



**中山大學**  
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**国家超级计算广州中心**  
NATIONAL SUPERCOMPUTER CENTER IN GUANGZHOU

# 用OpenMP进行共享内存编程

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# 课程内容

- 参考资料：
  - 并行政程序设计导论, Peter S Pacheco, 机械工业出版社, 2016
  - Chapter 5 Shared-Memory Programming With OpenMP

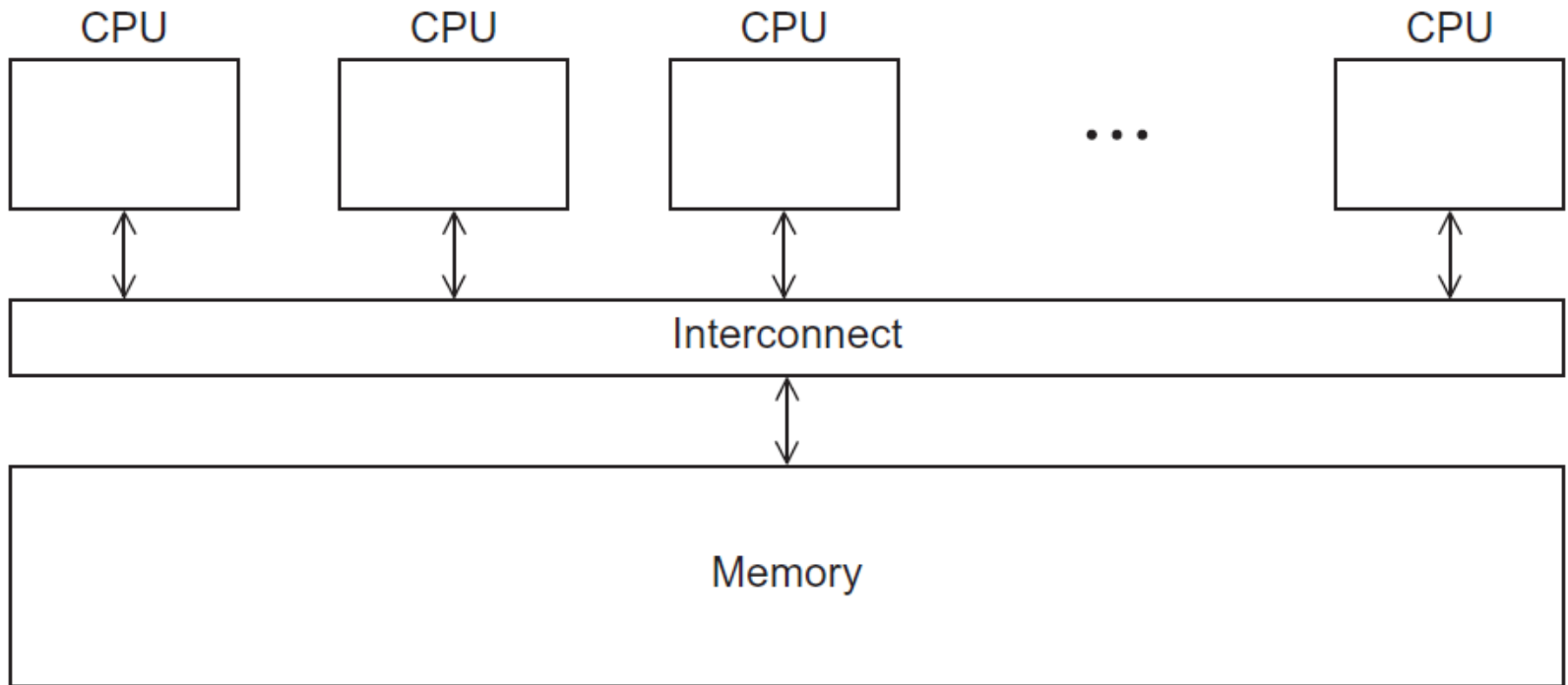
# Roadmap

- 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 (编译指示)

