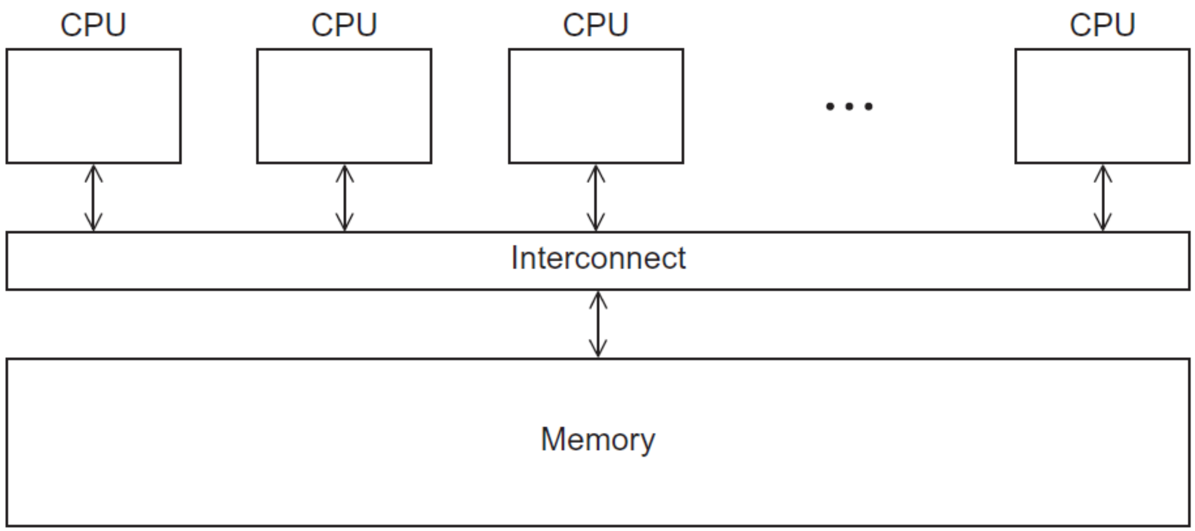
Chapter 5
Shared Memory Programming with OpenMP

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

```c
#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
```

compiling

running with 4 threads

possible outcomes

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

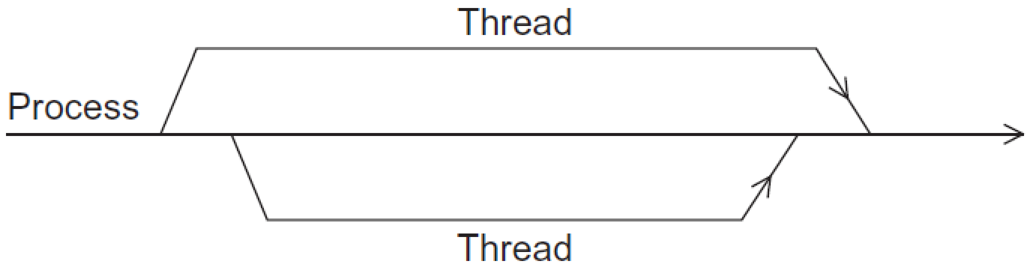
```
Hello from thread 1 of 4
Hello from thread 2 of 4
Hello from thread 0 of 4
Hello from thread 3 of 4
```

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

OpenMp pragmas

- # pragma omp parallel
  - Most basic parallel directive.
  - The number of threads that run the following structured block of code is determined by the run-time system.

A process forking and joining two threads



OpenMP work-sharing constructs

Functionality	Syntax in C/C++	Syntax in Fortran
Distribute iterations over the threads	#pragma omp for	!$omp do
Distribute independent work units	#pragma omp sections	!$omp sections
Only one thread executes the code block	#pragma omp single	!$omp single
Parallelize array-syntax		!$omp workshare

Syntax of the combined constructs in C/C++

<table>
<tr><th>Full version</th><th>Combined construct</th></tr>
<tr><td><pre>#pragma omp parallel
{
  #pragma omp for
    for-loop
}</pre></td><td><pre>#pragma omp parallel for
  for-loop</pre></td></tr>
<tr><td><pre>#pragma omp parallel
{
#pragma omp sections
{
  [#pragma omp section]
    structured block
  [#pragma omp section
    structured block]
  ...
}
}</pre></td><td><pre>#pragma omp parallel sections
{
  [#pragma omp section]

    structured block
  [#pragma omp section
    structured block]
  ...
}</pre></td></tr>
</table>

