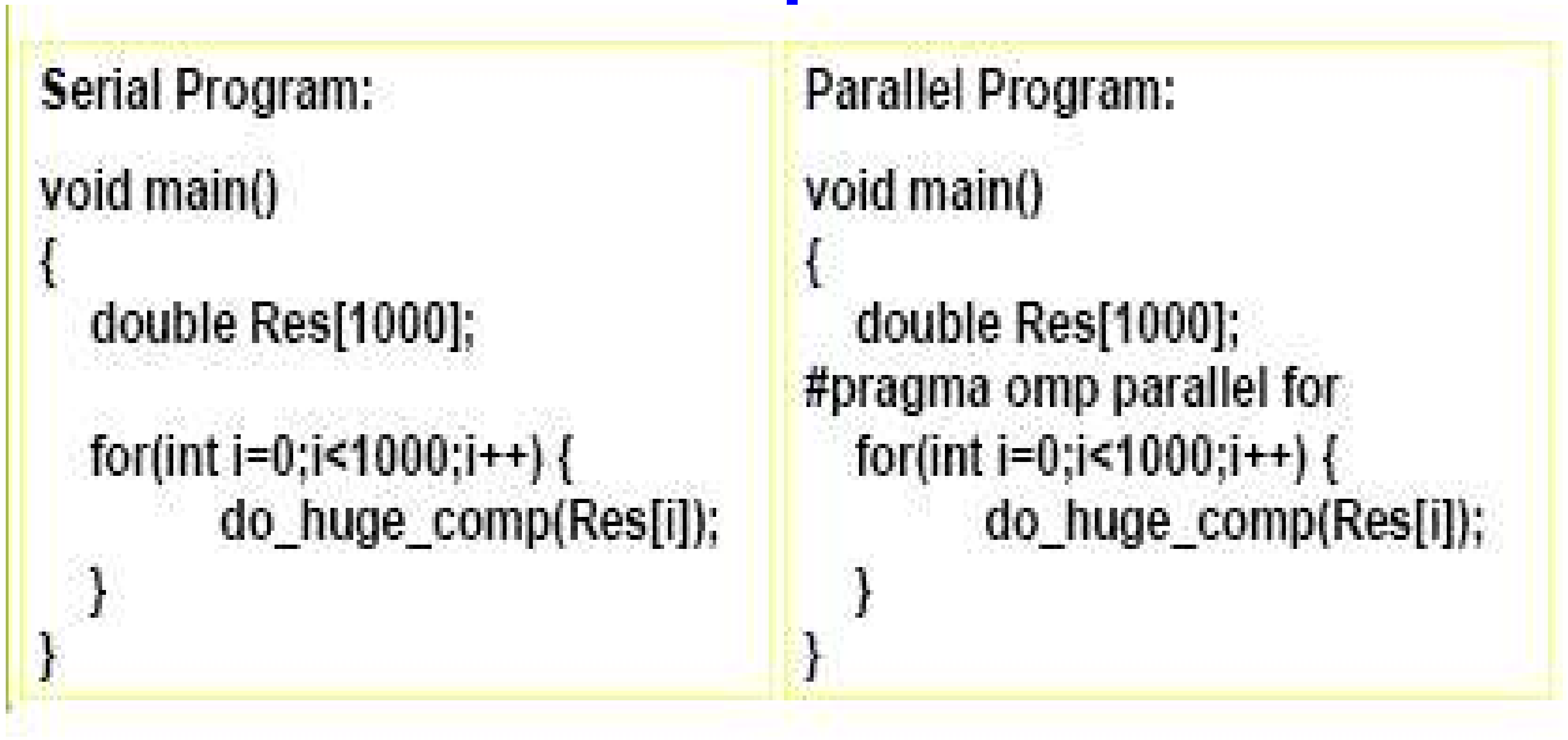
Small and Easy Motivation

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


int main() {



  // Do this part in parallel


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


  return 0;
}
```

Small and Easy Motivation

```c
 #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]);
    }
}
```

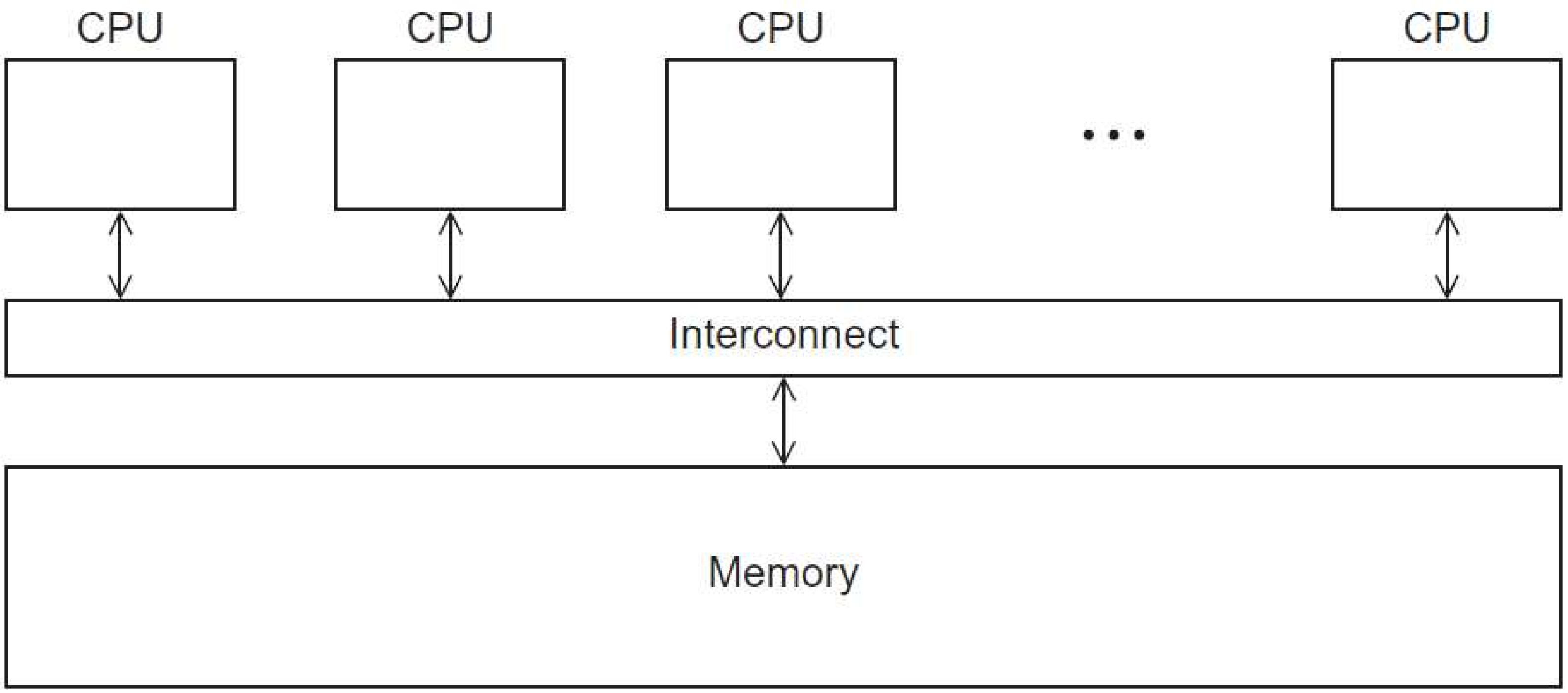
OpenMP can parallelize many serial programs with relatively few annotations that specify parallelism and independence

