

## Chapter 5

### Shared Memory Programming with OpenMP

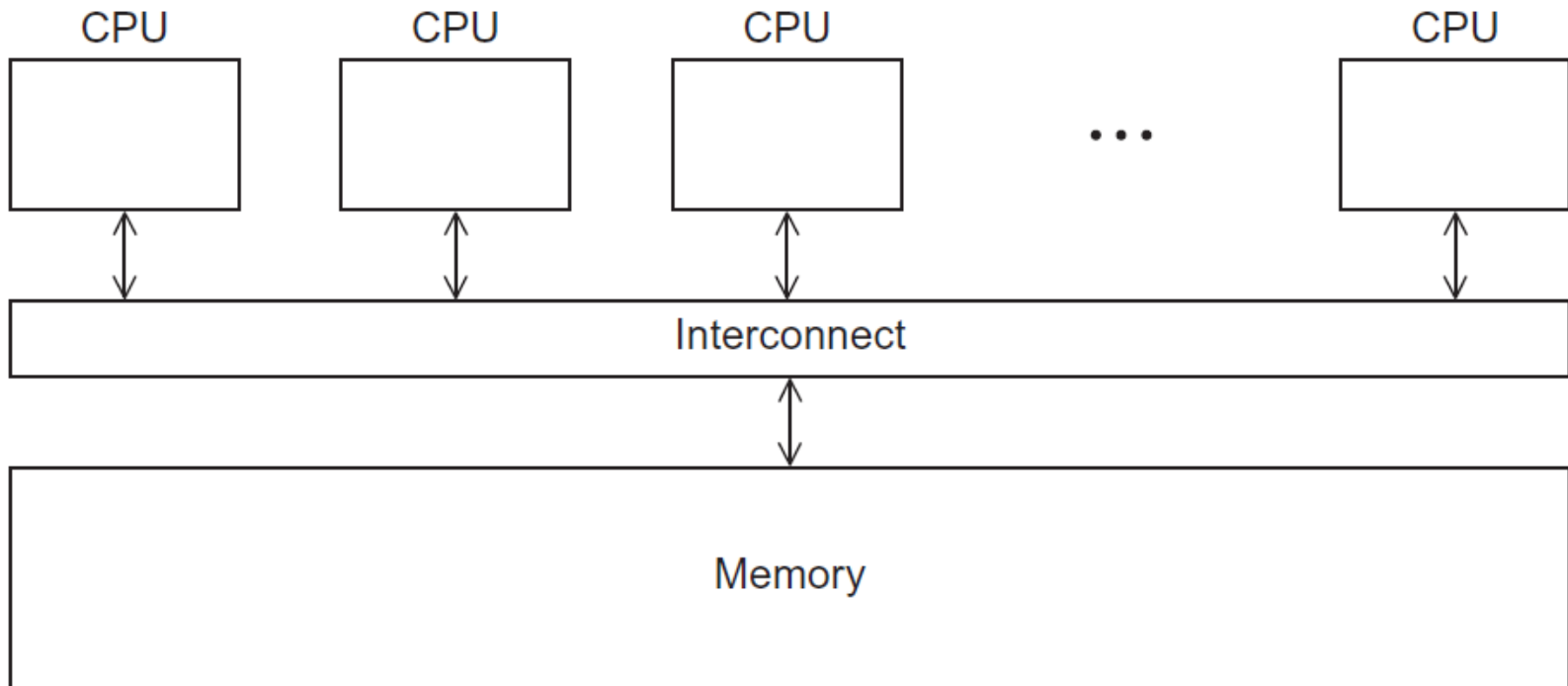
# Roadmap

- Writing programs that use OpenMP.
- Using OpenMP to parallelize many serial for loops with only small changes to the source code.
- Task parallelism.
- Explicit thread synchronization.
- Standard problems in shared-memory programming.

# OpenMP

- An API for shared-memory parallel programming.
- MP = multiprocessing
- Designed for systems in which each thread or process 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 main memory.

# A shared memory system



# Pragmas

- Special preprocessor instructions.
- Typically added to a system to allow behaviors that aren't part of the basic C specification.
- 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

