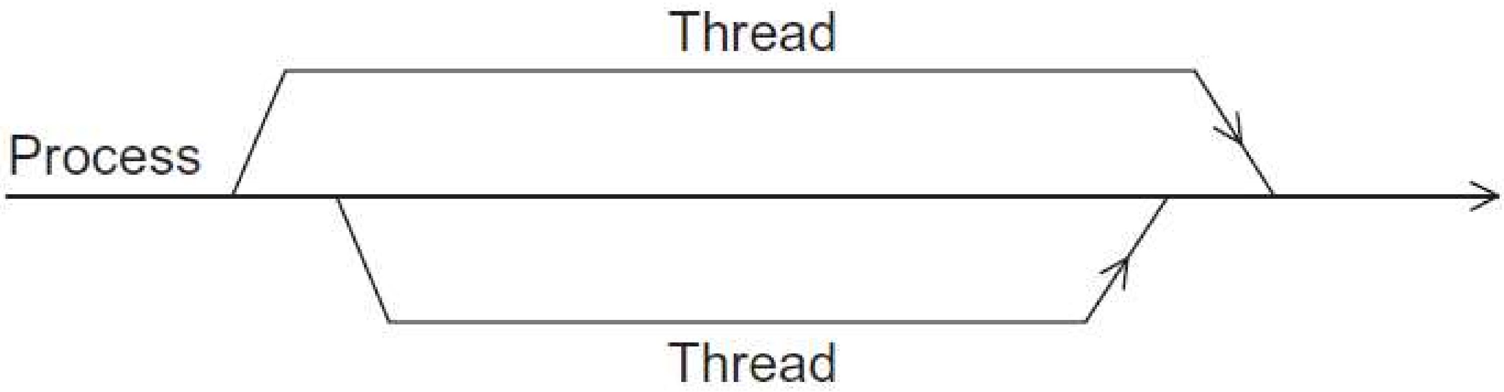
```
int main (int argc, char **argv)
{

  int numThr = atoi (argv[1]);


#pragma omp parallel num_threads(numThr)

  cout << "Hello from thread " <<
         Omp_get_thread_num () << endl;






  return 0;
}
```



OpenMP pragmas

- # pragma omp parallel
  - Most basic parallel directive.
  - The number of threads that run the following structured block of code is determined by the run-time system if the programmer does not specify a number of threads.

A process forking and joining two threads



clause

- Definition: text that modifies a directive.
- The num_threads clause can be added to a parallel directive.
  - It allows the programmer to specify the number of threads that should execute the following block.

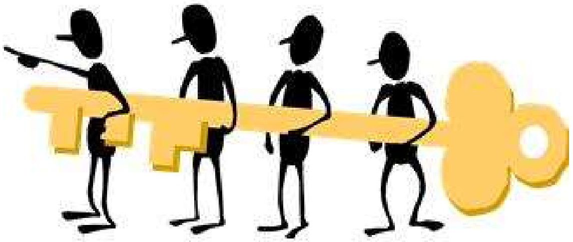
$$\texttt{\# pragma omp parallel } \underbrace{\texttt{num\_threads (thread\_count)}}_{\text{Clause}}$$

Of note…

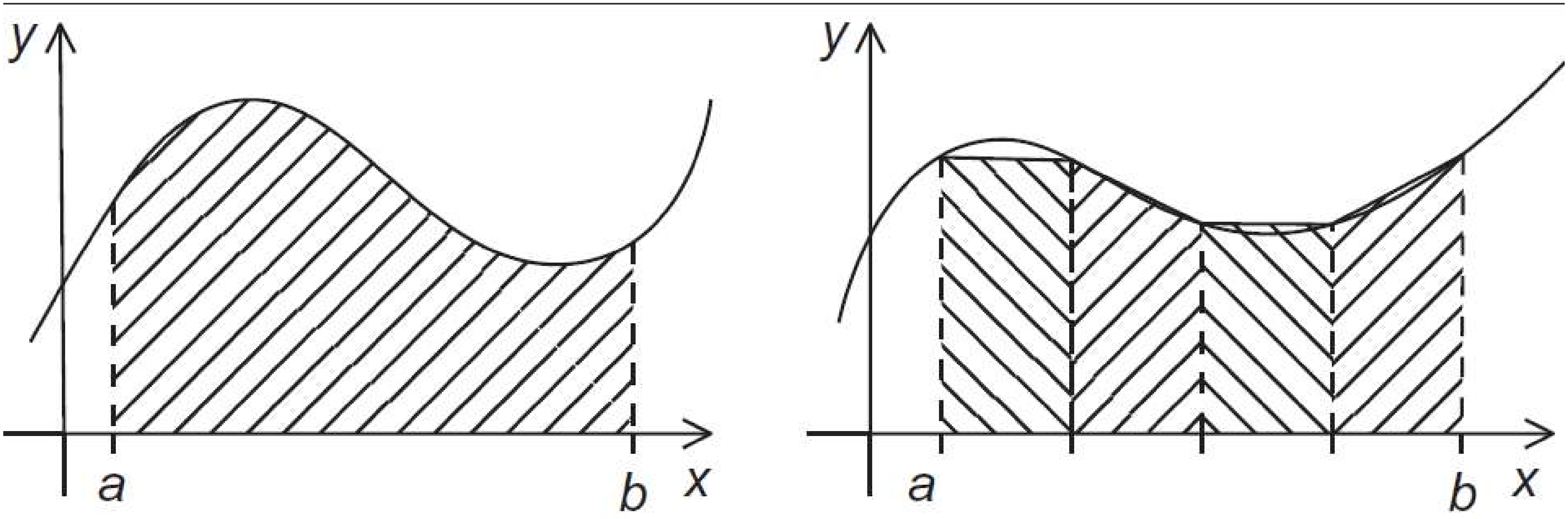
- There may be system-defined limitations on the number of threads that a program can start.
- The OpenMP standard doesn't guarantee that this will actually start thread_count threads.
- **However:** Unless we're trying to start a very large number of threads, we will almost always get the desired number of threads.

