OpenMP

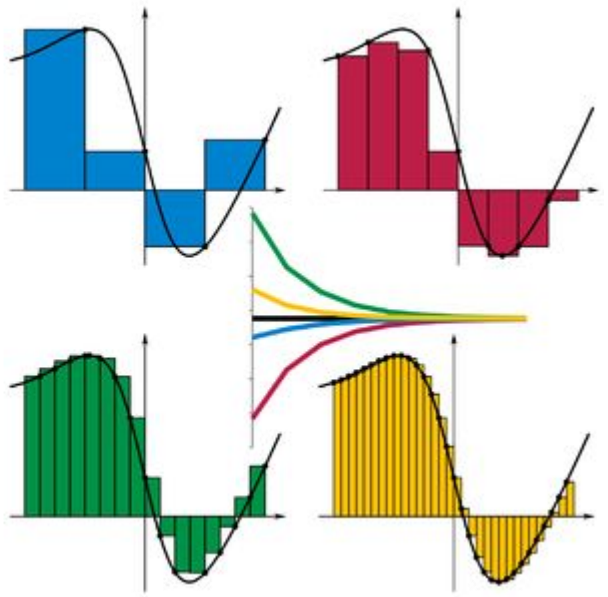
Open Multi-Processing

Exercise 5a

Numerical integration (Riemann sum)

Numerical integration is the approximate computation of an integral using numerical techniques

Write parallel version of the program using PThreads



Template: omp_integral_0.c (sequential)

OpenMP (Open Multi-Processing)

Open standard for parallelization of programs in C, C++, Fortran languages

Interface standard for parallel programming on shared memory

Brief history:

- Version 1.0 1997
- Version 4.0 July 2013
- Version 4.1 in progress

Compilers: GCC, Intel C++ compiler, Visual C++

Advantages Of OpenMP

- Ease of use
- Cross-platform for shared memory systems
- Hiding low-level operations
- Support for parallel and serial versions of programs

Core components

- Environment variable
- Compiler directive
- Functions

Steps of development

1. Write and debug a sequential program
2. Add OpenMP directives to the program
3. Use compiler with support for OpenMP
4. Set the environment variables
5. Run the program

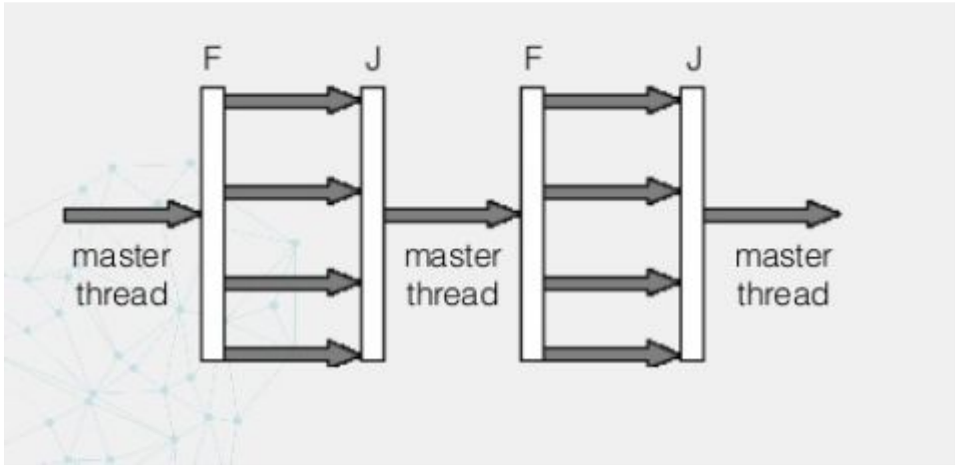
Compilation

```
gcc source.c -o source.x -fopenmp
```