compiling

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

possible  
outcomes

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

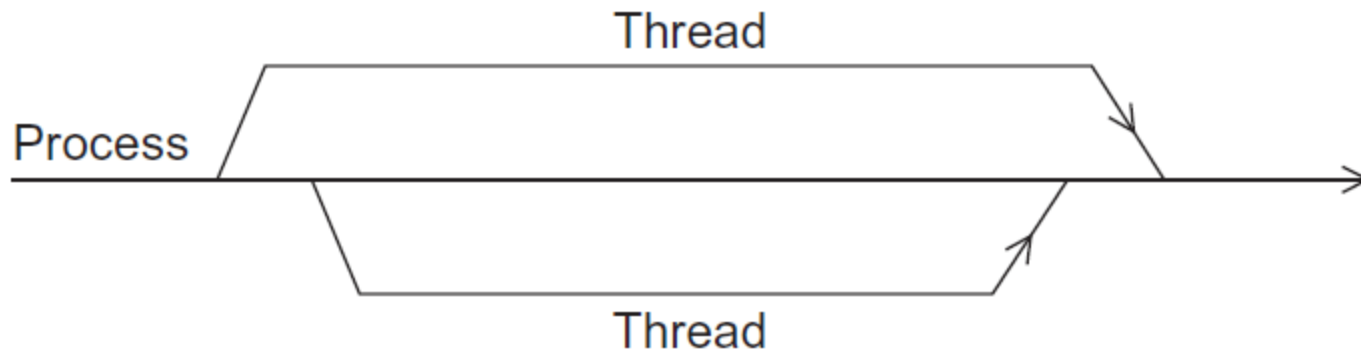
Hello from thread 3 of 4  
Hello from thread 1 of 4  
Hello from thread 2 of 4  
Hello from thread 0 of 4

# 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.

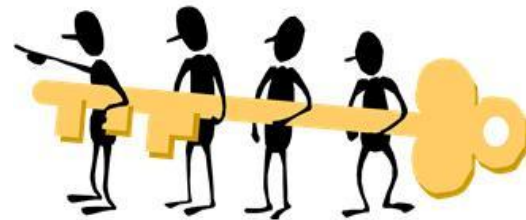
```
# pragma omp parallel num_threads ( thread_count )
```

# 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.
- Most current systems can start hundreds or even thousands of threads.
- Unless we're trying to start a lot of threads, we will almost always get the desired number of threads.

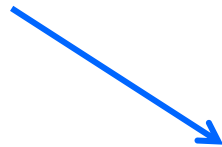
# Some terminology

- 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**.



# In case the compiler doesn't support OpenMP

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



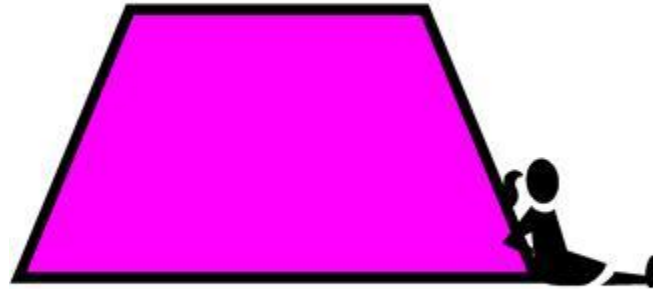
```
#ifdef _OPENMP
```

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

```
#endif
```

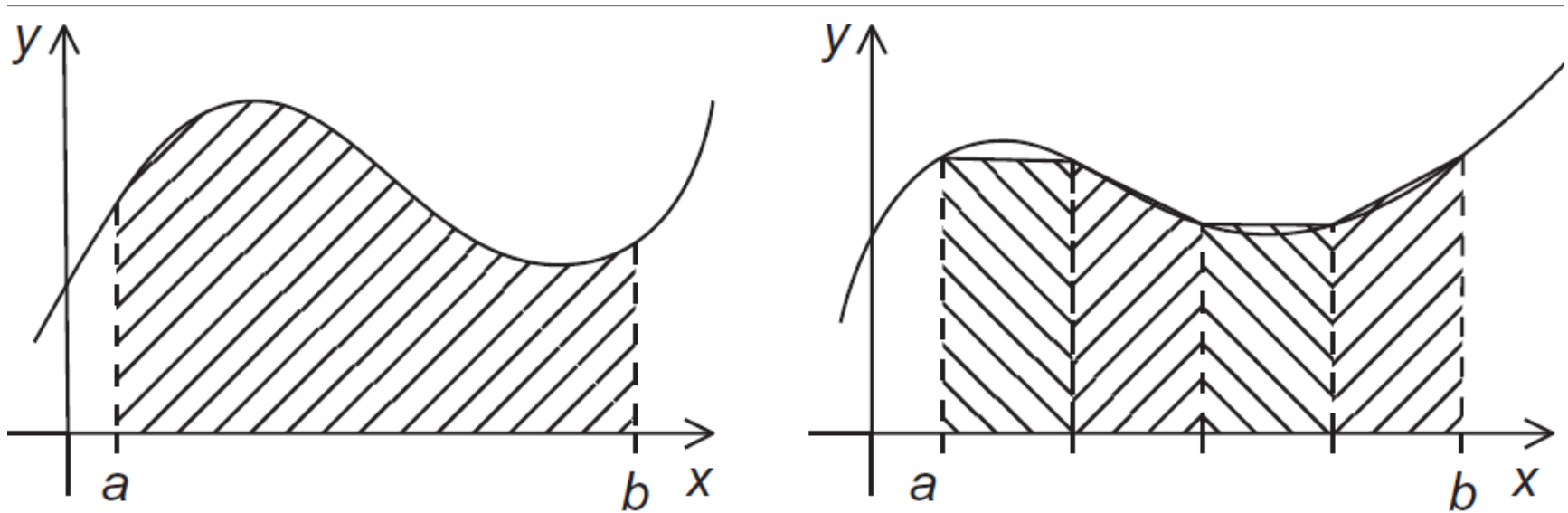
# In case the compiler doesn't support OpenMP

```
# ifdef _OPENMP
    int my_rank = omp_get_thread_num ( );
    int thread_count = omp_get_num_threads ( );
# e l s e
    int my_rank = 0;
    int thread_count = 1;
# endif
```