Some terminology

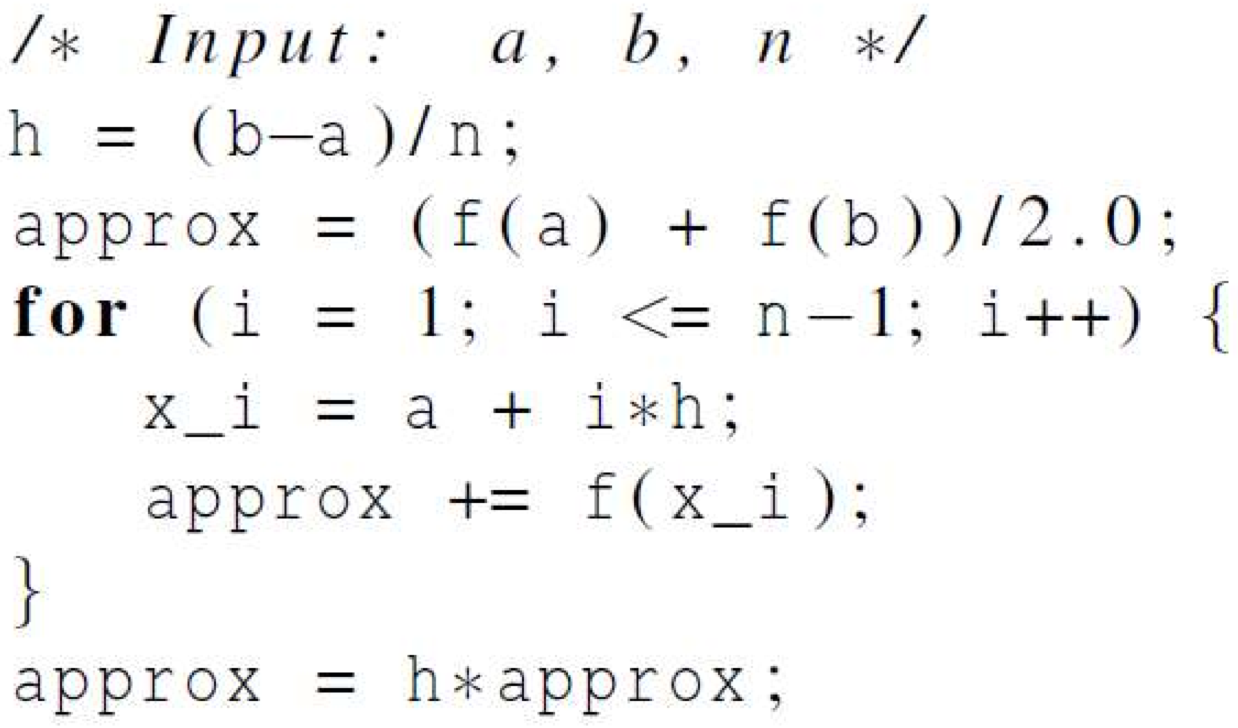
- In OpenMP parlance the collection of threads executing the parallel block — the original thread and the new threads — is called a team, the original thread is called the master, and the additional threads are called slaves.