Model

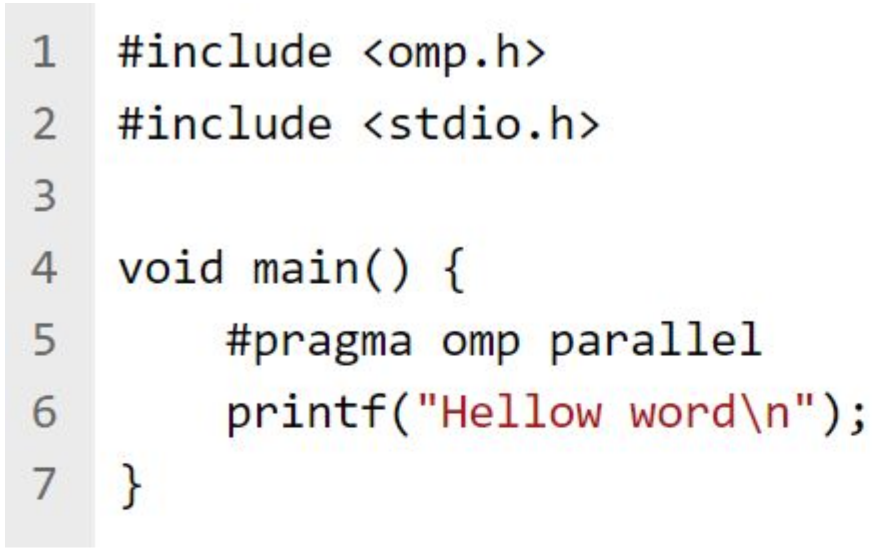
Parallelization in OpenMP is performed explicitly by inserting special directives into the program code, as well as calling auxiliary functions. OpenMP assumes an SPMD model (Single Program Multiple Data) of parallel programming in which the same code is used for all parallel threads.

Model Fork-Join



- Explicit indication of parallel sections
- Support for nested parallelism
- Dynamic threads support

Simple program



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

void main() {
    #pragma omp parallel
    printf("Hellow word\n");
}
```

Directives (Directive Format (C / C ++))

#pragma omp < name> [<attributes> {[,] <attributes>}]

name - the name of the **Directive**;

Attributes - a construction specifying additional information and depending on the **Directive**;

Directive parallel

```
#pragma omp parallel [<attributes>]
        <structural block>
```

- A thread that encounters a parallel construct creates a thread group, becoming the master.
- Threads are assigned unique integer numbers starting with 0 (the main thread).
- Each thread executes code defined by a building block, at the end of which a barrier is implicitly set

Declaring a parallel section

```
#include <omp.h>
int main()
{
   // Sequential code
   #pragma omp parallel
   {
      // Parallel code
   }
   // Sequential code

   return 0;
}
```

Условное объявление параллельной секции

```
#include <omp.h>
int main()
{
  //  Sequential code
  #pragma omp parallel if (expr)
  {
    //  Parallel code
  }
  //  Sequential code

  return 0;
}
```

Example

omp_hello.c

Environment variable

OMP_NUM_THREADS - Sets the number of threads in the parallel block. By default, the number of threads is equal to the number of virtual processors.

OMP_DYNAMIC - Allows or disables dynamic changes in the number of threads that are actually used for calculations (depending on system load). The default value depends on the implementation.

OMP_NESTED - Allows or disables nested parallelism (parallelization of nested loops). The default is disabled.

Example

omp_hello_env.c

Functions of OpenMP

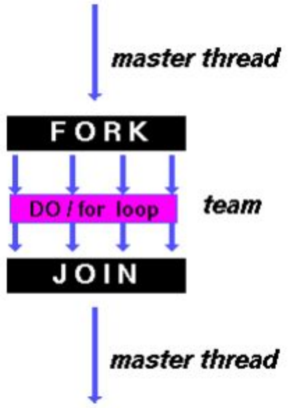
- **omp_set_num_threads** To set the number of threads
- **omp_get_num_threads** Return the number of threads in the group
- **omp_get_max_threads** Maximum number of threads
- **omp_get_thread_num** ID of thread
- **omp_get_num_procs** Maximum number of processors
- **omp_in_parallel** Check for location in a parallel region

Example

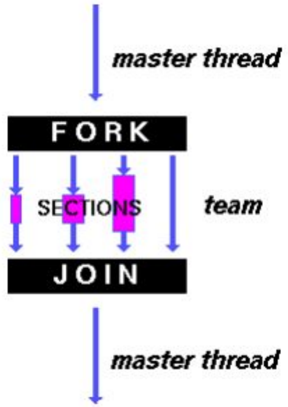
omp_hello_functions.c

Ways to divide work between threads

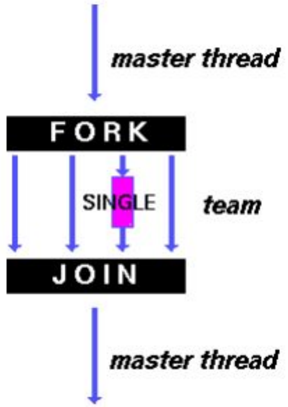
```
#pragma omp for
  for (i=0;i<N;i++)
  {
    // code
  }
```