# THE TRAPEZOIDAL RULE

# 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;
```

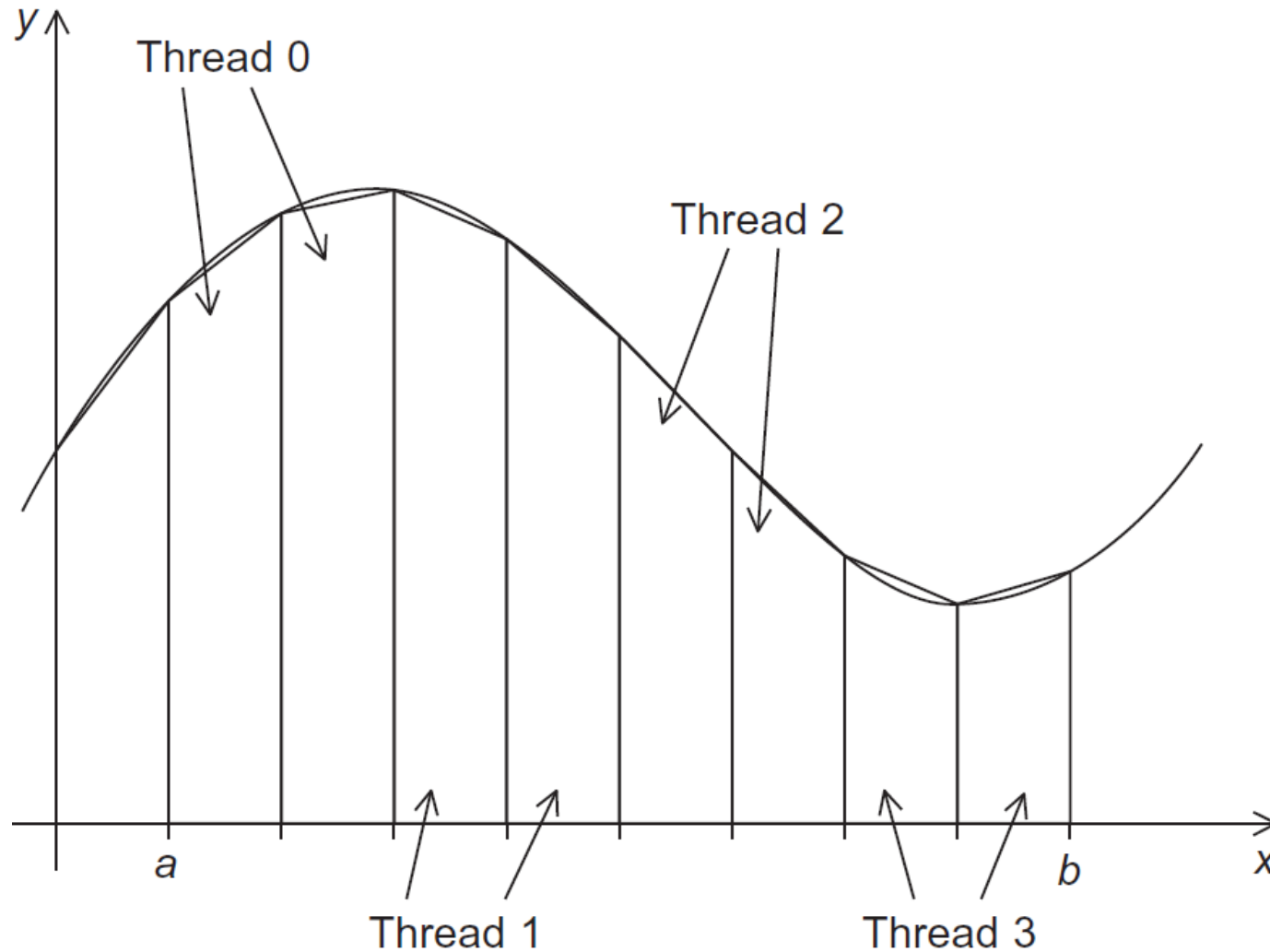
# A First OpenMP Version

- 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 (and a single thread to each core).

# Assignment of trapezoids to threads



Time	Thread 0	Thread 1
0	<code>global_result = 0 to register</code>	<code>finish my_result</code>
1	<code>my_result = 1 to register</code>	<code>global_result = 0 to register</code>
2	<code>add my_result to global_result</code>	<code>my_result = 2 to register</code>
3	<code>store global_result = 1</code>	<code>add my_result to global_result</code>
4		<code>store global_result = 2</code>

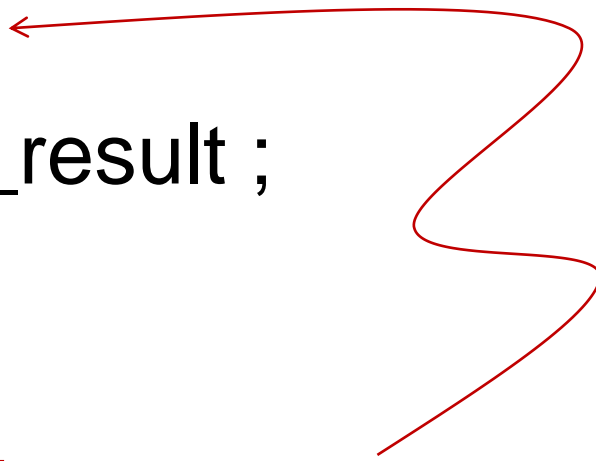
Unpredictable results when two (or more) threads attempt to simultaneously execute:

`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 OF VARIABLES

# 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**.





# THE REDUCTION CLAUSE

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);
```