- 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
```

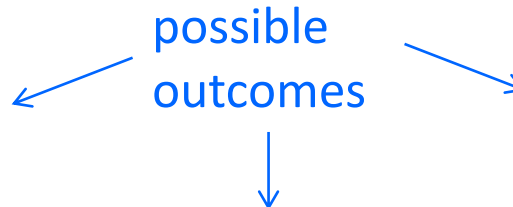


running with 4 threads



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



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

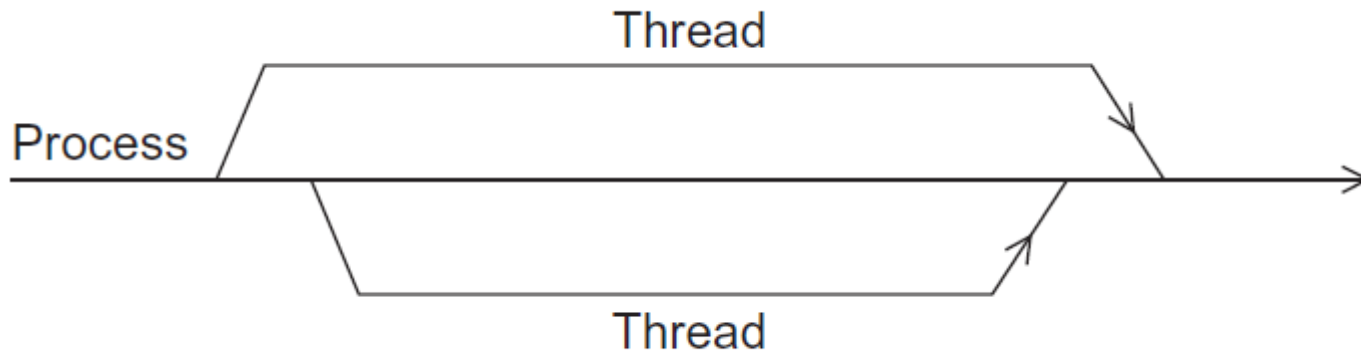
Hello from thread 3 of 4  
Hello from thread 1 of 4  
Hello from thread 2 of 4  
Hello from thread 0 of 4



# OpenMp pragmas

- `# pragma omp parallel`
- Most basic `parallel directive` (指令) .
- 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 (子句)

- 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.

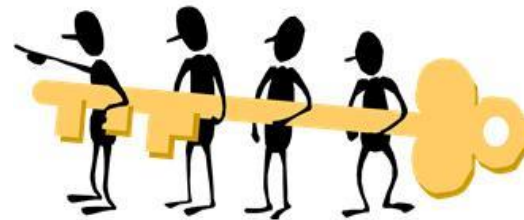
```
# pragma omp parallel num_threads ( thread_count )
```

# 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.

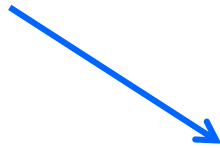
# Some terminology

- The **collection of threads** executing the parallel block 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 ( );
```

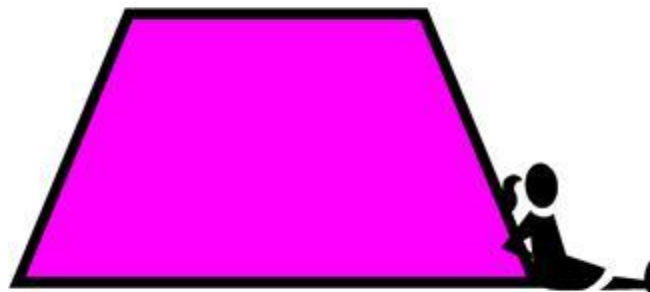
```
    int thread_count = omp_get_num_threads ( );
```

```
# else
```

```
    int my_rank = 0;
```

```
    int thread_count = 1;
```

