CS 7172
Parallel and Distributed Computation

OpenMP

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Outline

- OpenMP introduction
- Scope of variables
- The reduction clause
- Parallel for
- Loops in OpenMP and scheduling
- Producers and Consumers

OpenMP

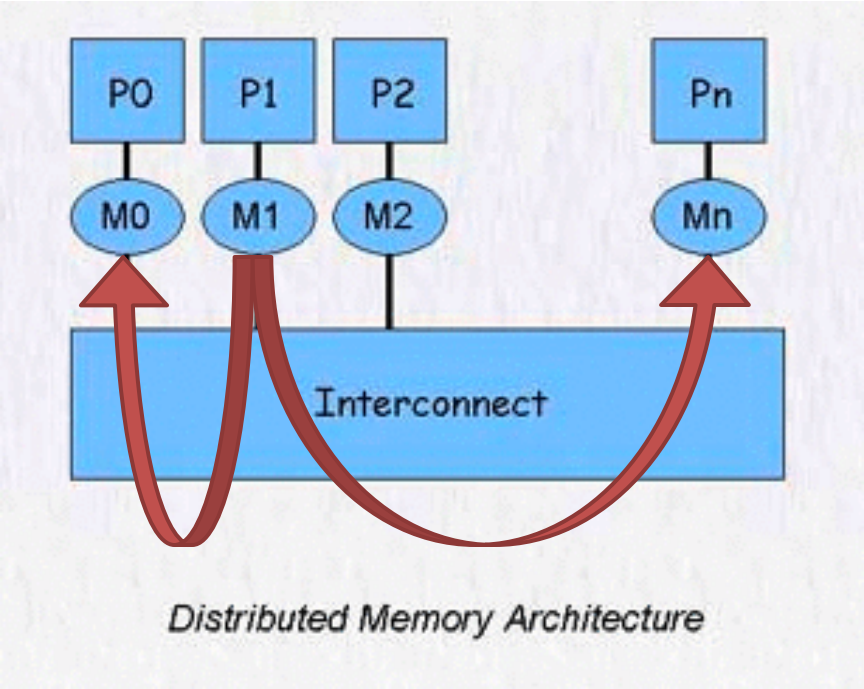
- An API for shared-memory parallel programming.

- MP = multiprocessing

https://www.openmp.org/

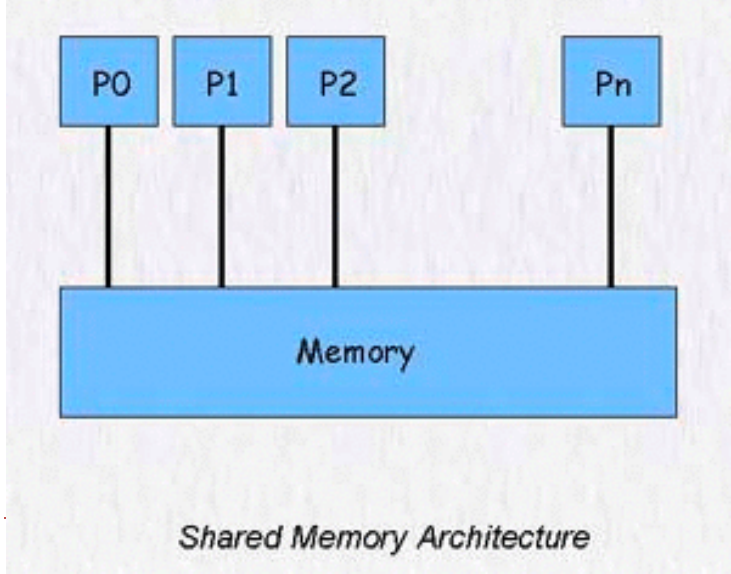
Distributed Memory

- Each processor has its own memory
- Parallel programming by message passing (MPI)



Shared Memory

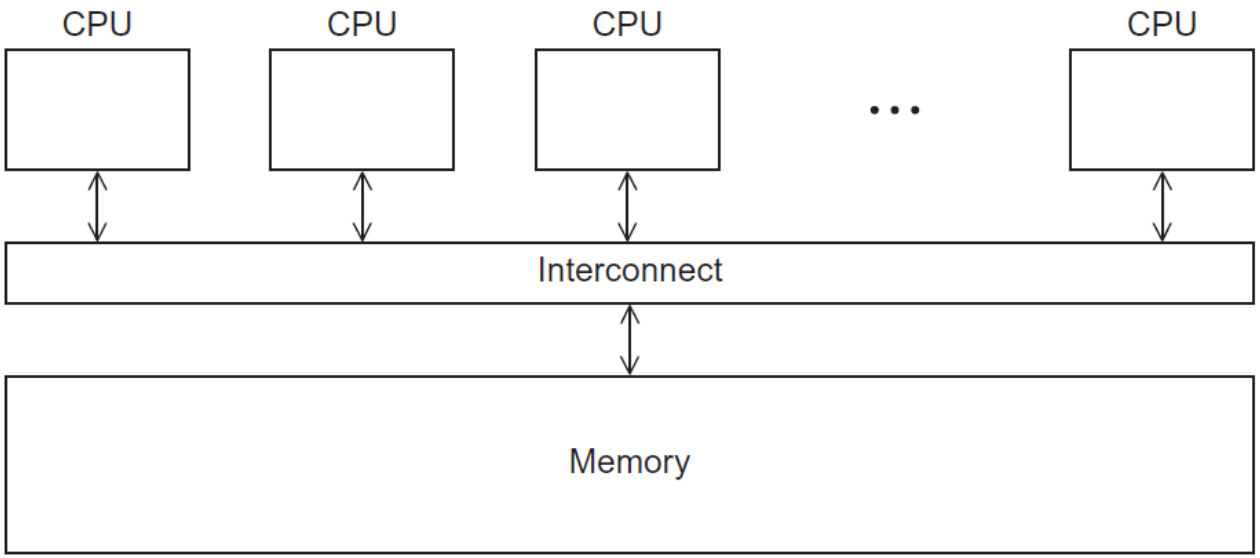
- Processors shared memory
- Two parallel programming approaches
  - message passing (MPI)
  - directives-based interface - OpenMP



OpenMP

- 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***.