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 )
```

Clauses supported by the parallel construct

if *(scalar-expression)*	(C/C++)
if *(scalar-logical-expression)*	(Fortran)
num_threads *(integer-expression)*	(C/C++)
num_threads *(scalar-integer-expression)*	(Fortran)
private *(list)*	
firstprivate *(list)*	
shared *(list)*	
default(none | shared)	(C/C++)
default(none | shared | private)	(Fortran)
copyin *(list)*	
reduction *(operator:list)*	(C/C++)
reduction *({operator | intrinsic_procedure_name}:list)*	(Fortran)

Clauses supported by the parallel construct

子句	描述
if	指定是否應以平行方式或在序列中執行迴圈。
num_threads	設定執行緒小組中的執行緒數目。
private	指定每個執行緒都應該有自己的變數實例。
firstprivate	指定每個執行緒應該有自己的變數實例，而且應該使用變數的值來初始化變數，因為它存在於平行結構之前。
lastprivate	指定將封入內容的變數版本設為等於執行最後反覆運算 (for 迴圈結構) 或最後一節 (# pragma 區段) 的私用版本。
shared	指定應在所有線程之間共用一或多個變數。
default	shared如果 default 未指定子句，就會生效，這表示會將平列區域中的任何變數視為使用 shared 子句來指定。 none 表示在非 私用、 共用、 縮減、 firstprivate或 lastprivate 子句範圍內的平列區域中使用的任何變數都會造成編譯器錯誤。
copyin	允許執行緒針對 threadprivate 變數存取主要執行緒的值。
reduction	指定每個執行緒私用的一或多個變數，在平列區域結束時進行聚集運算。

if

C++ 複製

```cpp
// omp_if.cpp
// compile with: /openmp
#include <stdio.h>
#include <omp.h>

void test(int val)
{
    #pragma omp parallel if (val)
    if (omp_in_parallel())
    {
        #pragma omp single
        printf_s("val = %d, parallelized with %d threads\n",
                 val, omp_get_num_threads());
    }
    else
    {
        printf_s("val = %d, serialized\n", val);
    }
}

int main( )
{
    omp_set_num_threads(2);
    test(0);
    test(2);
}
```

Output 複製

```
val = 0, serialized
val = 2, parallelized with 2 threads
```

num_threads

C++ 複製

```cpp
// omp_parallel.cpp
// compile with: /openmp
#include <stdio.h>
#include <omp.h>

int main() {
   #pragma omp parallel num_threads(4)
   {
      int i = omp_get_thread_num();
      printf_s("Hello from thread %d\n", i);
   }
}
```

Output 複製

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

C 複製

```c
// openmp_private.c
// compile with: /openmp
#include <windows.h>
#include <assert.h>
#include <stdio.h>
#include <omp.h>

#define NUM_THREADS 4
#define SLEEP_THREAD 1
#define NUM_LOOPS 2

enum Types {
   ThreadPrivate,
   Private,
   FirstPrivate,
   LastPrivate,
   Shared,
   MAX_TYPES
};

int nSave[NUM_THREADS][MAX_TYPES][NUM_LOOPS] = {{0}};
int nThreadPrivate;

#pragma omp threadprivate(nThreadPrivate)
#pragma warning(disable:4700)

int main() {
   int nPrivate = NUM_THREADS;
   int nFirstPrivate = NUM_THREADS;
   int nLastPrivate = NUM_THREADS;
   int nShared = NUM_THREADS;
   int nRet = 0;
   int i;
   int j;
   int nLoop = 0;

   nThreadPrivate = NUM_THREADS;
   printf_s("These are the variables before entry "
           "into the parallel region.\n");
   printf_s("nThreadPrivate = %d\n", nThreadPrivate);
```

```
printf_s("nThreadPrivate = %d\n", nThreadPrivate);
printf_s("      nPrivate = %d\n", nPrivate);
printf_s(" nFirstPrivate = %d\n", nFirstPrivate);
printf_s("  nLastPrivate = %d\n", nLastPrivate);
printf_s("       nShared = %d\n\n", nShared);
omp_set_num_threads(NUM_THREADS);