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

OpenMP

- An API for shared-memory parallel programming.
- Designed for systems in which each thread can potentially 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
```

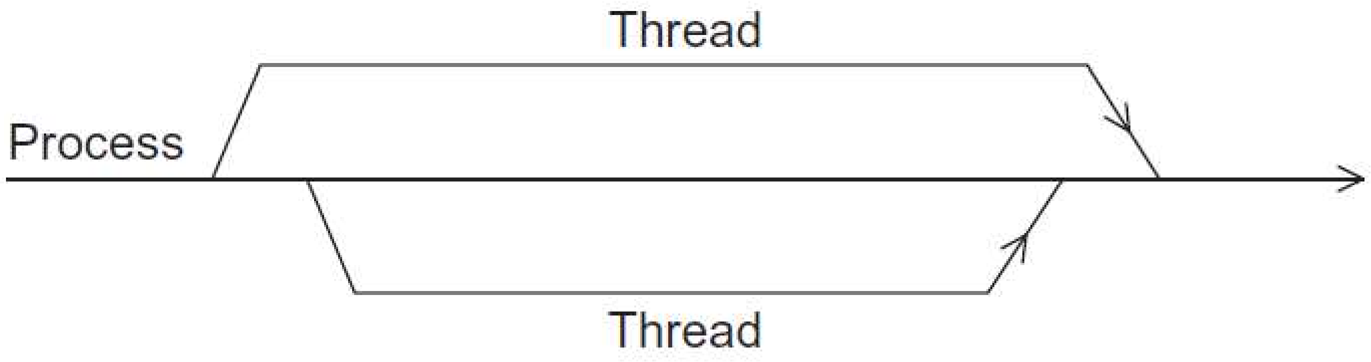
```
Hello from thread 1 of 4
Hello from thread 2 of 4
Hello from thread 0 of 4
Hello from thread 3 of 4
```

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

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.