Again: The trapezoidal rule



Serial algorithm



```
/* 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;
```

A First OpenMP Version

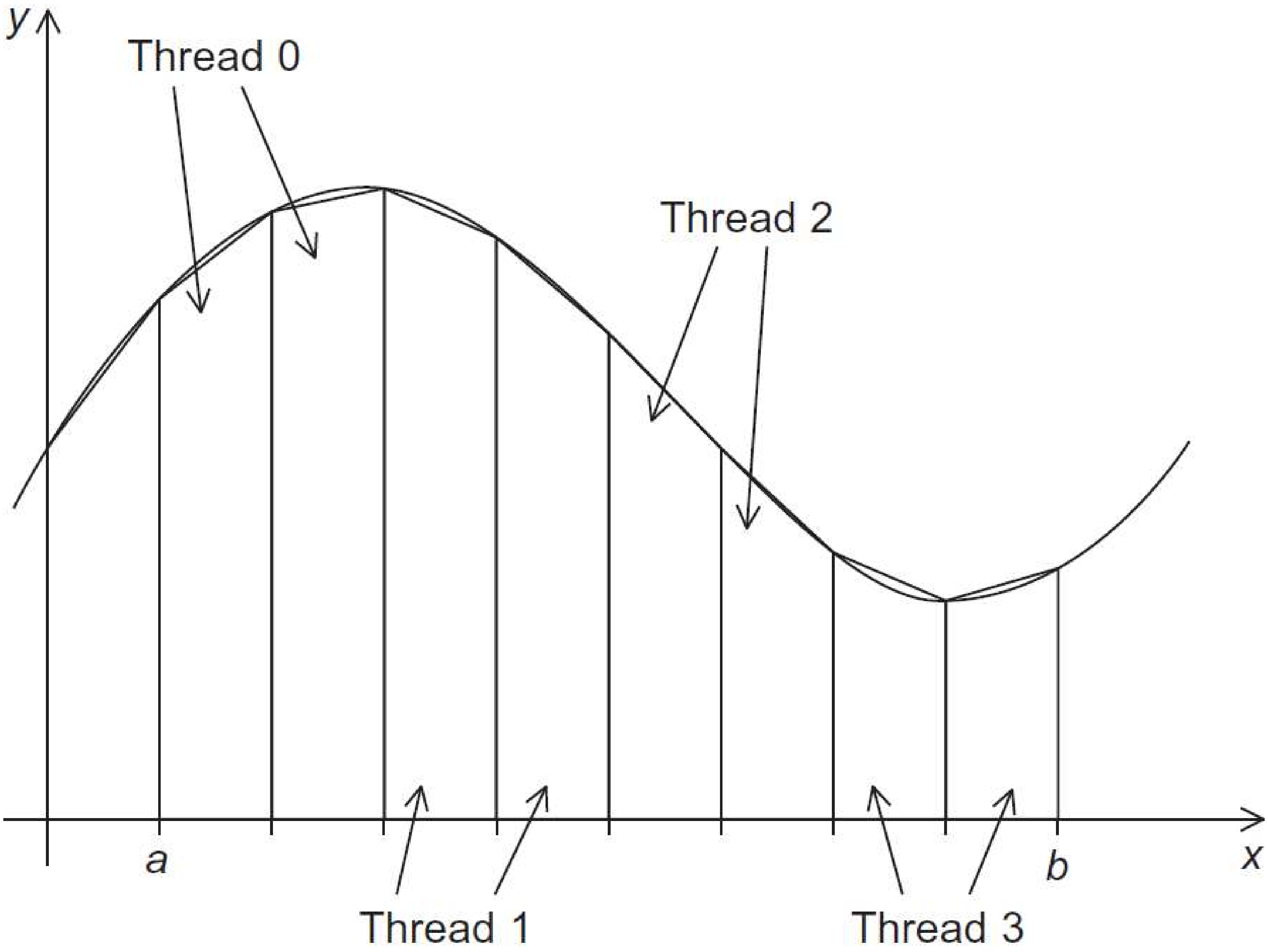
1) We identified two type of tasks:
   a) computation of the areas of individual trapezoids, and
   b) adding the areas of trapezoids.
2) There is no communication among the tasks in the first collection, but each task in the first collection communicates with task 1b.

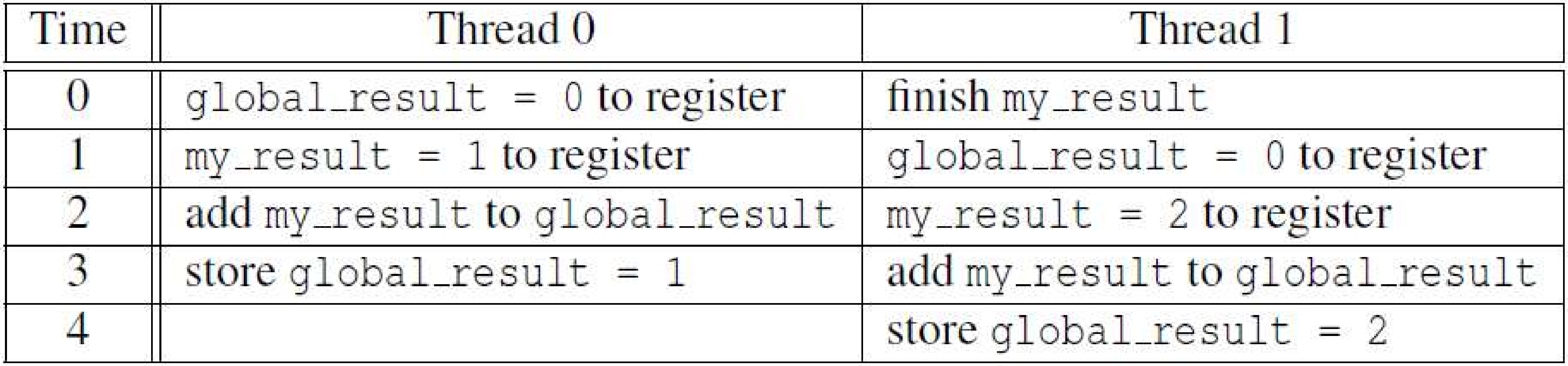
A First OpenMP Version

3) We assumed that there would be many more trapezoids than cores.