#pragma omp parallel copyin(nThreadPrivate) private(nPrivate) shared(nShared) firstprivate(nFirstPr
{
   #pragma omp for schedule(static) lastprivate(nLastPrivate)
   for (i = 0 ; i < NUM_THREADS ; ++i) {
      for (j = 0 ; j < NUM_LOOPS ; ++j) {
         int nThread = omp_get_thread_num();
         assert(nThread < NUM_THREADS);

         if (nThread == SLEEP_THREAD)
            Sleep(100);
         nSave[nThread][ThreadPrivate][j] = nThreadPrivate;
         nSave[nThread][Private][j] = nPrivate;
         nSave[nThread][Shared][j] = nShared;
         nSave[nThread][FirstPrivate][j] = nFirstPrivate;
         nSave[nThread][LastPrivate][j] = nLastPrivate;
         nThreadPrivate = nThread;
         nPrivate = nThread;
         nShared = nThread;
         nLastPrivate = nThread;
         --nFirstPrivate;
      }
   }
}

for (i = 0 ; i < NUM_LOOPS ; ++i) {
   for (j = 0 ; j < NUM_THREADS ; ++j) {
      printf_s("These are the variables at entry of "
               "loop %d of thread %d.\n", i + 1, j);
      printf_s("nThreadPrivate = %d\n",
               nSave[j][ThreadPrivate][i]);
      printf_s("      nPrivate = %d\n",
               nSave[j][Private][i]);
      printf_s(" nFirstPrivate = %d\n",
               nSave[j][FirstPrivate][i]);
      printf_s("  nLastPrivate = %d\n",
               nSave[j][LastPrivate][i]);
```

```
                nSave[j][LastPrivate][i]);
        printf_s("        nShared = %d\n\n",
                nSave[j][Shared][i]);
     }
   }

   printf_s("These are the variables after exit from "
           "the parallel region.\n");
   printf_s("nThreadPrivate = %d (The last value in the "
           "master thread)\n", nThreadPrivate);
   printf_s("      nPrivate = %d (The value prior to "
           "entering parallel region)\n", nPrivate);
   printf_s(" nFirstPrivate = %d (The value prior to "
           "entering parallel region)\n", nFirstPrivate);
   printf_s("  nLastPrivate = %d (The value from the "
           "last iteration of the loop)\n", nLastPrivate);
   printf_s("       nShared = %d (The value assigned, "
           "from the delayed thread, %d)\n\n",
           nShared, SLEEP_THREAD);
}
```

Output 複製

```
These are the variables before entry into the parallel region.
nThreadPrivate = 4
      nPrivate = 4
nFirstPrivate = 4
  nLastPrivate = 4
       nShared = 4

These are the variables at entry of loop 1 of thread 0.
nThreadPrivate = 4
      nPrivate = 1310720
nFirstPrivate = 4
  nLastPrivate = 1245104
       nShared = 3

These are the variables at entry of loop 1 of thread 1.
nThreadPrivate = 4
      nPrivate = 4488
nFirstPrivate = 4
  nLastPrivate = 19748
       nShared = 0

These are the variables at entry of loop 1 of thread 2.
nThreadPrivate = 4
      nPrivate = -132514848
nFirstPrivate = 4
  nLastPrivate = -513199792
       nShared = 4

These are the variables at entry of loop 1 of thread 3.
nThreadPrivate = 4
      nPrivate = 1206
nFirstPrivate = 4
  nLastPrivate = 1204
       nShared = 2

These are the variables at entry of loop 2 of thread 0.
nThreadPrivate = 0
      nPrivate = 0
nFirstPrivate = 3
  nLastPrivate = 0
```

```
These are the variables at entry of loop 2 of thread 0.
nThreadPrivate = 0
      nPrivate = 0
nFirstPrivate = 3
  nLastPrivate = 0
       nShared = 0

These are the variables at entry of loop 2 of thread 1.
nThreadPrivate = 1
      nPrivate = 1
nFirstPrivate = 3
  nLastPrivate = 1
       nShared = 1

These are the variables at entry of loop 2 of thread 2.
nThreadPrivate = 2
      nPrivate = 2
nFirstPrivate = 3
  nLastPrivate = 2
       nShared = 2

These are the variables at entry of loop 2 of thread 3.
nThreadPrivate = 3
      nPrivate = 3
nFirstPrivate = 3
  nLastPrivate = 3
       nShared = 3