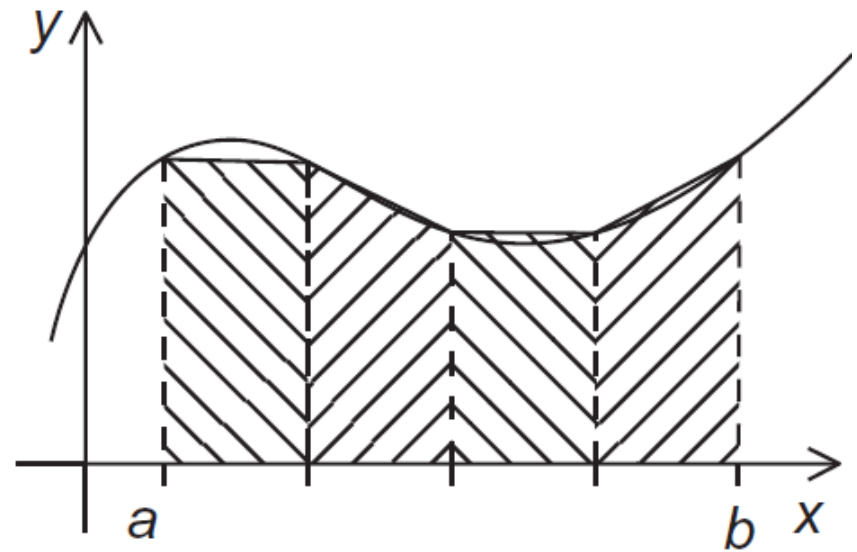
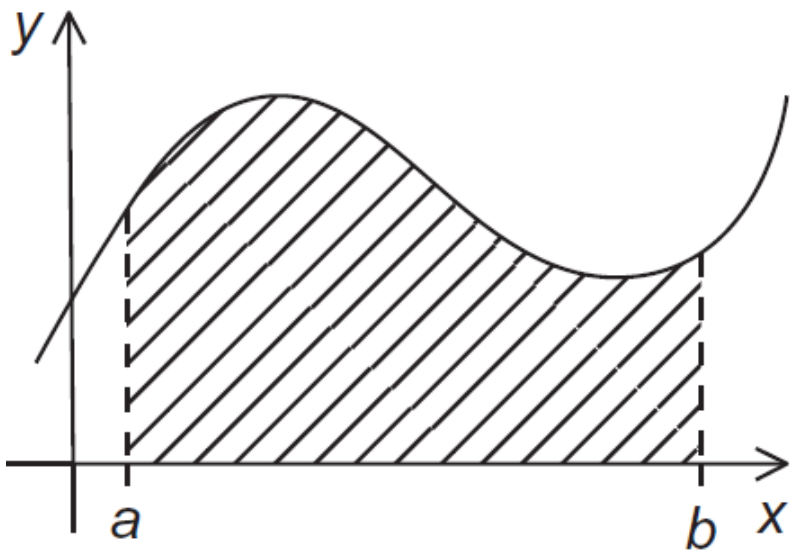
```
# endif
```