Pros and Cons Of OpenMP

- Pros
  - Prevalence of multi-core computers
  - Requires less code modification than using MPI
  - OpenMP directives can be treated as comments if OpenMP is not available
  - Directives can be added incrementally

Pros and Cons Of OpenMP

- Cons
  - OpenMP codes cannot be run on distributed memory computers (exception is Intel's OpenMP)
  - Requires a compiler that supports OpenMP (most do)
  - limited by the number of processors available on a single computer
  - often have lower parallel efficiency
  - rely more on parallelizable loops
  - tend to have a higher % of serial code
  - Amdahl's Law - if 50% of code is serial will only half wall clock time no matter how may processors

Examples of Applications That Use OpenMP

- Applications
  - Matlab
  - Mathematica

https://www.wolfram.com/mathematica/

Example

https://github.com/kevinsuo/CS7172/blob/master/omp-helloworld.c

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

void Hello(void)
{
        int my_thread_ID = omp_get_thread_num();
        int thread_count = omp_get_num_threads();
        printf( "Hello from thread %d of %d\n", my_thread_ID , thread_count );
}

int main (int argc, char *argv[]) {

#pragma omp parallel
        Hello();

        return 0;
}
```

Return 0,1,2,3

Thread number is decided by core number

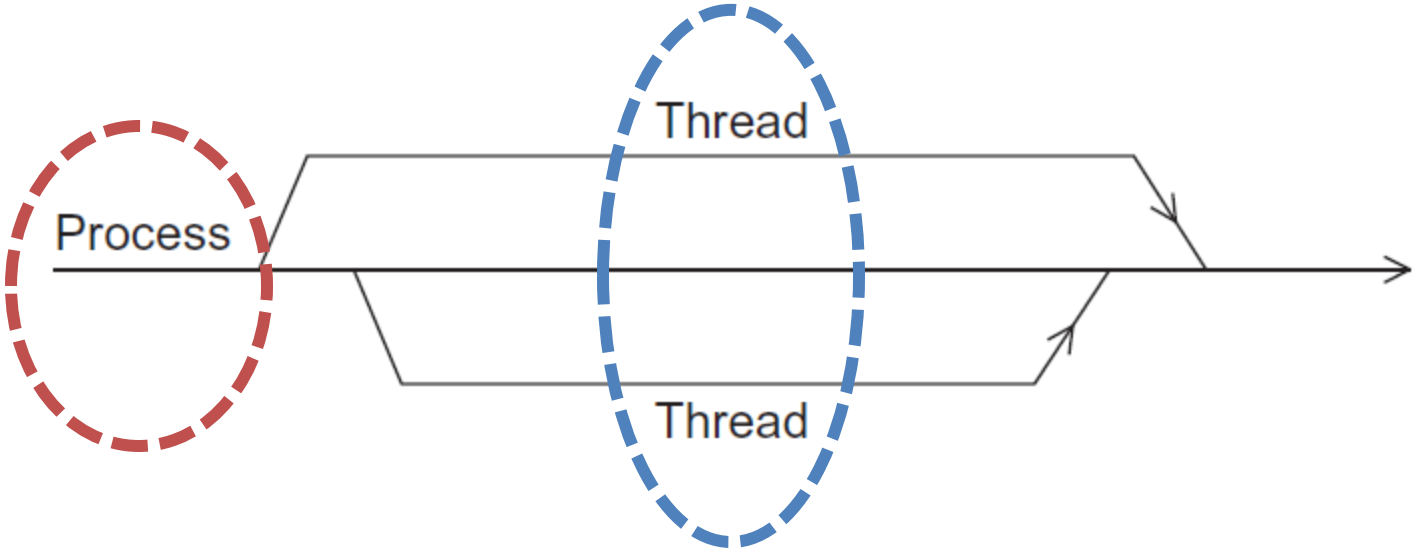
Pragmas

- 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.

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

#pragma omp parallel
        Hello();
```

Example

https://github.com/kevinsuo/CS7172/blob/master/omp-helloworld.c



Master thread

worker thread

How to Compile and Run an OpenMP Program

Compiler	Compiler Options	Default behavior for # of threads (OMP_NUM_THREADS not set)
GNU (gcc, g++, gfortran)	-fopenmp	as many threads as available cores
Intel (icc ifort)	-openmp	as many threads as available cores
Portland Group (pgcc,pgCC,pgf77,pgf90)	-mp	one thread

Example

- Compile
  - gcc -fopenmp omp-helloworld.c -o omp-helloworld.o

```
ksuo@ksuo-VirtualBox ~/cs7172> ./omp-helloworld.o
Hello from thread 1 of 4
Hello from thread 2 of 4
Hello from thread 0 of 4
Hello from thread 3 of 4
ksuo@ksuo-VirtualBox ~/cs7172> ./omp-helloworld.o
Hello from thread 0 of 4
Hello from thread 3 of 4
Hello from thread 1 of 4
Hello from thread 2 of 4
ksuo@ksuo-VirtualBox ~/cs7172> ./omp-helloworld.o
Hello from thread 0 of 4
Hello from thread 2 of 4
Hello from thread 3 of 4
Hello from thread 1 of 4
```

possible outcomes

Hello from thread 0
Hello from thread 1
Hello from thread 2
Hello from thread 3

Hello from thread 1
Hello from thread 2
Hello from thread 0
Hello from thread 3

Hello from thread 3
Hello from thread 1
Hello from thread 2
Hello from thread 0

Example 2

https://github.com/kevinsuo/CS7172/blob/master/omp-helloworld-2.c

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

void Hello(void)
{
        int my_thread_ID = omp_get_thread_num();
        int thread_count = omp_get_num_threads();
        printf( "Hello from thread %d of %d\n", my_thread_ID , thread_count );
}