A process forking and joining two threads



clause

- 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.

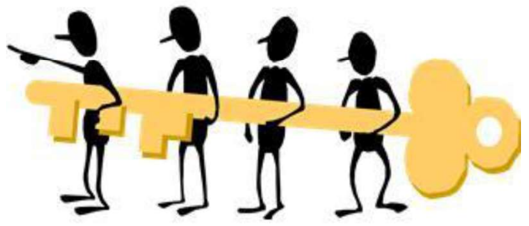
```
# pragma omp parallel num_threads ( thread_count )
```

Of note…

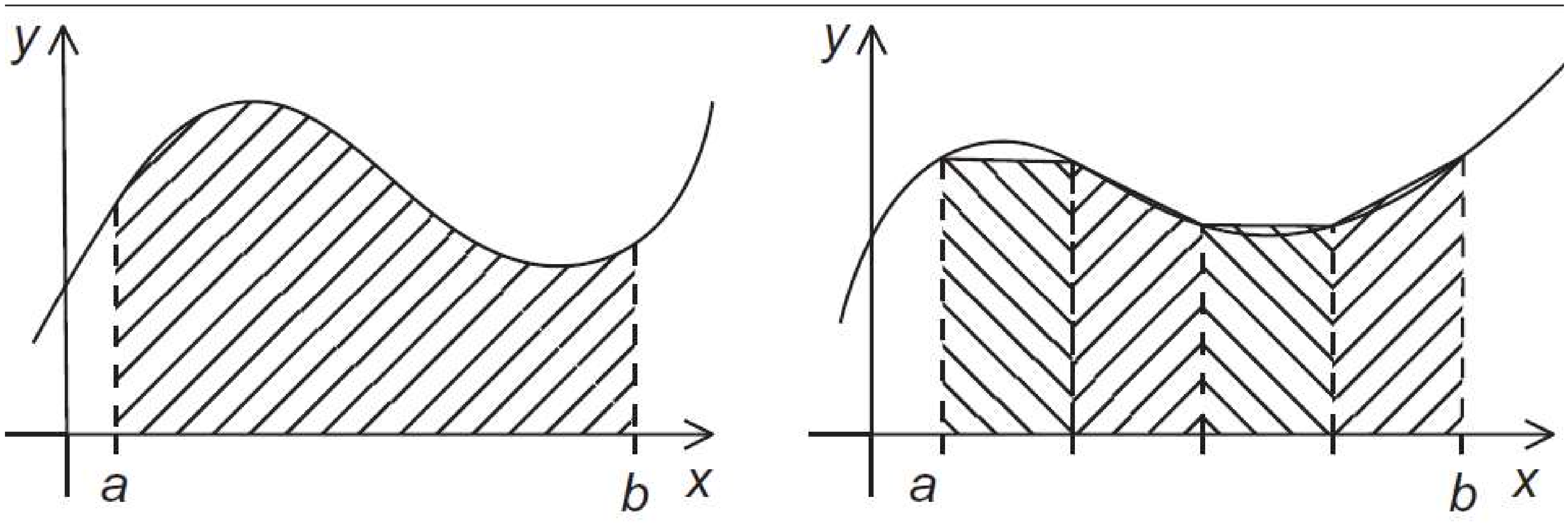
- There may be system-defined limitations on the number of threads that a program can start.
- The OpenMP standard doesn't guarantee that this will actually start thread_count threads.
- Unless we're trying to start a lot of threads, we will almost always get the desired number of threads.