These are the variables after exit from the parallel region.
nThreadPrivate = 0 (The last value in the master thread)
      nPrivate = 4 (The value prior to entering parallel region)
nFirstPrivate = 4 (The value prior to entering parallel region)
  nLastPrivate = 3 (The value from the last iteration of the loop)
       nShared = 1 (The value assigned, from the delayed thread, 1)
```

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.

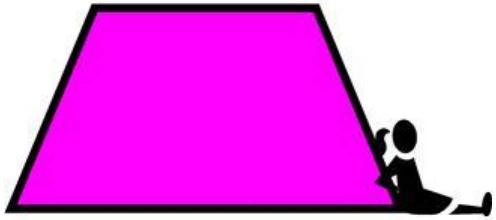
In case the compiler doesn't support OpenMP

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

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

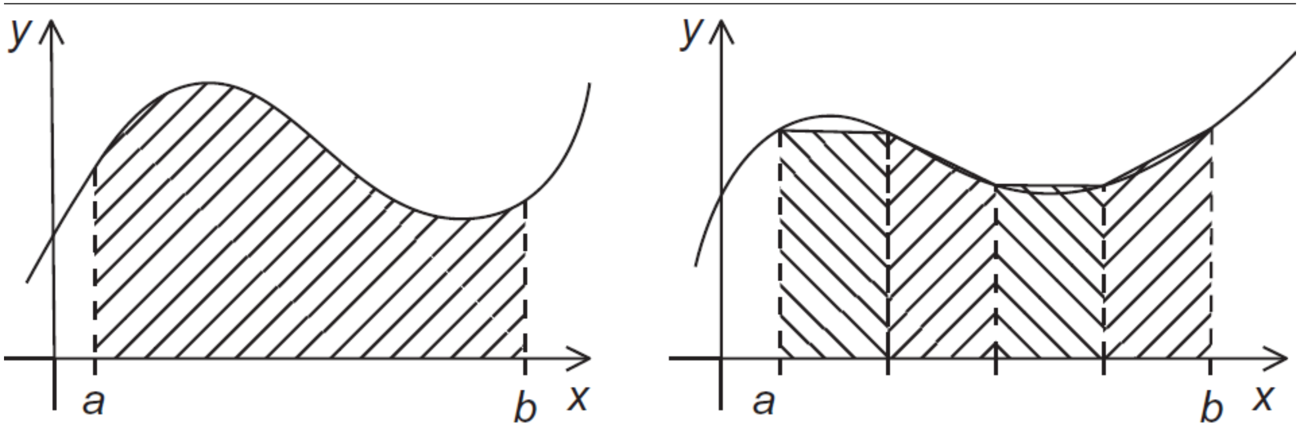
In case the compiler doesn't support OpenMP

```
# 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

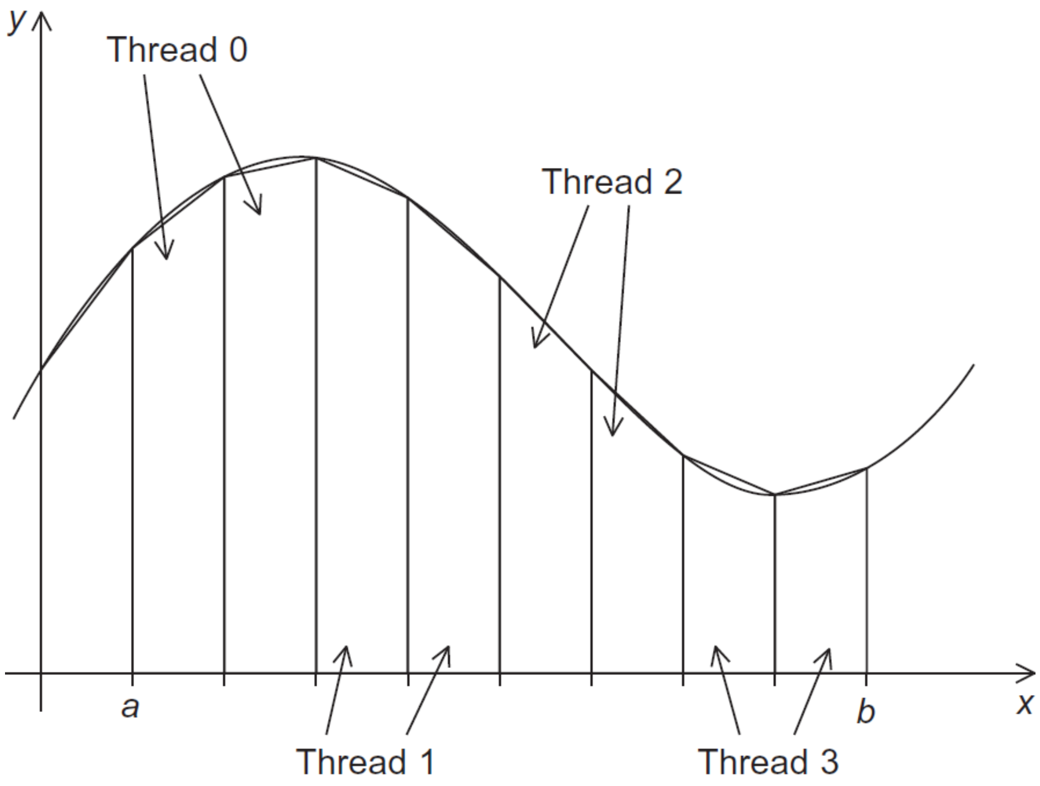
1) We identified two types of tasks:
   a) computation of the areas of individual trapezoids, and
   b) adding the areas of trapezoids.
2) There is no communication among the tasks in the first collection, but each task in the first collection communicates with task 1 (b).