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;
}
```

Thread number is decided by user input

Example 2

- Compile
  - gcc -fopenmp -o omp-helloworld-2.o omp-helloworld-2.c

```
ksuo@ksuo-VirtualBox ~/cs7172> ./omp-helloworld-2.o 8
Hello from thread 3 of 8
Hello from thread 4 of 8
Hello from thread 1 of 8
Hello from thread 6 of 8
Hello from thread 5 of 8
Hello from thread 2 of 8
Hello from thread 7 of 8
Hello from thread 0 of 8
ksuo@ksuo-VirtualBox ~/cs7172> ./omp-helloworld-2.o 8
Hello from thread 0 of 8
Hello from thread 6 of 8
Hello from thread 1 of 8
Hello from thread 4 of 8
Hello from thread 3 of 8
Hello from thread 5 of 8
Hello from thread 7 of 8
Hello from thread 2 of 8
ksuo@ksuo-VirtualBox ~/cs7172> ./omp-helloworld-2.o 8
Hello from thread 1 of 8
Hello from thread 6 of 8
Hello from thread 2 of 8
Hello from thread 0 of 8
Hello from thread 5 of 8
Hello from thread 3 of 8
Hello from thread 7 of 8
Hello from thread 4 of 8
```

clause

- 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 )
        Hello();

        return 0;
}
```

Thread number is decided by user input

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.

Of note…

```
fish  /home/ksuo/c
ksuo@ksuo-VirtualBox ~/cs7172> ./omp-helloworld-2.o 1000
Hello from thread 999 of 1000
Hello from thread 0 of 1000
Hello from thread 883 of 1000
Hello from thread 884 of 1000
Hello from thread 201 of 1000
Hello from thread 755 of 1000
Hello from thread 853 of 1000
Hello from thread 208 of 1000
Hello from thread 889 of 1000
Hello from thread 932 of 1000
Hello from thread 918 of 1000
Hello from thread 920 of 1000
Hello from thread 749 of 1000
Hello from thread 924 of 1000
Hello from thread 205 of 1000
Hello from thread 207 of 1000
Hello from thread 204 of 1000
Hello from thread 203 of 1000
Hello from thread 206 of 1000
Hello from thread 202 of 1000
Hello from thread 209 of 1000
Hello from thread 748 of 1000
Hello from thread 200 of 1000
```

```
fish  /home/ksuo/cs7172
ksuo@ksuo-VirtualBox ~/cs7172> ./omp-helloworld-2.o 10000

libgomp: Thread creation failed: Resource temporarily unavailable
```

10000 threads fail!

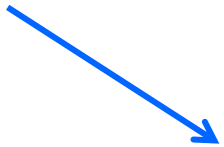
Too many.

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>
```

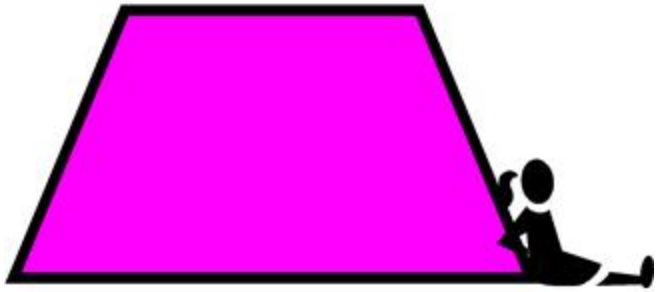