- So we aggregated tasks by assigning a contiguous block of trapezoids to each thread.

Assignment of trapezoids to threads





Time	Thread 0	Thread 1
0	global_result = 0 to register	finish my_result
1	my_result = 1 to register	global_result = 0 to register
2	add my_result to global_result	my_result = 2 to register
3	store global_result = 1	add my_result to global_result
4		store global_result = 2

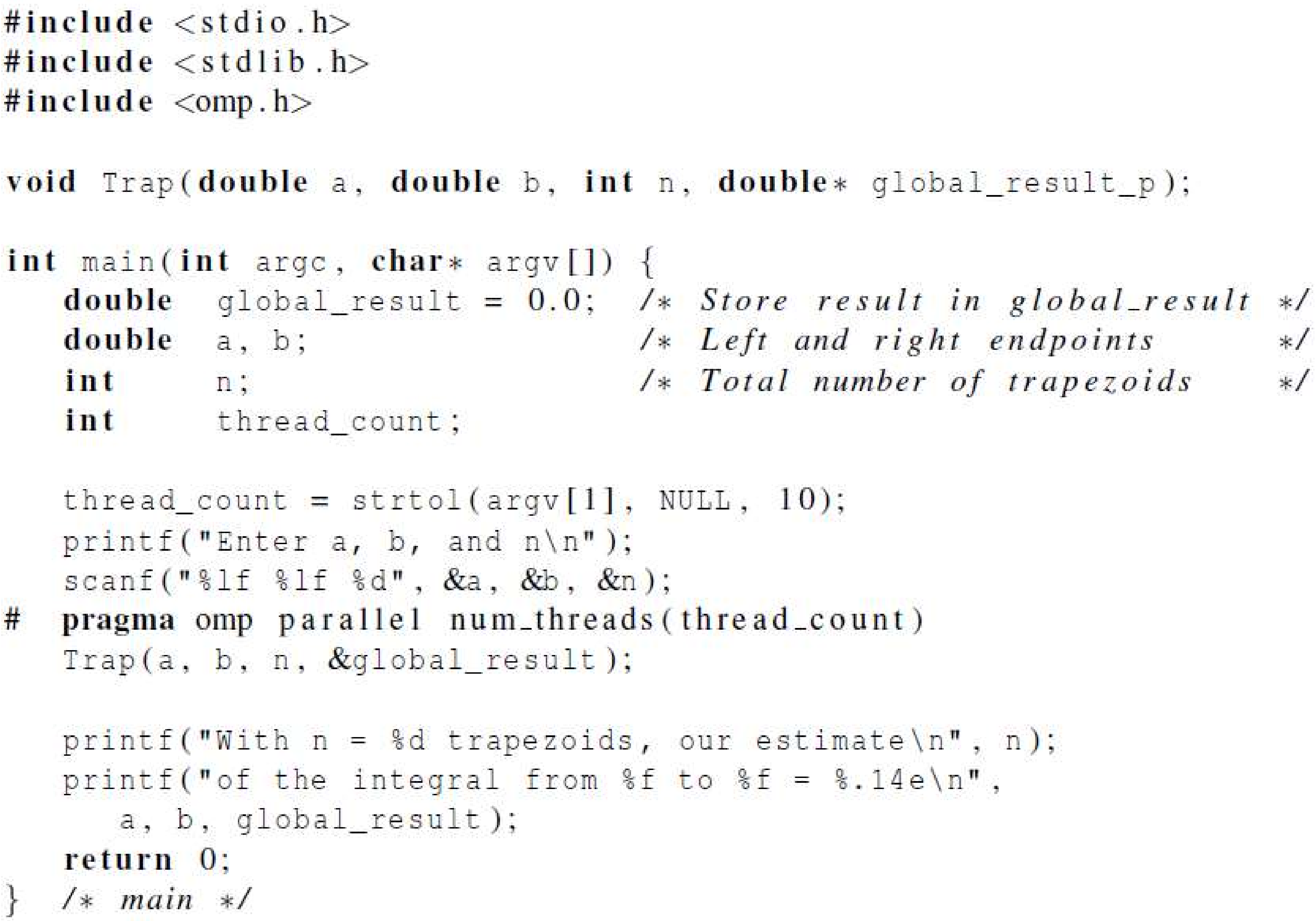
Unpredictable results when two (or more) threads attempt to simultaneously execute:

global_result += my_result ;