If we use this, there's no critical section!

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

If we fix 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.

We can avoid this problem by declaring a private variable inside the parallel block and 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;
}
```



I don't like it.

Neither do I.

I think we can do better.



# Reduction operators

- A **reduction operator** is a binary operation (such as addition or multiplication).
- A **reduction** is a computation that repeatedly applies the same reduction operator to a sequence of operands in order to get a single result.
- All of the intermediate results of the operation should be stored in the same variable: the reduction variable.

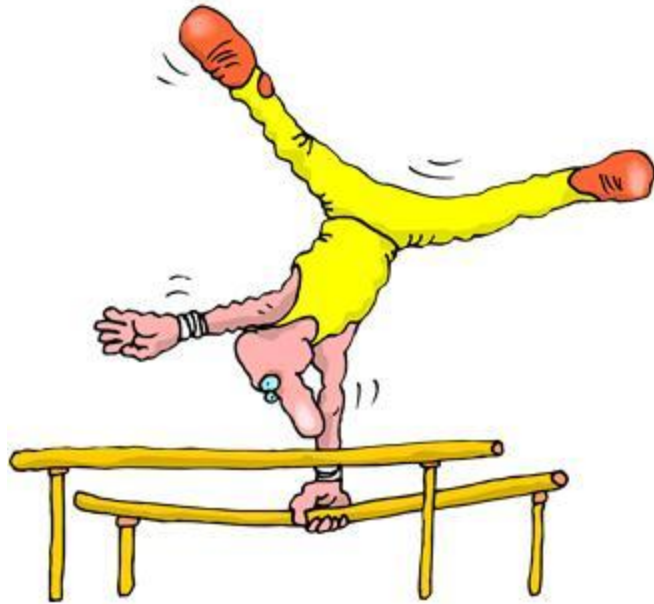
A reduction clause can be added to a parallel directive.

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



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

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

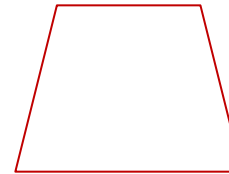


# THE “PARALLEL FOR” DIRECTIVE

# Parallel for

- Forks a team of threads to execute the following structured block.
- However, the structured block following the parallel for directive must be a for loop.
- Furthermore, with the parallel for directive 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;
```

# Legal forms for parallelizable for statements

**for**  $\left( \begin{array}{l} \text{index} = \text{start} ; \text{index} < \text{end} ; \text{index}++ \\ \text{index} = \text{start} ; \text{index} \leq \text{end} ; \text{index}++ \\ \text{index} = \text{start} ; \text{index} > \text{end} ; \text{index}-- \\ \text{index} = \text{start} ; \text{index} \geq \text{end} ; \text{index}-- \\ \text{index} = \text{start} ; \text{index} += \text{incr} \\ \text{index} = \text{start} ; \text{index} -= \text{incr} \\ \text{index} = \text{start} ; \text{index} = \text{index} + \text{incr} \\ \text{index} = \text{start} ; \text{index} = \text{incr} + \text{index} \\ \text{index} = \text{start} ; \text{index} = \text{index} - \text{incr} \end{array} \right)$

# 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

```
fibonacci[0] = fibonacci[1] = 1;  
for (i = 2; i < n; i++)  
    fibonacci[i] = fibonacci[i - 1] + fibonacci[i - 2];
```