```
#ifdef _OPENMP
# include <omp.h>
#endif
```

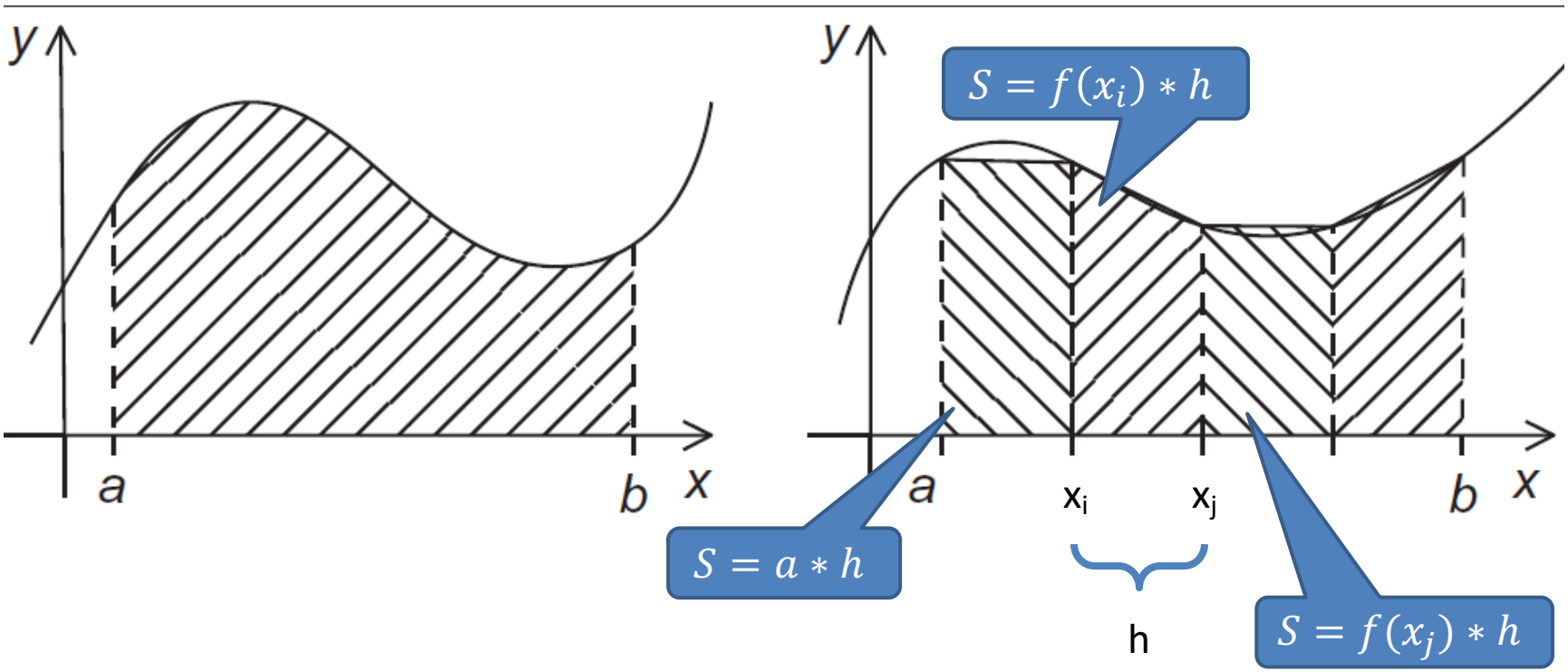
In case the compiler doesn't support OpenMP

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

The Trapezoidal Rule



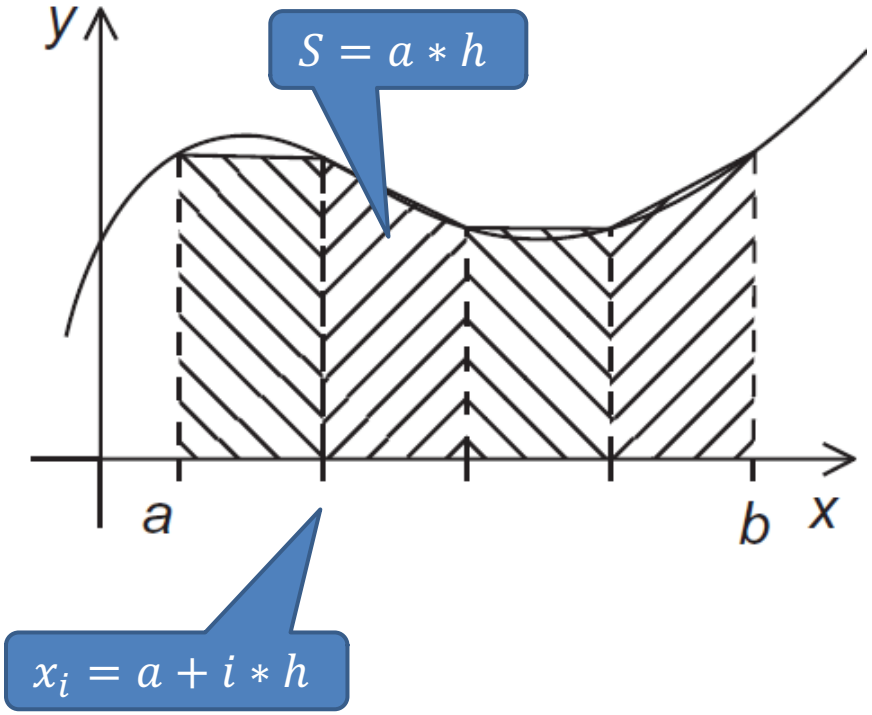
The trapezoidal rule



Serial algorithm

https://github.com/kevinsuo/CS7172/blob/master/trapezoidal-serial.c

```
double f(double x)
{
        return sin(x) + 2;
}

double Trap(double a, double b, int n)
{
        double h = (b-a)/n;
        int i;

        for (i = 0; i < n; i++) {
                double x_i = a + i*h;
                Size = Size + f(x_i) * h;
        }

        return Size;
}
```



A First OpenMP Version

```
double f(double x)
{
        return sin(x) + 2;
}

double Trap(double a, double b, int n)
{
        double h = (b-a)/n;
        int i;

        for (i = 0; i < n; i++) {
                double x_i = a + i*h;
                Size = Size + f(x_i) * h;
        }

        return Size;
}
```

(a)

(b)

1) We identified two types of tasks:

   a) computation of the areas of individual trapezoids, and

   b) adding the areas of trapezoids.

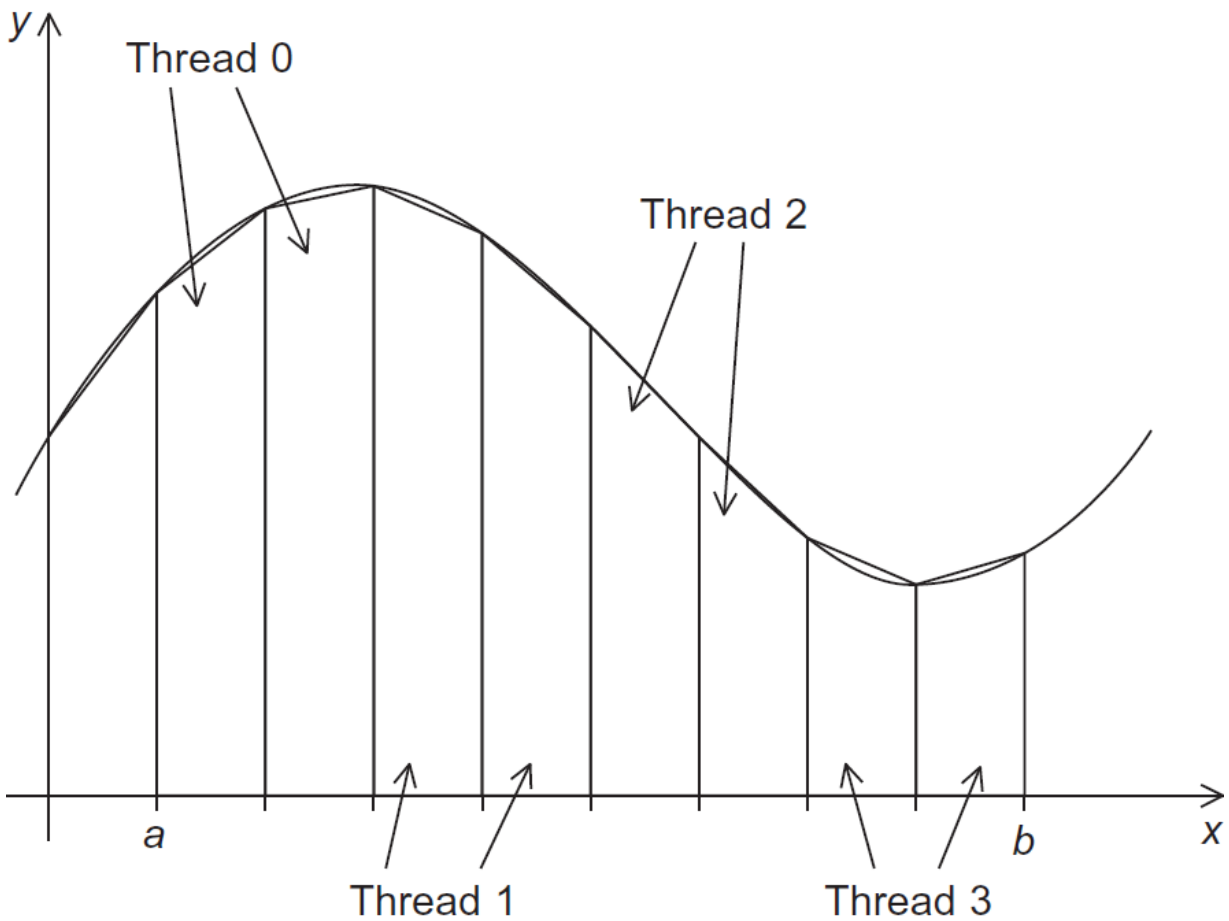
2) There is no communication among the tasks in the first collection, but each task in the first collection communicates with task 1b.

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



Unpredictable results