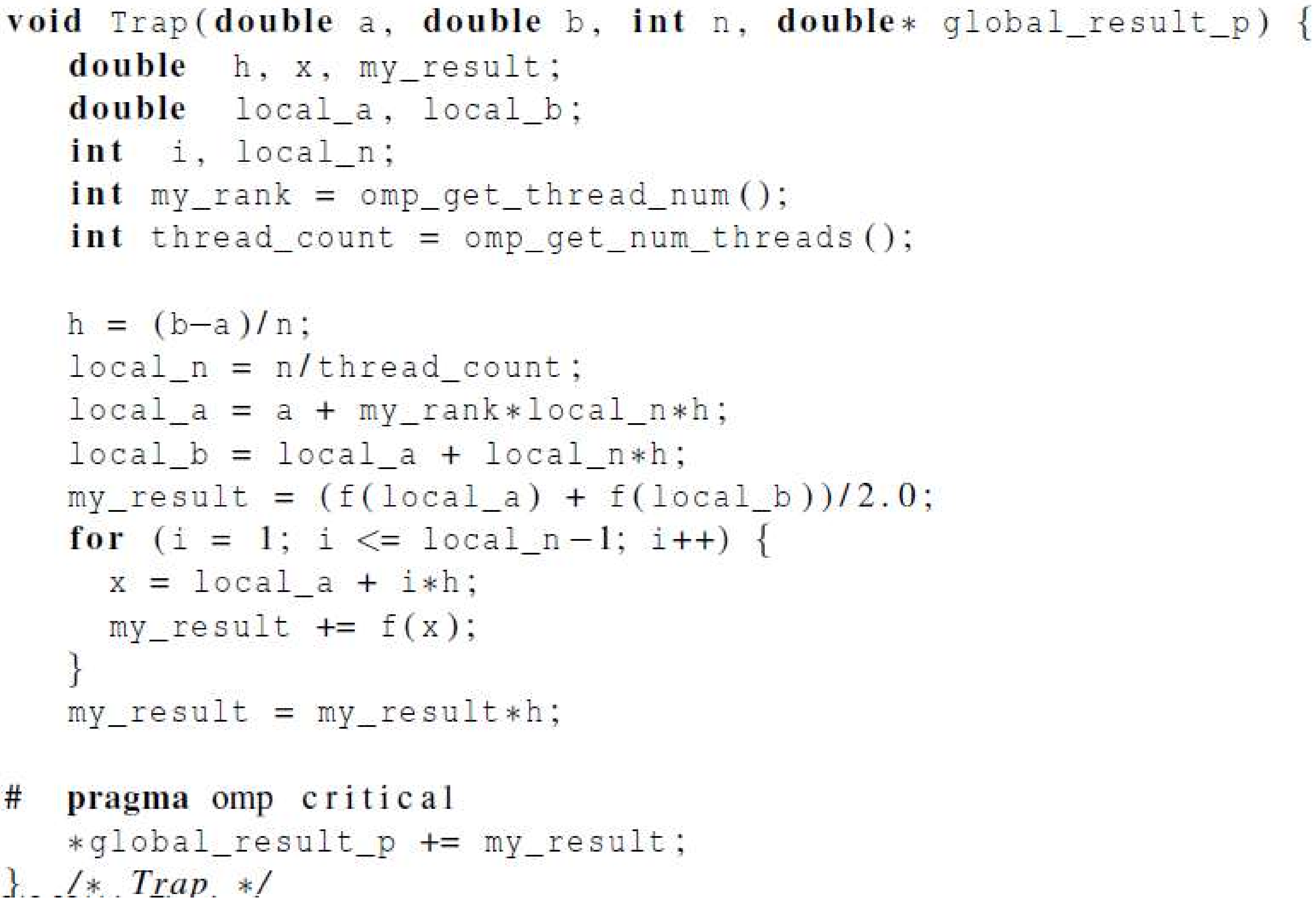
Mutual exclusion

```
# pragma omp critical
 global_result += my_result ;
```

only **one thread** can execute the following structured block at a time



```
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>

void Trap(double a, double b, int n, double* global_result_p);

int main(int argc, char* argv[]) {
   double  global_result = 0.0;  /* Store result in global_result */
   double  a, b;                 /* Left and right endpoints      */
   int     n;                    /* Total number of trapezoids    */
   int     thread_count;

   thread_count = strtol(argv[1], NULL, 10);
   printf("Enter a, b, and n\n");
   scanf("%lf %lf %d", &a, &b, &n);
#  pragma omp parallel num_threads(thread_count)
   Trap(a, b, n, &global_result);

   printf("With n = %d trapezoids, our estimate\n", n);
   printf("of the integral from %f to %f = %.14e\n",
      a, b, global_result);
   return 0;
}  /* main */
```