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

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

global_result += my_result ;

Mutual excluslon

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

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

```c
#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;
   }
```

Reduction operators

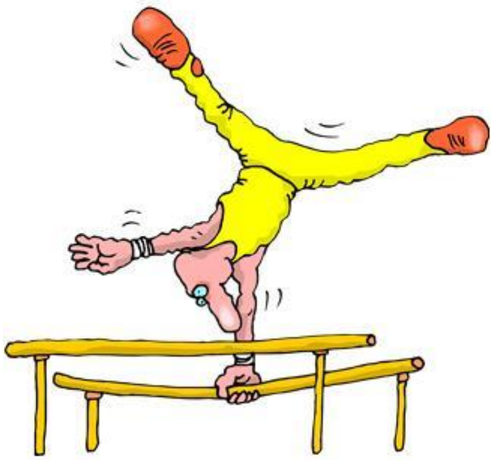
- A reduction operator is a binary operation (such as addition or multiplication).
- A reduction is a computation that repeatedly applies the same reduction operator to a sequence of operands in order to get a single result.
- All of the intermediate results of the operation should be stored in the same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

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

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.
- These restrictions allow the run-time system to determine the number of iterations prior to execution of the loop.

Data dependencies

```
1   int Linear_search(int key, int A[], int n) {
2      int i;
3      /* thread_count is global */
4   #  pragma omp parallel for num_threads(thread_count)
5      for (i = 0; i < n; i++)
6         if (A[i] == key) return i;
7      return -1;  /* key not in list */
8   }
```

The gcc compiler reports:

```
Line 6: error: invalid exit from OpenMP structured block
```

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 ];
```

but sometimes we get this

1 1 2 3 5 8 13 21 34 55

this is correct

1 1 2 3 5 8 0 0 0 0

What happened?

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

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.

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);
    }
```

```
   int x = 5;
#  pragma omp parallel num_threads(thread_count) \
      private(x)
   {
      int my_rank = omp_get_thread_num();
      printf("Thread %d > before initialization, x = %d\n",
            my_rank, x);
      x = 2*my_rank + 2;
      printf("Thread %d > after initialization, x = %d\n",
            my_rank, x);
   }
   printf("After parallel block, x = %d\n", x);
```

```
indx = 4;
#pragma omp parallel default(none) firstprivate(indx) \
                     private(i,TID) shared(n,a)
  {
     TID = omp_get_thread_num();

     indx += n*TID;
     for(i=indx; i<indx+n; i++)
        a[i] = TID + 1;
  } /*-- End of parallel region --*/

printf("After the parallel region:\n");
for (i=0; i<vlen; i++)
    printf("a[%d] = %d\n",i,a[i]);
```

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;
            }
         }
   }
```

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

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.

```
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*.

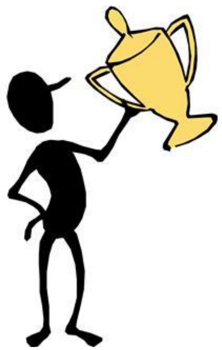
Results

- 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)
```

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

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.

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.

```
$ export OMP_SCHEDULE="static,1"
```

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

$$+,\ *,\ -,\ /,\ \&,\ \hat{},\ |,\ <<,\ \texttt{or}\ >>$$

- 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, 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] */
    Dequeue(q_p, &src, &mesg);
```

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

Some Caveats

- You shouldn't mix the different types of mutual exclusion for a single critical section.

```
#  pragma omp atomic
   x += f(y);
```

```
#  pragma omp critical
   x = g(x);
```

Some Caveats

- There is no guarantee of fairness in mutual exclusion constructs.

```
while(1) {
      . . .
#     pragma omp critical
      x = g(my_rank);
      . . .
}
```

Some Caveats

- It can be dangerous to "nest" mutual exclusion constructs.

```
#  pragma omp critical
   y = f(x);
   . . .
   double f(double x) {
#     pragma omp critical
      z = g(x);  /* z is shared */
      . . .
   }
```

Some Caveats

```
#   pragma omp critical(one)
    y = f(x);
    . . .
    double f(double x) {
#      pragma omp critical(two)
       z = g(x);  /* z is global */
       . . .
    }
```

Matrix-vector multiplication

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

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

```
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

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.