```
double f(double x)
{
        return sin(x) + 2;
}

double Trap(double a, double b, int n)
{
        double h = (b-a)/n;
        int i;

        for (i = 0; i < n; i++) {
                double x_i = a + i*h;
                Size = Size + f(x_i) * h;
        }

        return Size;
}
```

```
double f(double x)
{
        return sin(x) + 2;
}

double Trap(double a, double b, int n)
{
        double h = (b-a)/n;
        int i;

        for (i = 0; i < n; i++) {
                double x_i = a + i*h;
                Size = Size + f(x_i) * h;
        }

        return Size;
}
```

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

Size = Size + f(x_i) * h ;

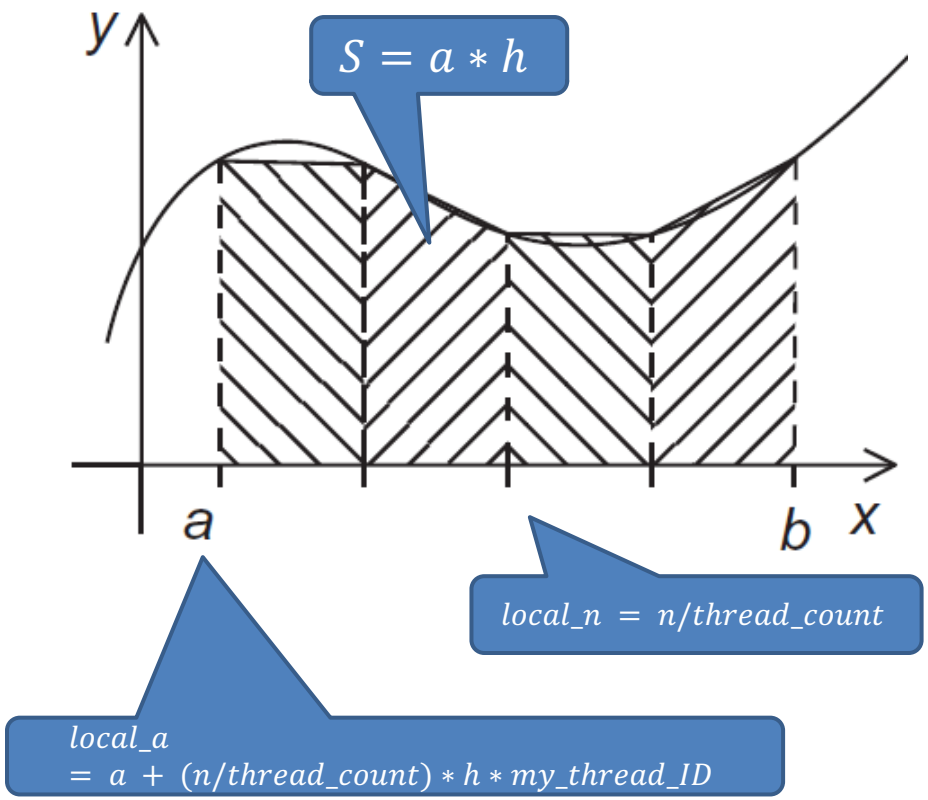
Mutual exclusion