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

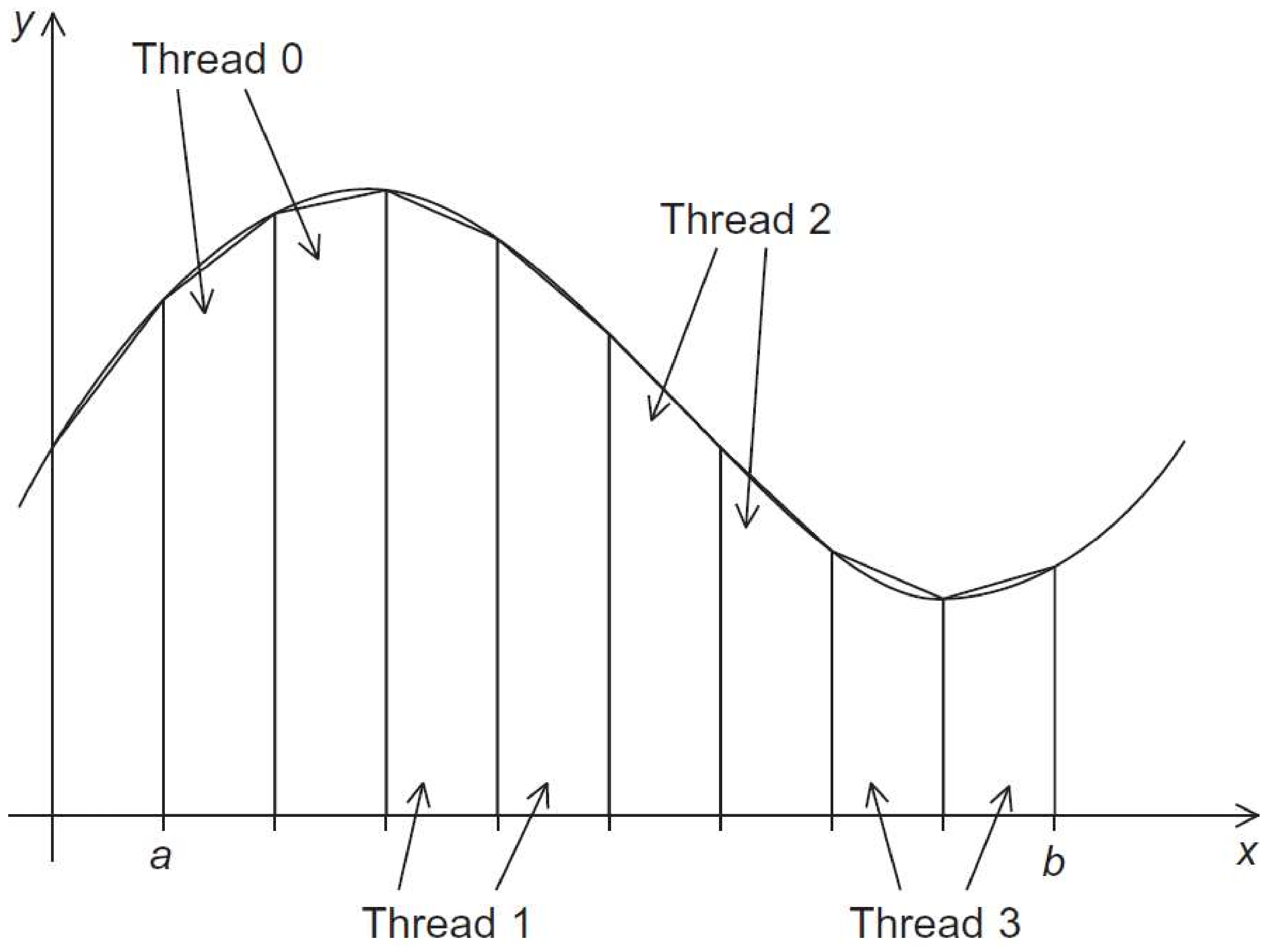
1) We identified two types of tasks:
   a) computation of the areas of individual trapezoids, and
   b) adding the areas of trapezoids.
2) There is no communication among the tasks in the first collection, but each task in the first collection communicates with task 1b.

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 */
```

Scope

- In serial programming, the scope of a variable consists of those parts of a program in which the variable can be used.

- In OpenMP, the scope of a variable refers to the set of threads that can access the variable in a parallel block.

Scope in OpenMP

- A variable that can be accessed by all the threads in the team has shared scope.
- A variable that can only be accessed by a single thread has private scope.
- The default scope for variables declared before a parallel block is shared.

```
#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 */
```

shared

private

```
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 */
```

Do you remember the trapezoidal?

We need this more complex version to add each thread's local calculation to get *global_result*.

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

Although we'd prefer this.