```
#pragma omp sections
{
 #pragma omp section
 // code 1
 #pragma omp section
 // code 2
}
```



```
#pragma omp single
{
  // code
}
```



Low-level parallelization

You can program at the lowest level by distributing work using the **omp_get_thread_num()** and **omp_get_num_threads()** functions, which return the thread number and the total number of threads generated in the current parallel region, respectively.

Example: omp_low_level.c

Directive **for**

#pragma omp for [<attributes>]

<loop body>

Restrictions:

- **The only counter is an integer, pointer, or random access iterator. Should only change in the loop header.**
- **Loop condition: comparing a variable with a loop-invariant expression using <, <=, >, >=.**
- **Changing the counter: using ++,--, i += d, i -= d, i = i + d, i = d + i, i = i - d (d — cycle-invariant integer expression)**

Directive **for**

```
#include <stdio.h>
#include <omp.h>
int main()
{ int i;
  #pragma omp parallel
  {
    #pragma omp for
    for (i=0;i<1000;i++)
      printf("%d ",i);
  }
  return 0;
}
```

Directive **for**

```
#include <stdio.h>
#include <omp.h>
int main()
{ int i;

  #pragma omp parallel for
    for (i=0;i<1000;i++)
      printf("%d ",i);

  return 0;
}
```

Example

omp_for.c

omp_for_2.c

The distribution of the iterations among the threads

for option **schedule:**

- static
- dynamic
- guided
- auto
- runtime (by env var)

static

Block-cyclic distribution of loop iterations; block size – chunk.

The first block of the chunk of iterations performs the zero thread, the second block the next and so on until the last thread, then the distribution starts again with zero threads.

dynamic

Dynamic distribution of iterations with fixed block size: first, each thread gets a chunk of iterations (default chunk=1), the thread that finishes executing its portion of iterations gets the first free portion of the chunk iterations.

Example

omp_schedule.c

Time measurement

omp_get_wtime() - returns in the calling thread the astronomical time in seconds (a double-precision real number) that has elapsed since some point in the past.

omp_get_wtick() returns the timer resolution in seconds in the calling thread. This time can be seen as a measure of timer accuracy.

Example: omp_time.c

Directive **sections**

```
#include <stdio.h>
#include <omp.h>
int main()
{ int i;
  #pragma omp parallel sections private(i)
  {
    #pragma omp section
    { printf("1st half\n");
      for (i=0;i<500;i++) printf("%d ",i);
    }
    #pragma omp section
    { printf("2nd half\n");
      for (i=501;i<1000;i++) printf("%d ",i);
    }
  }
  return 0;
}
```

In this case, you need to keep in mind the need to support the serial version of the program.

Directive **omp single**

```
#include <stdio.h>
#include <omp.h>
int main()
{ int i;
  #pragma omp parallel private(i)
  {
    #pragma omp for
      for (i=0;i<1000;i++) printf("%d ",i);
    #pragma omp single
      printf("I'm thread %d!\n",get_thread_num());
    #pragma omp for
      for (i=0;i<1000;i++) printf("%d ",i);
  }
  return 0;
}
```

Directive **omp single**