# The Trapezoidal Rule



# The trapezoidal rule



# Serial algorithm

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

```
/* 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**
- b) **adding the areas** of trapezoids.

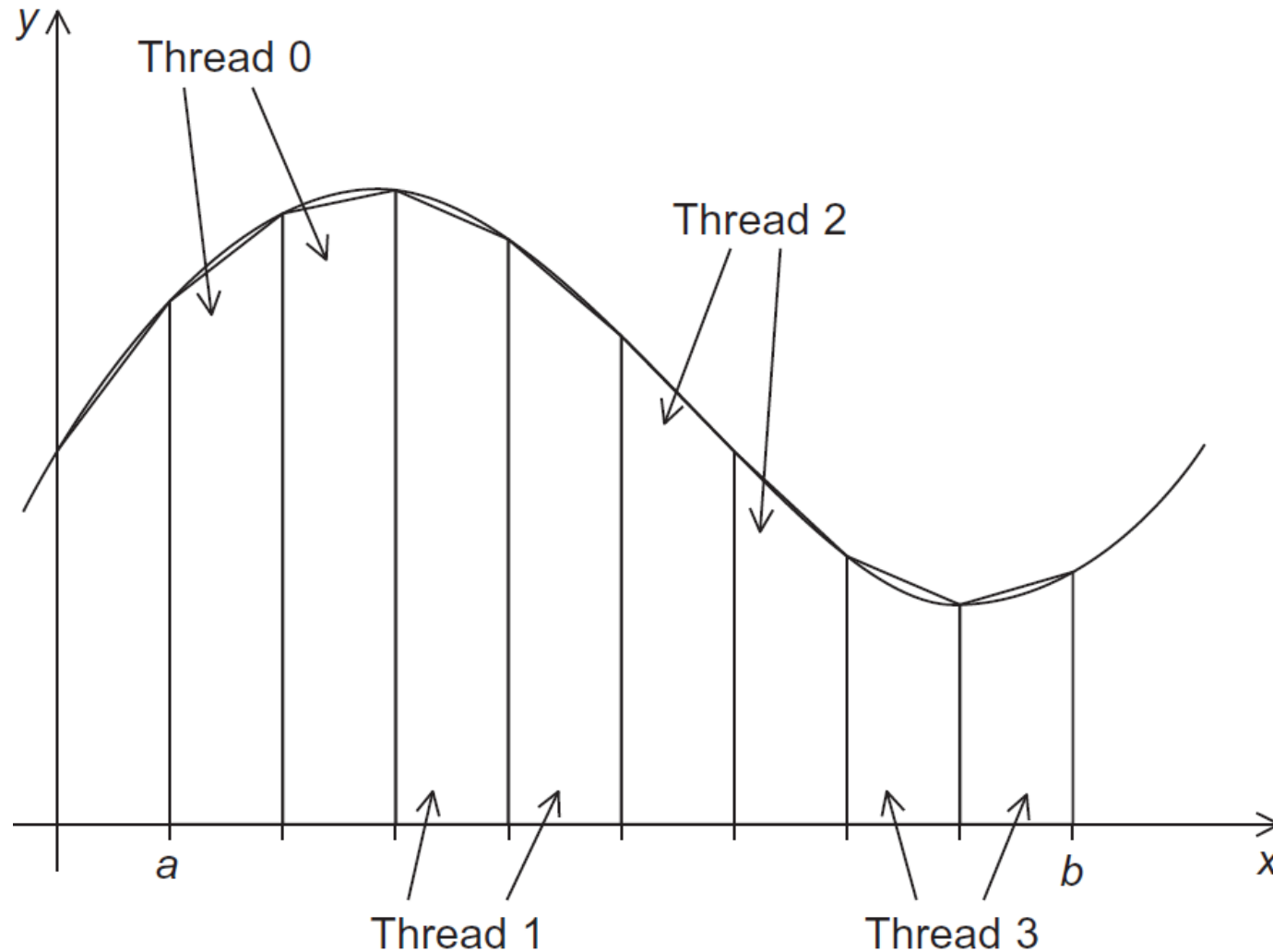
2) There is **no communication** among the tasks in **the first collection**, but each task in the first collection communicates with **task 1b**.

# 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>

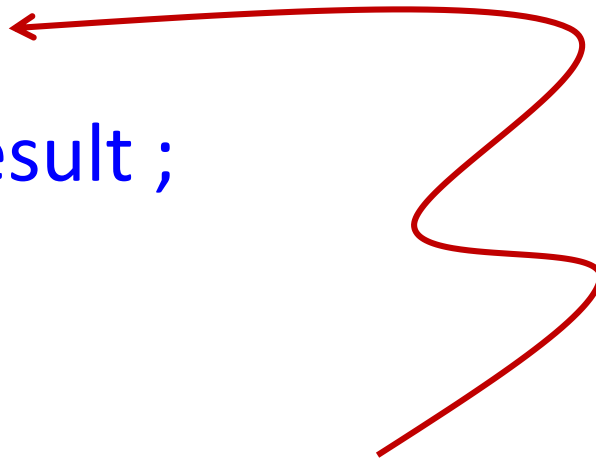
Unpredictable results when two (or more) threads attempt to simultaneously execute:

`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.

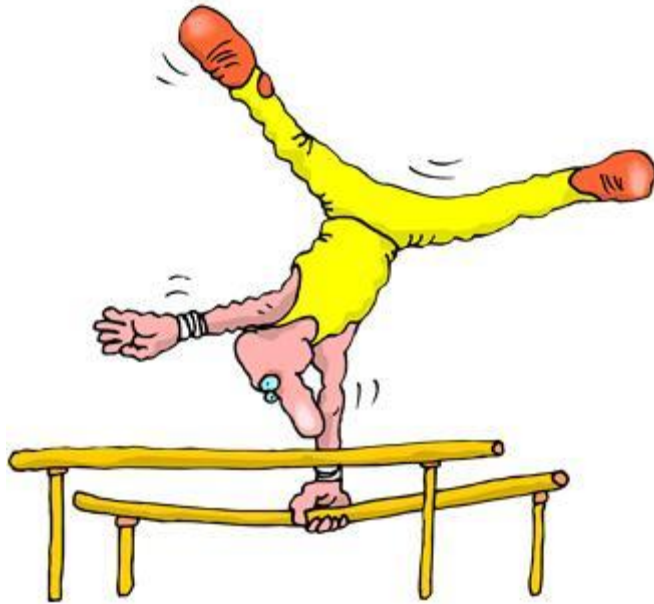
A reduction clause can be added to a parallel directive.