```
# pragma omp critical
  Size = Size + f(x_i) * h ;
```

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

OpenMP Version

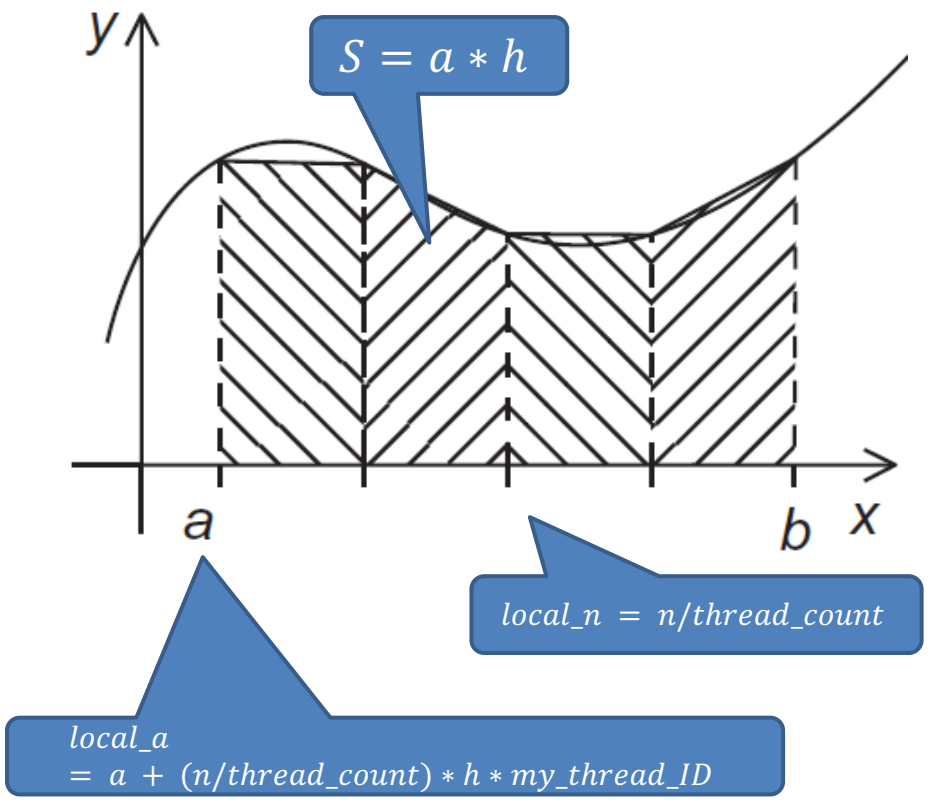
https://github.com/kevinsuo/CS7172/blob/master/trapezoidal-omp.c




```c
#include <stdio.h>
#include <math.h>
#include <sys/time.h>
#include <unistd.h>
#include <omp.h>
#include <stdlib.h>

double Size;

double f(double x)
{
        return sin(x) + 2;
}

double Trap(double a, double b, int n)
{
        double h = (b-a)/n;
        int i;

        double local_a;
        int local_n;
        double local_Size;

        int my_thread_ID = omp_get_thread_num();
        int thread_count = omp_get_num_threads();

        local_n = n/thread_count;
        local_a = a + (n/thread_count)*h*my_thread_ID;

        for (i = 0; i < local_n; i++) {
                double x_i = local_a + i*h;
                local_Size = local_Size + f(x_i) * h;
        }

#pragma omp critical
        Size = Size + local_Size;

        return Size;
}
```

OpenMP Version

https://github.com/kevinsuo/CS7172/blob/master/trapezoidal-omp.c




```
int main(int argc, char* argv[]) {
        double a, b, Size;
        int n;
        struct timeval tvs,tve;

        gettimeofday(&tvs,NULL);  //get start time

        a = 1, b = 10;
        n = 1000;

        /* Get number of threads from command line */
        int thread_count = strtol(argv[1], NULL, 10);
#pragma omp parallel num_threads( thread_count )
        Size = Trap(a, b, n);

        printf("Size = %.2lf\n", Size);

        gettimeofday(&tve,NULL);   //get end time
        double span = tve.tv_sec-tvs.tv_sec + (tve.tv_usec-tv
s.tv_usec)/1000000.0;
        printf("Time: %.12f\n", span);

        return 0;
}
```

OpenMP Version

```
ksuo@ksuo-VirtualBox ~/cs7172> ./trapezoidal-serial.o
Size = 19.39
Time: 0.000133000000
ksuo@ksuo-VirtualBox ~/cs7172> ./trapezoidal-omp.o 10
Size = 19.39
Time: 0.000494000000
ksuo@ksuo-VirtualBox ~/cs7172> ./trapezoidal-omp.o 100
Size = 19.39
Time: 0.002283000000
```

- Sometime the overhead of synchronization is larger than the benefit of parallelism

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 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

Vairable k and factor are private;
Variable n is shared.

```
        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);
        }
```

The Reduction Clause

Our example

- If we write the code 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.

Our example

- 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;
    }
```

The Reduction Clause

- A common loop is to accumulate variables

```
int sum = 0;

for (int i = 0; i < 100; i++) {
    sum += array[i];
}
```

sum needs to be ***private*** for parallelization

sum needs to be ***public*** for the correct answer

The Reduction Clause

```
int sum = 0;

for (int i = 0; i < 100; i++) {
    sum += array[i];
}
```

```
int sum = 0;

#pragma omp parallel for reduction(+:sum)
for (int i = 0; i < 100; i++) {
        sum += array[i];
}
```

In the internal implementation, OpenMP provides a private sum variable for each thread.

When the thread exits, OpenMP adds the sum of each thread's parts to get the final result.

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.

Reduction operators

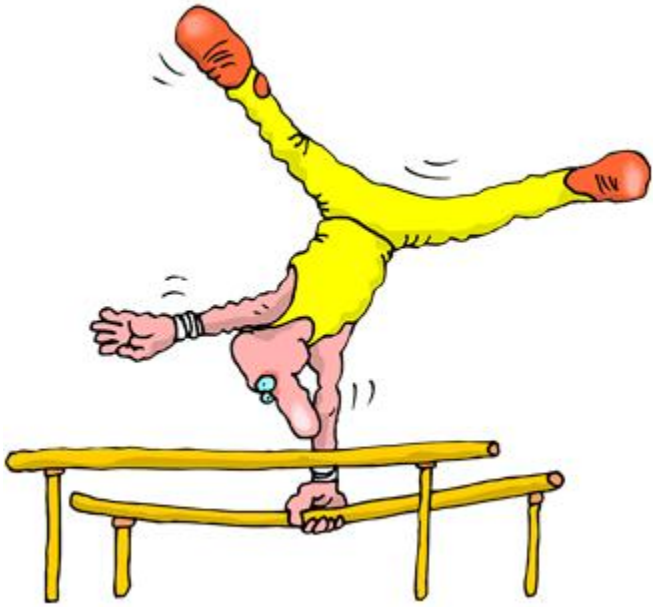
```
reduction(<operator>: <variable list>)
```