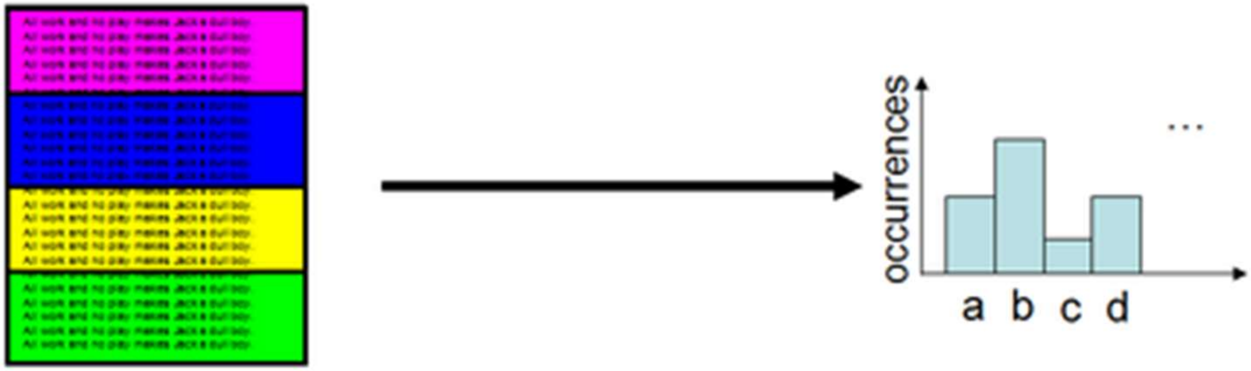
```
void Trap(double a, double b, int n, double* global_result_p) {
   double  h, x, my_result;
   double  local_a, local_b;
   int  i, local_n;
   int my_rank = omp_get_thread_num();
   int thread_count = omp_get_num_threads();

   h = (b-a)/n;
   local_n = n/thread_count;
   local_a = a + my_rank*local_n*h;
   local_b = local_a + local_n*h;
   my_result = (f(local_a) + f(local_b))/2.0;
   for (i = 1; i <= local_n-1; i++) {
     x = local_a + i*h;
     my_result += f(x);
   }
   my_result = my_result*h;

#  pragma omp critical
   *global_result_p += my_result;
}  /* Trap */
```

Another Example

- **Problem:** Count the number of times each ASCII character occurs on a page of text.
- **Input:** ASCII text stored as an array of characters.
- **Output**: A histogram with 128 buckets – one for each ASCII character

source: http://www.futurechips.org/tips-for-power-coders/writing-optimizing-parallel-programs-complete.html

Another Example



Speed on Quad Core:
10.36 seconds

```
void compute_histogram_st(char *page, int page_size, int *histogram){
for(int i = 0; i < page_size; i++){
    char read_character = page[i];
    histogram[read_character]++;
  }
}
```

Sequential Version

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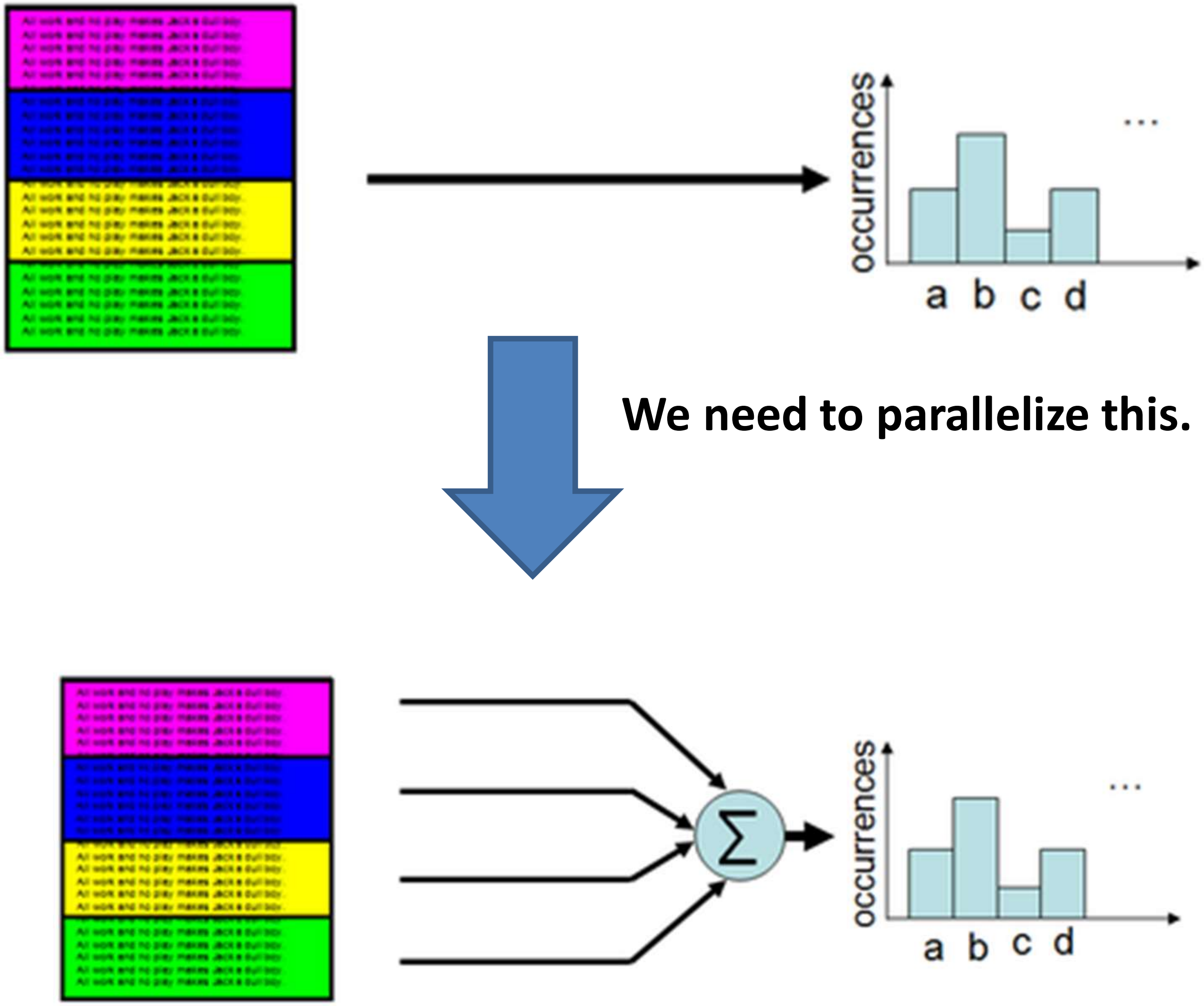
Another Example