```
double Trap(double a, double b, int n);
```

```
        global_result = Trap(a, b, n);
```

How about this:

```
double Local_trap(double a, double b, int n);
```

and we use it like this:

```
   global_result = 0.0;
#  pragma omp parallel num_threads(thread_count)
   {
#     pragma omp critical
      global_result += Local_trap(double a, double b, int n);
   }
```

… we force the threads to execute sequentially.

It is now slower than a version with single thread!

How can we fix this?

We can avoid this problem by:

1. declaring a private variable inside the parallel block
2. moving the critical section after the function call

```
    global_result = 0.0;
#   pragma omp parallel num_threads(thread_count)
    {
       double my_result = 0.0;  /* private */

       my_result += Local_trap(double a, double b, int n);
#      pragma omp critical
       global_result += my_result;
    }
```

Can we do better?

Reduction operators

- Is a binary operation
- A reduction is a computation that repeatedly applies the same reduction operator to a sequence of operands in order to get a single result (we have seen that in MPI!).
- All of the intermediate results of the operation should be stored in the same variable: the reduction variable.

A reduction clause can be added to a parallel directive.

```
reduction(<operator>: <variable list>)
```

+, *, -, &, |, ^, &&, ||

Be careful of:
- subtraction
- floating points

And the code becomes:

```
   global_result = 0.0;
#  pragma omp parallel num_threads(thread_count) \
      reduction(+: global_result)
   global_result += Local_trap(double a, double b, int n);
```

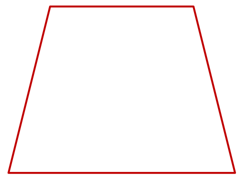
How Does OpenMP Do it?

- The reduction variable is shared.
- OpenMP create a local variable for each thread
- Those local variables are initialized to the identity value for the reduction operator
- When the parallel block ends, the values in the private variables are combined into the shared variable.

#pragma omp parallel for

- Forks a team of threads to execute the following structured block.
- The structured block following the parallel for directive must be a for loop.
- The system parallelizes the for loop by dividing the iterations of the loop among the threads.

```
h = (b-a)/n;
approx = (f(a) + f(b))/2.0;
for (i = 1; i <= n-1; i++)
   approx += f(a + i*h);
approx = h*approx;
```



```
    h = (b-a)/n;
    approx = (f(a) + f(b))/2.0;
#   pragma omp parallel for num_threads(thread_count) \
       reduction(+: approx)
    for (i = 1; i <= n-1; i++)
       approx += f(a + i*h);
    approx = h*approx;
```

In a loop that is parallelized with *parallel for* the default scope of a loop variable is private

Legal forms for parallelizable *for statements*

$$
\textbf{for}\left(\begin{array}{lllll}
 & & & & \texttt{index++} \\
 & & & & \texttt{++index} \\
 & & \texttt{index < end} & & \texttt{index--} \\
 & & \texttt{index <= end} & & \texttt{--index} \\
\texttt{index = start} & ; & \texttt{index >= end} & ; & \texttt{index += incr} \\
 & & \texttt{index > end} & & \texttt{index -= incr} \\
 & & & & \texttt{index = index + incr} \\
 & & & & \texttt{index = incr + index} \\
 & & & & \texttt{index = index - incr}
\end{array}\right)
$$

Number of iterations MUST be known prior to the loop execution.

There can be a call to *exit* in the loop body.

OpenMP won't parallelize while loops or do-while loops.

Caveats

- The variable index must have integer or pointer type (e.g., it can't be a float).
- The expressions start, end, and incr must have a compatible type. For example, if index is a pointer, then incr must have integer type.

Caveats

- The expressions start, end, and incr must not change during execution of the loop.
- During execution of the loop, the variable index can only be modified by the "increment expression" in the for statement.

Data dependencies

```
fibo[ 0 ] = fibo[ 1 ] = 1;
for (i = 2; i < n; i++)
    fibo[ i ] = fibo[ i – 1 ] + fibo[ i – 2 ];
```

note 2 threads

```
    fibo[ 0 ] = fibo[ 1 ] = 1;
#   pragma omp parallel for num_threads(2)
    for (i = 2; i < n; i++)
        fibo[ i ] = fibo[ i – 1 ] + fibo[ i – 2 ];
```

```
1 1 2 3 5 8 13 21 34 55
```

this is correct

but sometimes we get this

```
1 1 2 3 5 8 0 0 0 0
```

What happened?

1. OpenMP compilers don't check for dependences among iterations in a loop that's being parallelized with a parallel for directive.
2. A loop in which the results of one or more iterations depend on other iterations cannot, in general, be correctly parallelized by OpenMP.

Question

Do we have to worry about the following:

```
#pragma omp parallel for num_threads(2)
  for( i =0 ; i < n; i++) {
       x[i] = a + i*h;
       y[i] = exp(x[i]);
  }
```