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

```
   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 global_result is private for each thread and public for the master thread

The “Parallel For” Directive



Parallel for

- Forks a team of threads to execute the following structured block.

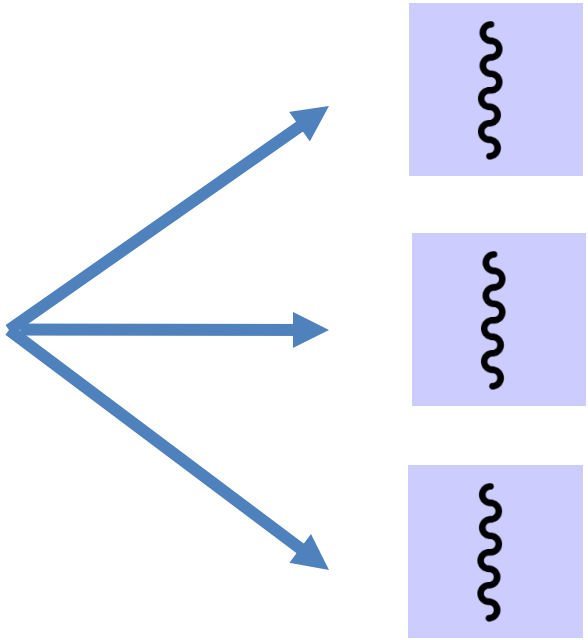
- However, the structured block following the parallel for directive must be ***a for loop***.

```
int sum = 0;

#pragma omp parallel for reduction(+:sum)
for (int i = 0; i < 100; i++) {
        sum += array[i];
}
```

Parallel for

- Furthermore, with the parallel for directive the system parallelizes the for loop by dividing the iterations of the loop among the threads.

```
int sum = 0;

for (int i = 0; i < 100; i++) {
    sum += array[i];
}
```



Parallel for Example

```
int sum = 0;

for (int i = 0; i < 100; i++) {
    sum += array[i];
}
```

```
int sum = 0;

#pragma omp parallel for reduction(+:sum)
for (int i = 0; i < 100; i++) {
        sum += array[i];
}
```

Legal forms for parallelizable for statements

```
for ( index = start ; index < end      ; index++                )
                      index <= end      ; ++index
                      index >= end      ; index--
                      index > end       ; --index
                                        ; index += incr
                                        ; index -= incr
                                        ; index = index + incr
                                        ; index = incr + index
                                        ; index = index - incr )
```

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

Data dependencies

https://github.com/kevinsuo/CS7172/blob/master/fibonacci.c

- Fibonacci in serial

```c
#include <stdio.h>

int main()
{
        int fibo[10];
        fibo[0] = fibo[1] = 1;
        int i;

        printf("%d\n", fibo[0]);
        printf("%d\n", fibo[1]);

        for (i = 2; i < 10; i++)
        {
                fibo[i] = fibo[i-1] + fibo[i-2];
                printf("%d\n", fibo[i]);
        }

        return 0;
}
```

```
ksuo@ksuo-VirtualBox ~/cs7172> ./fibonacci.o
1
1
2
3
5
8
13
21
34
55
```

Data dependencies

https://github.com/kevinsuo/CS7172/blob/master/fibonacci-omp.c

- Fibonacci in openmp

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

int main()
{
        int fibo[10];
        fibo[0] = fibo[1] = 1;
        int i;

        printf("%d\n", fibo[0]);
        printf("%d\n", fibo[1]);

#pragma omp parallel for num_threads(2)
        for (i = 2; i < 10; i++)
        {
                fibo[i] = fibo[i-1] + fibo[i-2];
                printf("%d\n", fibo[i]);
        }

        return 0;
}
```

```
ksuo@ksuo-VirtualBox ~/cs7172> ./fibonacci-omp.o
1
1
2
3
5
8
303804267
303804275
607608542
911412817
```

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.

Example: Estimating π

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

```
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

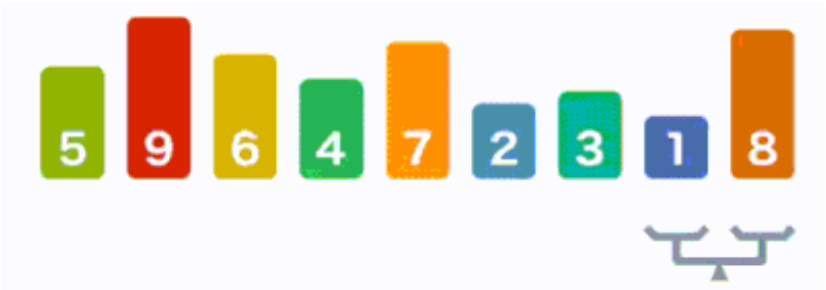
```
        double sum = 0.0;
#       pragma omp parallel for num_threads(thread_count) \
            reduction(+:sum) private(factor)
        for (k = 0; k < n; k++) {
            if (k % 2 == 0)
                factor = 1.0;
            else
                factor = -1.0;
            sum += factor/(2*k+1);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

Insures factor has private scope.