We need to parallelize this.

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Another Example

```
void compute_histogram_st(char *page, int page_size, int *histogram){
#pragma omp parallel for
for(int i = 0; i < page_size; i++){
        char read_character = page[i];
         histogram[read_character]++;
   }
```

The above code does not work!!   Why?

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Another Example

```
void compute_histogram_mt2(char *page, int page_size, int *histogram){
#pragma omp parallel for
for(int i = 0; i < page_size; i++){
     char read_character = page[i];
     #pragma omp atomic
      histogram[read_character]++;
    }
}
```

Speed on Quad Core:
 114.89 seconds
> 10x slower than the single thread version!!

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Another Example

```
void compute_histogram_mt3(char *page,
                           int page_size,
                           int *histogram, int num_buckets){
#pragma omp parallel
{
    int local_histogram[NUM_THREADS][num_buckets];
    int tid = omp_get_thread_num();
    #pragma omp for nowait
    for(int i = 0; i < page_size; i++){
        char read_character = page[i];
        local_histogram[tid][read_character]++;
    }
    for(int i = 0; i < num_buckets; i++){
        #pragma omp atomic
        histogram[i] += local_histogram[tid][i];
    }
  }
}
```

Runs in 3.8 secs
Why speedup
is not 4 yet?

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Another Example

```
void compute_histogram_mt4(char *page, int page_size,
                                             int *histogram, int num_buckets){
        int num_threads = omp_get_max_threads();
        #pragma omp parallel
        {
        __declspec (align(64)) int local_histogram[num_threads][num_buckets];
        int tid = omp_get_thread_num();
        #pragma omp for
        for(int i = 0; i < page_size; i++){
                char read_character = page[i];
                local_histogram[tid][read_character]++;
        }

        #pragma omp single
        for(int t = 0; t < num_threads; t++){
                for(int i = 0; i < num_buckets; i++)
                        histogram[i] += local_histogram[t][i];
        }
}
```

Speed is 4.42 seconds. Slower than the previous version.

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Another Example

```
void compute_histogram_mt4(char *page, int page_size,
                                        int *histogram, int num_buckets){
        int num_threads = omp_get_max_threads();
        #pragma omp parallel
        {
        __declspec (align(64)) int local_histogram[num_threads][num_buckets];
        int tid = omp_get_thread_num();
        #pragma omp for
        for(int i = 0; i < page_size; i++){
                char read_character = page[i];
                local_histogram[tid][read_character]++;
        }

        #pragma omp for
        for(int i = 0; i < num_buckets; i++){
                for(int t = 0; t < num_threads; t++)
                        histogram[i] += local_histogram[t][i];
        }
}
```

Speed is
3.60 seconds.