note 2 threads

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

1 1 2 3 5 8 13 21 34 55

this is correct

1 1 2 3 5 8 0 0 0 0

but sometimes  
we get this

# 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.

# Estimating $\pi$

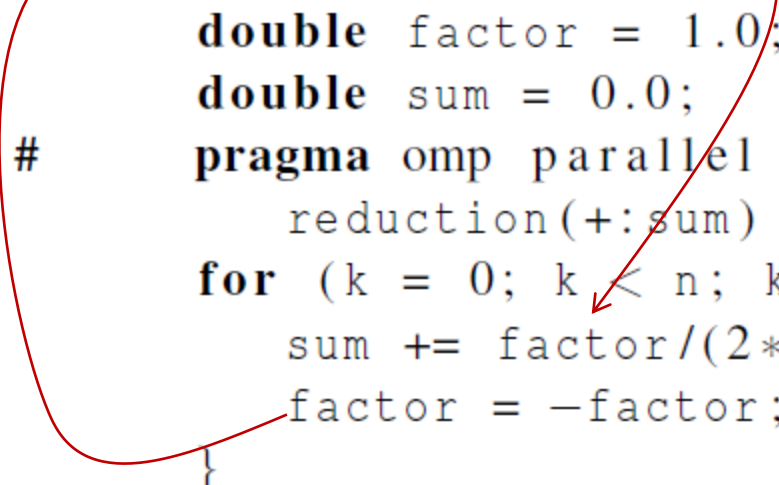
$$\pi = 4 \left[ 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \dots \right] = 4 \sum_{k=0}^{\infty} \frac{(-1)^k}{2k+1}$$

```
double factor = 1.0;
double sum = 0.0;
for (k = 0; k < n; k++) {
    sum += factor/(2*k+1);
    factor = -factor;
}
pi_approx = 4.0*sum;
```

# OpenMP solution #1


loop dependency

```
# double factor = 1.0;
double sum = 0.0;
#pragma omp parallel for num_threads(thread_count) \
    reduction(+:sum)
for (k = 0; k < n; k++) {
    sum += factor/(2*k+1);
    factor = -factor;
}
pi_approx = 4.0*sum;
```



# OpenMP solution #2

```
# double sum = 0.0;
  pragma omp parallel for num_threads(thread_count) \
    reduction(+:sum) private(factor)
  for (k = 0; k < n; k++) {
    if (k % 2 == 0)
      factor = 1.0;
    else
      factor = -1.0;
    sum += factor/(2*k+1);
  }
```



Insures factor has  
private scope.

# The default clause

- Lets the programmer specify the scope of each variable in a block.

**default**(none)

- With this clause the compiler will require that we specify the scope of each variable we use in the block and that has been declared outside the block.

# The default clause

```
double sum = 0.0;
# pragma omp parallel for num_threads(thread_count) \
    default(none) reduction(+:sum) private(k, factor) \
    shared(n)
for (k = 0; k < n; k++) {
    if (k % 2 == 0)
        factor = 1.0;
    else
        factor = -1.0;
    sum += factor/(2*k+1);
}
```



# MORE ABOUT LOOPS IN OPENMP: SORTING



# Bubble Sort

```
for (list_length = n; list_length >= 2; list_length--)  
    for (i = 0; i < list_length-1; i++)  
        if (a[i] > a[i+1]) {  
            tmp = a[i];  
            a[i] = a[i+1];  
            a[i+1] = tmp;  
        }
```



# Serial Odd-Even Transposition Sort

```
for (phase = 0; phase < n; phase++)  
    if (phase % 2 == 0)  
        for (i = 1; i < n; i += 2)  
            if (a[i-1] > a[i]) Swap(&a[i-1], &a[i]);  
    else  
        for (i = 1; i < n-1; i += 2)  
            if (a[i] > a[i+1]) Swap(&a[i], &a[i+1]);
```

# Serial Odd-Even Transposition Sort

Phase	Subscript in Array			
	0	1	2	3
0	9	$\leftrightarrow$ 7	8	$\leftrightarrow$ 6
	7	9	6	8
1	7	9	$\leftrightarrow$ 6	8
	7	6	9	8
2	7	$\leftrightarrow$ 6	9	$\leftrightarrow$ 8
	6	7	8	9
3	6	7	$\leftrightarrow$ 8	9
	6	7	8	9

# First OpenMP Odd-Even Sort

```
for (phase = 0; phase < n; phase++) {
    if (phase % 2 == 0)
#       pragma omp parallel for num_threads(thread_count) \
        default(none) shared(a, n) private(i, tmp)
        for (i = 1; i < n; i += 2) {
            if (a[i-1] > a[i]) {
                tmp = a[i-1];
                a[i-1] = a[i];
                a[i] = tmp;
            }
        }
    else
#       pragma omp parallel for num_threads(thread_count) \
        default(none) shared(a, n) private(i, tmp)
        for (i = 1; i < n-1; i += 2) {
            if (a[i] > a[i+1]) {
                tmp = a[i+1];
                a[i+1] = a[i];
                a[i] = tmp;
            }
        }
}
```