More Loops in OpenMP: Sorting

Bubble Sort

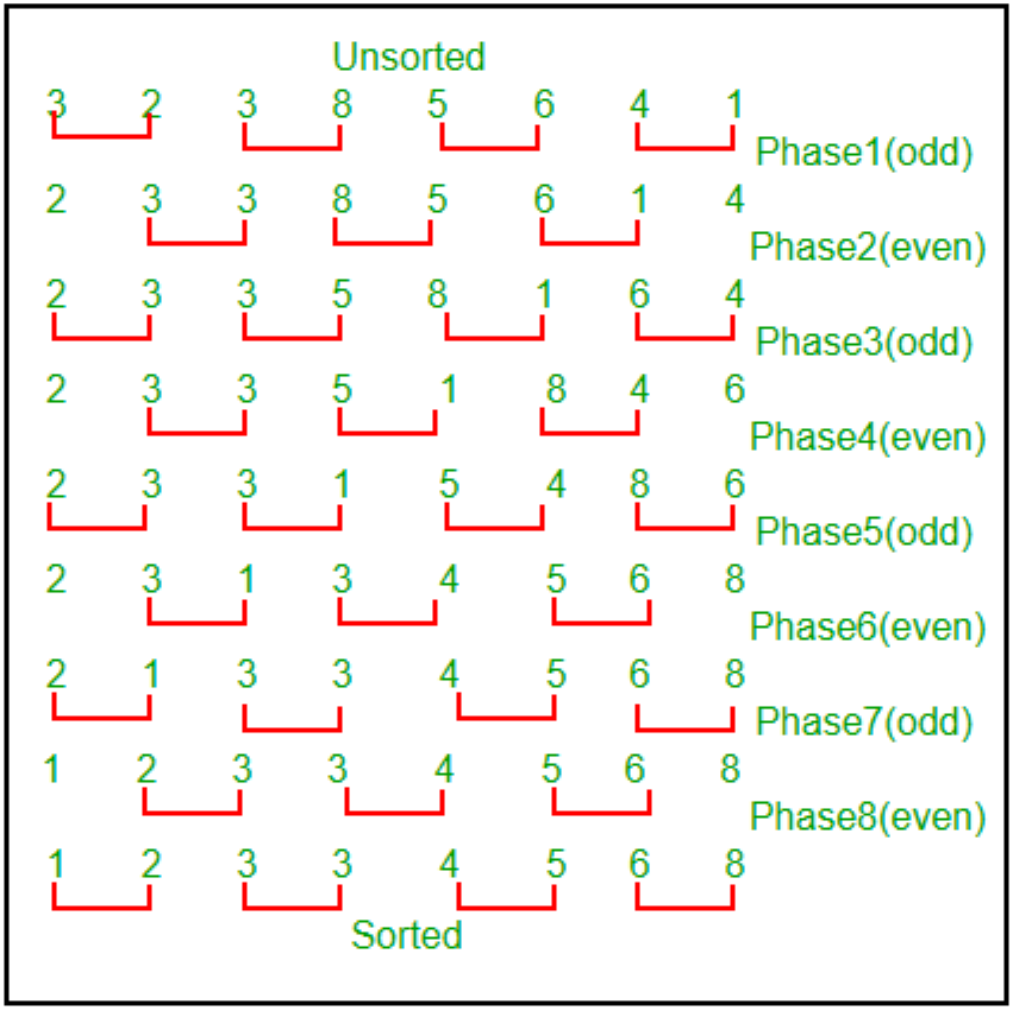
```
for (list_length = n; list_length >= 2; list_length--)
    for (i = 0; i < list_length-1; i++)
        if (a[i] > a[i+1]) {
            tmp = a[i];
            a[i] = a[i+1];
            a[i+1] = tmp;
        }
```



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



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;
                }
            }
    }
```

Performance

Odd-even sort with two parallel for directives and two for directives.

(Times are in seconds.)

thread_count	1	2	3	4
Two parallel **for** directives	0.770	0.453	0.358	0.305
Two **for** directives	0.732	0.376	0.294	0.239

Scheduling Loops

Scheduling Loops

We want to parallelize this loop.

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

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

Assignment of work using cyclic partitioning.

Scheduling Loops

```
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

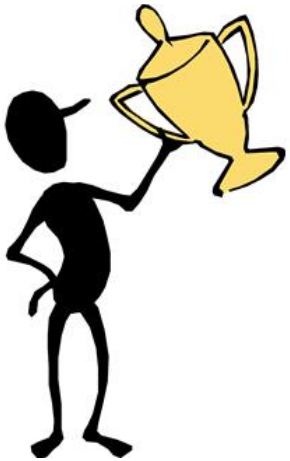
- f(i) calls the sin function *i* times.
- Assume the time to execute f(2i) requires approximately twice as much time as the time to execute f(i).

- 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)
```

$$\begin{aligned} \text{Thread } 0: &\quad 0, 3, 6, 9 \\ \text{Thread } 1: &\quad 1, 4, 7, 10 \\ \text{Thread } 2: &\quad 2, 5, 8, 11 \end{aligned}$$

The Static Schedule Type

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

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

$$\begin{aligned} \text{Thread } 0: &\quad 0, 1, 6, 7 \\ \text{Thread } 1: &\quad 2, 3, 8, 9 \\ \text{Thread } 2: &\quad 4, 5, 10, 11 \end{aligned}$$

The Static Schedule Type

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

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

$$\begin{aligned} \text{Thread } 0: &\quad 0, 1, 2, 3 \\ \text{Thread } 1: &\quad 4, 5, 6, 7 \\ \text{Thread } 2: &\quad 8, 9, 10, 11 \end{aligned}$$

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.

The Guided Schedule Type

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

```
    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, &mesg);
    else
        Dequeue(queue, &src, &mesg);
    Print_message(src, mesg);
```

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;
```

Matrix-vector multiplication

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

$$\begin{bmatrix} a_{00} & a_{01} & \cdots & a_{0,n-1} \\ a_{10} & a_{11} & \cdots & a_{1,n-1} \\ \vdots & \vdots & & \vdots \\ a_{i0} & a_{i1} & \cdots & a_{i,n-1} \\ \vdots & \vdots & & \vdots \\ a_{m-1,0} & a_{m-1,1} & \cdots & a_{m-1,n-1} \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \\ \vdots \\ x_{n-1} \end{bmatrix} = \begin{bmatrix} y_0 \\ y_1 \\ \vdots \\ y_i = a_{i0}x_0 + a_{i1}x_1 + \cdots a_{i,n-1}x_{n-1} \\ \vdots \\ y_{m-1} \end{bmatrix}$$

```
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					
	$8,000,000 \times 8$		8000×8000		$8 \times 8,000,000$	
	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

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.