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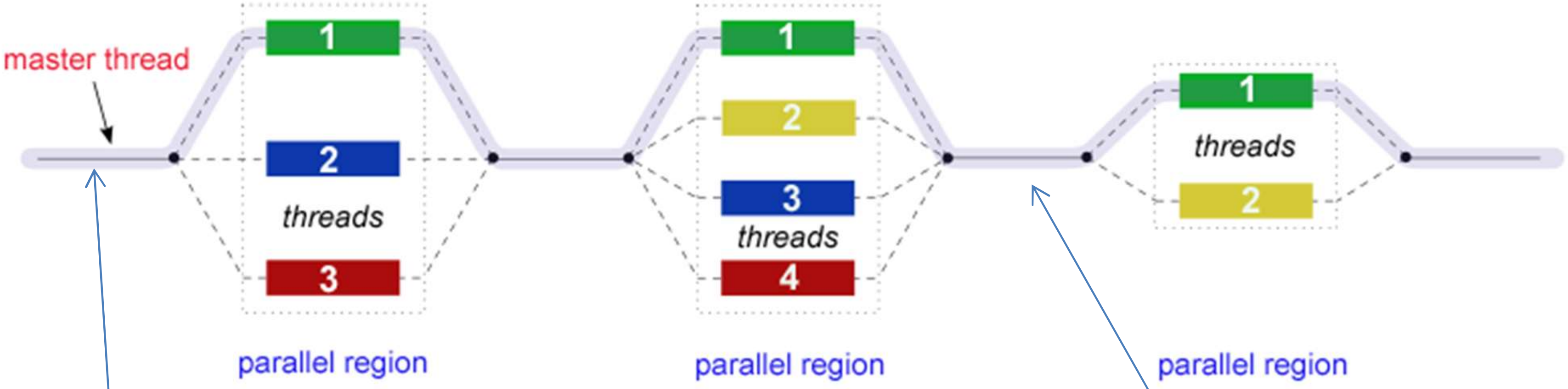
What Can We Learn from the Previous Example?

- Atomic operations
  - They are expensive
  - Yet, they are fundamental building blocks.
- Synchronization:
  - correctness vs performance loss
  - Rich interaction of hardware-software tradeoffs

OpenMP Parallel Programming

1. Start with a *parallelizable* algorithm
   - loop-level parallelism is necessary
2. Implement serially
3. Test and Debug
4. Annotate the code with parallelization (and synchronization) directives
   - Hope for linear speedup
5. Test and Debug

OpenMP uses the fork-join model of parallel execution.



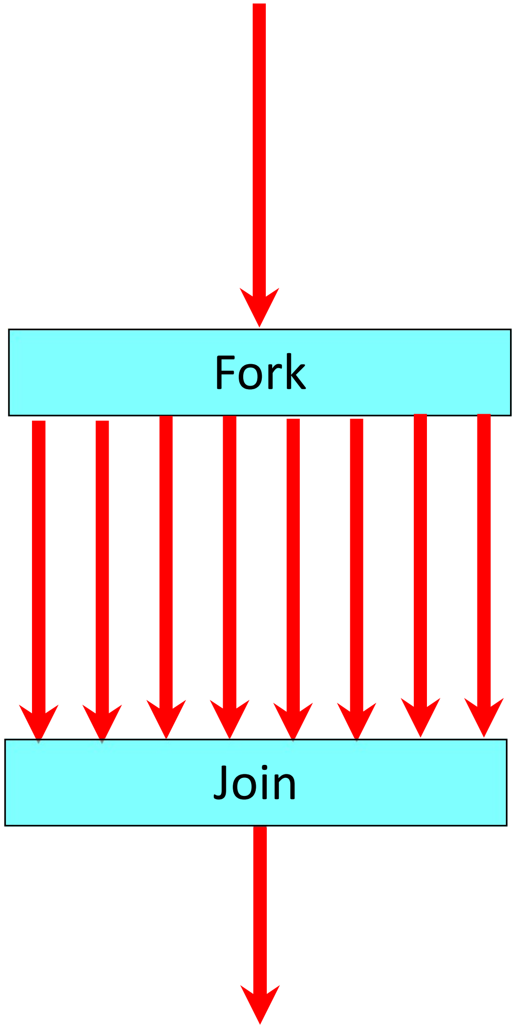
All OpenMP programs begin with a single thread: **master thread** (ID = 0)

FORK: the master thread then creates a team of parallel ***threads***.

JOIN: When the team threads complete the statements in the parallel region construct, they synchronize and terminate

Programming Model - Threading

```
int main() {
   // serial region
   printf(“Hello…”);
  // parallel region
  #pragma omp parallel
  {
    printf(“World”);
  }
  // serial again
  printf(“!”);
}
```



We didn’t use omp_set_num_threads(), what will be the output?

What we learned so far

- #include <omp.h>
- gcc -fopenmp …
- omp_set_num_threads(x);
- omp_get_thread_num();
- omp_get_num_threads();
- #pragma omp parallel [num_threads(x)]
- #pragma omp atomic
- #pragma omp single

Conclusions

- OpenMP is a standard for programming shared-memory systems.
- OpenMP uses both special functions and preprocessor directives called pragmas.
- OpenMP programs start multiple threads rather than multiple processes.
- Many OpenMP directives can be modified by clauses.