```
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);
```

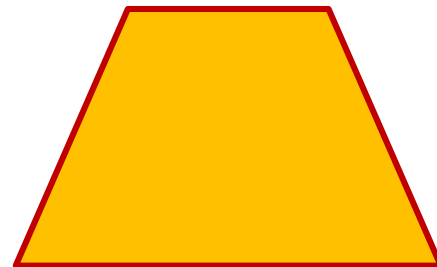
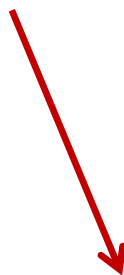


# The “Parallel For” Directive

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

# 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?

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



# Estimating $\pi$

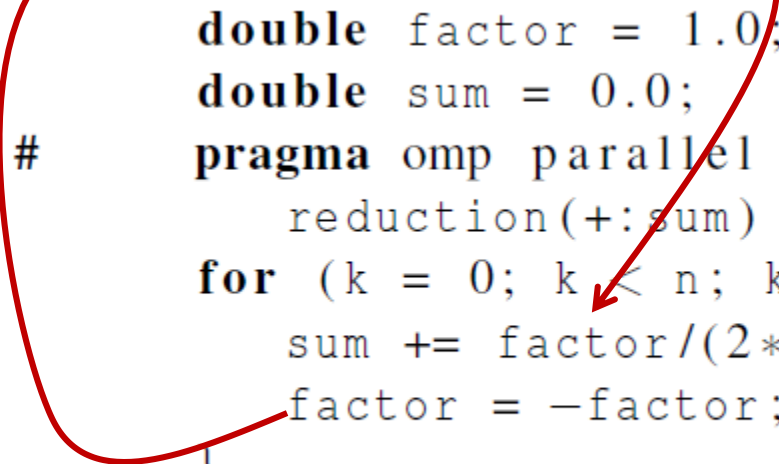
$$\pi = 4 \left[ 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \cdots \right] = 4 \sum_{k=0}^{\infty} \frac{(-1)^k}{2k+1}$$

```
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

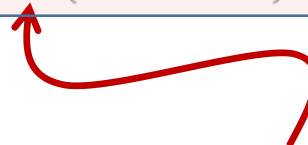
loop dependency

```
# 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 ↔ 7		8 ↔ 6	
	7	9	6	8
1	7	9 ↔ 6		8
	7	6	9	8
2	7 ↔ 6		9 ↔ 8	
	6	7	8	9
3	6	7 ↔ 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;
                    }
                }
    }
}
```

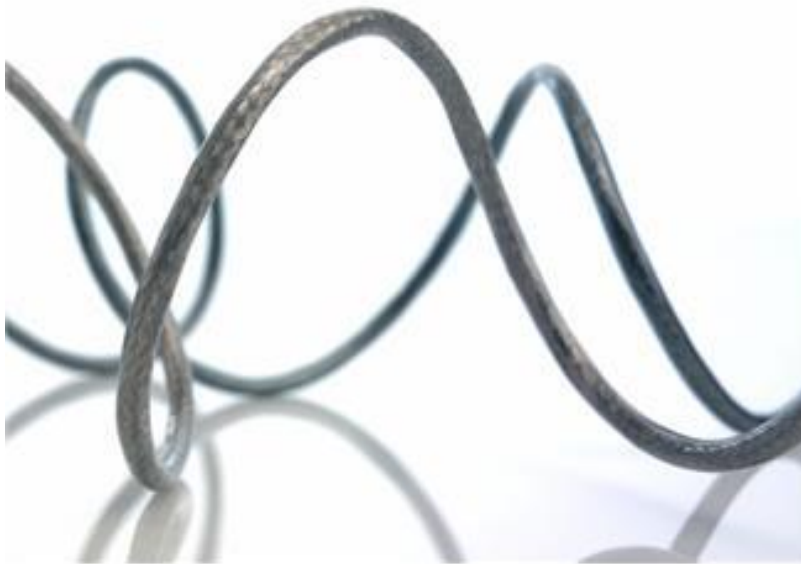
Tells OpenMP to  
parallelize the  
for loop with  
existing team of  
threads

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



## Our definition of function $f$ .

```
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 */
```

*The time required by the call to  $f$   
is proportional to the size of  $i$*

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.

# 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

```
    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 **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 **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**.

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
- 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

```
mesg = random();  
dest = random() % thread_count;
```

```
# pragma omp critical  
  Enqueue(queue, dest, my_rank, mesg);
```

# 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.



# 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;

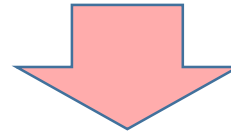
. . .

*/\* Executed by one thread \*/*

Destroy the lock data structure;

# Using Locks in the Message-Passing Program

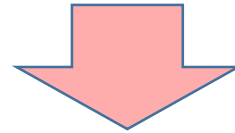
```
#  pragma omp critical
    /* q_p = msg_queues[dest] */
    Enqueue(q_p, my_rank, mesg);
```



```
/* q_p = msg_queues[dest] */
omp_set_lock(&q_p→lock);
Enqueue(q_p, my_rank, mesg);
omp_unset_lock(&q_p→lock);
```

# Using Locks in the Message-Passing Program

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



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

# Some Caveats

- You **shouldn't mix** the **different types** of mutual exclusion for **a single critical section**.
  - E.g., *critical* may not exclude *atomic*.
- There is **no guarantee of fairness** in mutual exclusion constructs.
  - E.g., it is possible that a thread can be blocked forever
- 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



## Thread-Safety

```
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.