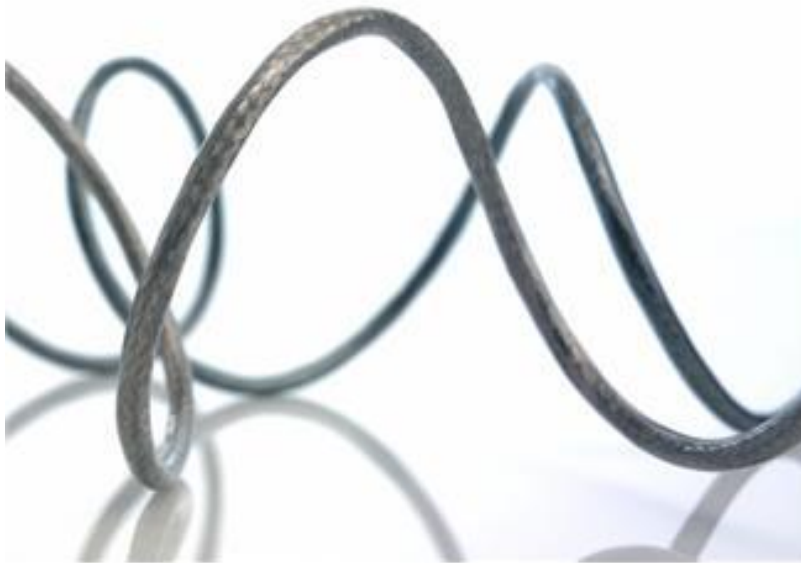
# Second OpenMP Odd-Even Sort

```
# pragma omp parallel num_threads(thread_count) \  
    default(none) shared(a, n) private(i, tmp, phase)  
    for (phase = 0; phase < n; phase++) {  
        if (phase % 2 == 0)  
#            pragma omp for  
            for (i = 1; i < n; i += 2) {  
                if (a[i-1] > a[i]) {  
                    tmp = a[i-1];  
                    a[i-1] = a[i];  
                    a[i] = tmp;  
                }  
            }  
        else  
#            pragma omp for  
            for (i = 1; i < n-1; i += 2) {  
                if (a[i] > a[i+1]) {  
                    tmp = a[i+1];  
                    a[i+1] = a[i];  
                    a[i] = tmp;  
                }  
            }  
    }  
}
```

Odd-even sort with two parallel **for** directives and two **for** directives.  
(Times are in seconds.)

thread_count	1	2	3	4
Two parallel <b>for</b> directives	0.770	0.453	0.358	0.305
Two <b>for</b> directives	0.732	0.376	0.294	0.239





# SCHEDULING LOOPS

We want to parallelize  
this loop.

```
sum = 0.0;  
for (i = 0; i <= n; i++)  
    sum += f(i);
```

Thread	Iterations
0	$0, n/t, 2n/t, \dots$
1	$1, n/t + 1, 2n/t + 1, \dots$
$\vdots$	$\vdots$
$t - 1$	$t - 1, n/t + t - 1, 2n/t + t - 1, \dots$

Assignment of work  
using cyclic partitioning.



```
double f(int i) {  
    int j, start = i*(i+1)/2, finish = start + i;  
    double return_val = 0.0;  
  
    for (j = start; j <= finish; j++) {  
        return_val += sin(j);  
    }  
    return return_val;  
} /* f */
```

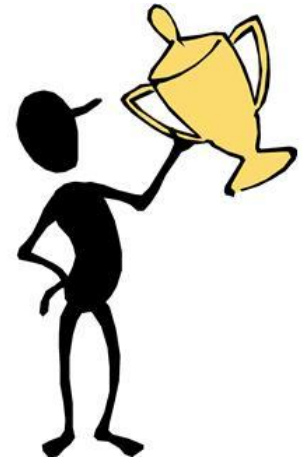
Our definition of function  $f$ .

# Results

- $f(i)$  calls the sin function  $i$  times.
- Assume the time to execute  $f(2i)$  requires approximately twice as much time as the time to execute  $f(i)$ .
- $n = 10,000$ 
  - one thread
  - run-time = 3.67 seconds.

# Results

- $n = 10,000$ 
  - two threads
  - default assignment
  - run-time = 2.76 seconds
  - speedup = 1.33
- $n = 10,000$ 
  - two threads
  - cyclic assignment
  - run-time = 1.84 seconds
  - speedup = 1.99



# The Schedule Clause

- Default schedule:

```
sum = 0.0;
# pragma omp parallel for num_threads(thread_count) \
    reduction(+:sum)
    for (i = 0; i <= n; i++)
        sum += f(i);
```

- Cyclic schedule:

```
sum = 0.0;
# pragma omp parallel for num_threads(thread_count) \
    reduction(+:sum) schedule(static,1)
    for (i = 0; i <= n; i++)
        sum += f(i);
```

# schedule ( type , chunksize )

- Type can be:
  - static: the iterations can be assigned to the threads before the loop is executed.
  - dynamic or guided: the iterations are assigned to the threads while the loop is executing.
  - auto: the compiler and/or the run-time system determine the schedule.
  - runtime: the schedule is determined at run-time.
- The chunksize is a positive integer.

# The Static Schedule Type

twelve iterations, 0, 1, . . . , 11, and three threads

```
schedule(static, 1)
```

Thread 0 : 0, 3, 6, 9

Thread 1 : 1, 4, 7, 10

Thread 2 : 2, 5, 8, 11

# The Static Schedule Type

twelve iterations, 0, 1, . . . , 11, and three threads

```
schedule(static,2)
```

Thread 0 : 0, 1, 6, 7

Thread 1 : 2, 3, 8, 9

Thread 2 : 4, 5, 10, 11

# The Static Schedule Type

twelve iterations, 0, 1, . . . , 11, and three threads

```
schedule(static, 4)
```

Thread 0 : 0, 1, 2, 3

Thread 1 : 4, 5, 6, 7

Thread 2 : 8, 9, 10, 11



# The Dynamic Schedule Type

- The iterations are also broken up into chunks of **chunksize** consecutive iterations.
- Each thread executes a chunk, and when a thread finishes a chunk, it requests another one from the run-time system.
- This continues until all the iterations are completed.
- The **chunksize** can be omitted. When it is omitted, a **chunksize** of 1 is used.

# The Guided Schedule Type

- Each thread also executes a chunk, and when a thread finishes a chunk, it requests another one.
- However, in a guided schedule, as chunks are completed the size of the new chunks decreases.
- If no **chunksize** is specified, the size of the chunks decreases down to 1.
- If **chunksize** is specified, it decreases down to **chunksize**, with the exception that the very last chunk can be smaller than **chunksize**.

Thread	Chunk	Size of Chunk	Remaining Iterations
0	1 – 5000	5000	4999
1	5001 – 7500	2500	2499
1	7501 – 8750	1250	1249
1	8751 – 9375	625	624
0	9376 – 9687	312	312
1	9688 – 9843	156	156
0	9844 – 9921	78	78
1	9922 – 9960	39	39
1	9961 – 9980	20	19
1	9981 – 9990	10	9
1	9991 – 9995	5	4
0	9996 – 9997	2	2
1	9998 – 9998	1	1
0	9999 – 9999	1	0

Assignment of trapezoidal rule iterations 1–9999 using a guided schedule with two threads.

# The Runtime Schedule Type

- The system uses the environment variable `OMP_SCHEDULE` to determine at run-time how to schedule the loop.
- The `OMP_SCHEDULE` environment variable can take on any of the values that can be used for a static, dynamic, or guided schedule.



# PRODUCERS AND CONSUMERS

# Queues

- Can be viewed as an abstraction of a line of customers waiting to pay for their groceries in a supermarket.
- A natural data structure to use in many multithreaded applications.
- For example, suppose we have several “producer” threads and several “consumer” threads.
  - Producer threads might “produce” requests for data.
  - Consumer threads might “consume” the request by finding or generating the requested data.

# Message-Passing

- Each thread could have a shared message queue, and when one thread wants to “send a message” to another thread, it could enqueue the message in the destination thread’s queue.
- A thread could receive a message by dequeuing the message at the head of its message queue.

# Message-Passing

```
for (sent_msgs = 0; sent_msgs < send_max; sent_msgs++) {  
    Send_msg();  
    Try_receive();  
}  
  
while (!Done())  
    Try_receive();
```



# Sending Messages

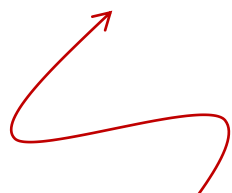
```
msg = random();  
dest = random() % thread_count;  
# pragma omp critical  
  Enqueue(queue, dest, my_rank, msg);
```

# Receiving Messages

```
    if (queue_size == 0) return;  
    else if (queue_size == 1)  
#        pragma omp critical  
        Dequeue(queue, &src, &msg);  
    else  
        Dequeue(queue, &src, &msg);  
    Print_message(src, msg);
```

# Termination Detection

```
queue_size = enqueued - dequeued;  
if (queue_size == 0 && done_sending == thread_count)  
    return TRUE;  
else  
    return FALSE;
```



each thread increments this after  
completing its for loop

# Startup (1)

- When the program begins execution, a single thread, the master thread, will get command line arguments and allocate an array of message queues: one for each thread.
- This array needs to be shared among the threads, since any thread can send to any other thread, and hence any thread can enqueue a message in any of the queues.

# Startup (2)

- One or more threads may finish allocating their queues before some other threads.
- We need an explicit barrier so that when a thread encounters the barrier, it blocks until all the threads in the team have reached the barrier.
- After all the threads have reached the barrier all the threads in the team can proceed.

```
# pragma omp barrier
```

# The Atomic Directive (1)

- Unlike the critical directive, it can only protect critical sections that consist of a single C assignment statement.

```
# pragma omp atomic
```

- Further, the statement must have one of the following forms:

```
x <op>= <expression>;  
x++;  
++x;  
x--;  
--x;
```

# The Atomic Directive (2)

- Here <op> can be one of the binary operators

`+, *, -, /, &, ^, |, <<, or >>`

- Many processors provide a special load-modify-store instruction.
- A critical section that only does a load-modify-store can be protected much more efficiently by using this special instruction rather than the constructs that are used to protect more general critical sections.

# Critical Sections

- OpenMP provides the option of adding a name to a critical directive:

```
# pragma omp critical(name)
```

- When we do this, two blocks protected with critical directives with different names can be executed simultaneously.
- However, the names are set during compilation, and we want a different critical section for each thread's queue.



# Locks

- A lock consists of a data structure and functions that allow the programmer to explicitly enforce mutual exclusion in a critical section.



# Locks

```
/* Executed by one thread */
Initialize the lock data structure;
. . .
/* Executed by multiple threads */
Attempt to lock or set the lock data structure;
Critical section;
Unlock or unset the lock data structure;
. . .
/* Executed by one thread */
Destroy the lock data structure;
```

# Using Locks in the Message-Passing Program

```
# pragma omp critical
  /* q_p = msg_queues[dest] */
  Enqueue(q_p, my_rank, msg);
```

```
/* q_p = msg_queues[dest] */
omp_set_lock(&q_p->lock);
Enqueue(q_p, my_rank, msg);
omp_unset_lock(&q_p->lock);
```

# Using Locks in the Message-Passing Program

```
# pragma omp critical
  /* q_p = msg_queues[my_rank] */
  Dequeue(q_p, &src, &msg);
```

```
/* q_p = msg_queues[my_rank] */
omp_set_lock(&q_p->lock);
Dequeue(q_p, &src, &msg);
omp_unset_lock(&q_p->lock);
```

# Some Caveats

1. You shouldn't mix the different types of mutual exclusion for a single critical section.
2. There is no guarantee of fairness in mutual exclusion constructs.
3. It can be dangerous to “nest” mutual exclusion constructs.

# Matrix-vector multiplication

$$y_i = a_{i0}x_0 + a_{i1}x_1 + \cdots + a_{i,n-1}x_{n-1}$$

$a_{00}$	$a_{01}$	$\cdots$	$a_{0,n-1}$
$a_{10}$	$a_{11}$	$\cdots$	$a_{1,n-1}$
$\vdots$	$\vdots$		$\vdots$
$a_{i0}$	$a_{i1}$	$\cdots$	$a_{i,n-1}$
$\vdots$	$\vdots$		$\vdots$
$a_{m-1,0}$	$a_{m-1,1}$	$\cdots$	$a_{m-1,n-1}$

$x_0$
$x_1$
$\vdots$
$x_{n-1}$

=

$y_0$
$y_1$
$\vdots$
$y_i = a_{i0}x_0 + a_{i1}x_1 + \cdots + a_{i,n-1}x_{n-1}$
$\vdots$
$y_{m-1}$

```

for (i = 0; i < m; i++) {
    y[i] = 0.0;
    for (j = 0; j < n; j++)
        y[i] += A[i][j]*x[j];
}

```

# Matrix-vector multiplication

```
# pragma omp parallel for num_threads(thread_count) \
    default(none) private(i, j) shared(A, x, y, m, n)
for (i = 0; i < m; i++) {
    y[i] = 0.0;
    for (j = 0; j < n; j++)
        y[i] += A[i][j]*x[j];
}
```

Run-times and efficiencies  
of matrix-vector multiplication  
(times are in seconds)

Threads	Matrix Dimension					
	8,000,000 × 8		8000 × 8000		8 × 8,000,000	
	Time	Eff.	Time	Eff.	Time	Eff.
1	0.322	1.000	0.264	1.000	0.333	1.000
2	0.219	0.735	0.189	0.698	0.300	0.555
4	0.141	0.571	0.119	0.555	0.303	0.275

```
void Tokenize(  
    char*   lines[]           /* in/out */,  
    int     line_count       /* in     */,  
    int     thread_count     /* in     */) {  
    int my_rank, i, j;  
    char *my_token;  
  
    # pragma omp parallel num_threads(thread_count) \  
        default(none) private(my_rank, i, j, my_token) \  
        shared(lines, line_count)  
    {  
        my_rank = omp_get_thread_num();  
    # pragma omp for schedule(static, 1)  
        for (i = 0; i < line_count; i++) {  
            printf("Thread %d > line %d = %s", my_rank, i, lines[i]);  
            j = 0;  
            my_token = strtok(lines[i], " \t\n");  
            while ( my_token != NULL ) {  
                printf("Thread %d > token %d = %s\n", my_rank, j, my_token);  
                my_token = strtok(NULL, " \t\n");  
                j++;  
            }  
        } /* for i */  
    } /* omp parallel */  
  
} /* Tokenize */
```



# Concluding Remarks (1)

- 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.

# Concluding Remarks (2)

- A major problem in the development of shared memory programs is the possibility of race conditions.
- OpenMP provides several mechanisms for insuring mutual exclusion in critical sections.
  - Critical directives
  - Named critical directives
  - Atomic directives
  - Simple locks

# Concluding Remarks (3)

- By default most systems use a block-partitioning of the iterations in a parallelized for loop.
- OpenMP offers a variety of scheduling options.
- In OpenMP the scope of a variable is the collection of threads to which the variable is accessible.

# Concluding Remarks (4)

- A reduction is a computation that repeatedly applies the same reduction operator to a sequence of operands in order to get a single result.