```
#include <stdio.h>
#include <omp.h>
int main()
{ int i;
  #pragma omp parallel private(i)
  {
    #pragma omp for
      for (i=0;i<1000;i++) printf(“%d ”,i);
    #pragma omp single
      printf(“I’m thread %d!\n”,get_thread_num());
    #pragma omp for
      for (i=0;i<1000;i++) printf(“%d ”,i);
  }
  return 0;
}
```

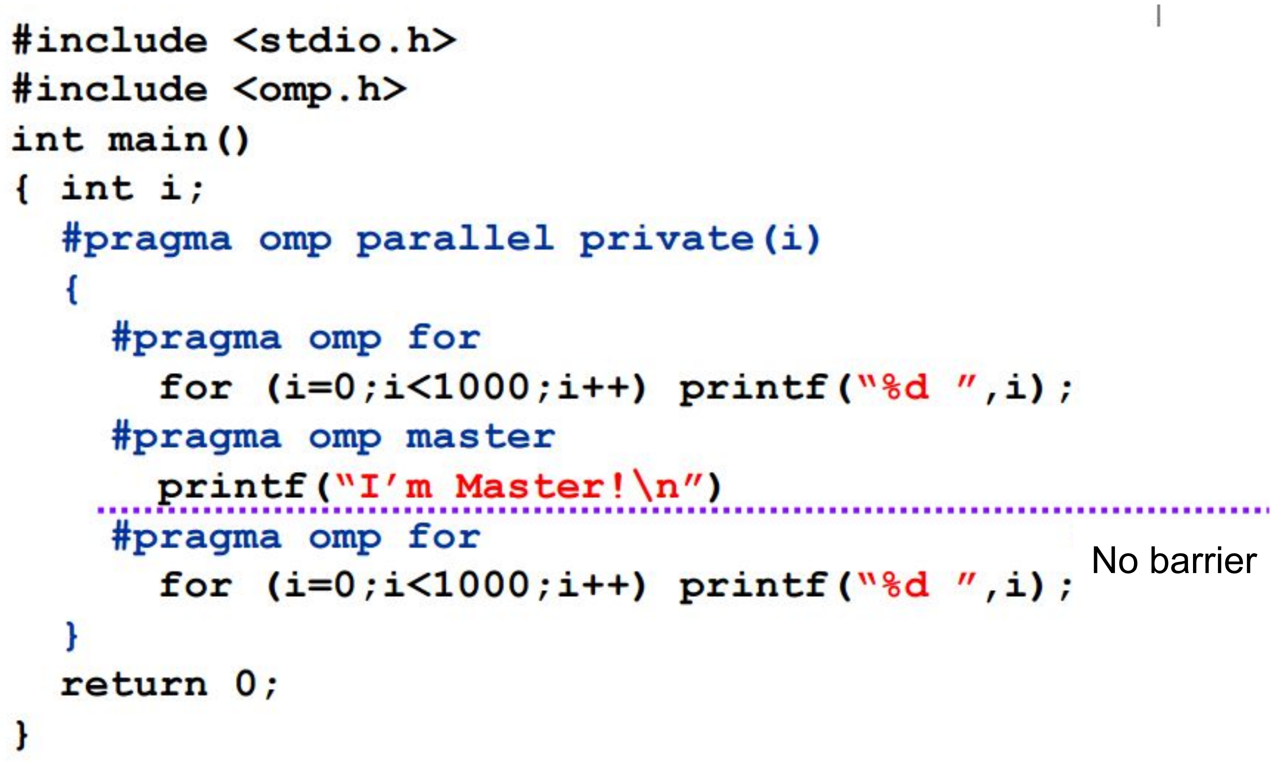
barrier

Directive **omp single**

```
#include <stdio.h>
#include <omp.h>
int main()
{ int i;
  #pragma omp parallel private(i)
  {
    #pragma omp for
      for (i=0;i<1000;i++) printf("%d ",i);
    #pragma omp single nowait
      printf("I'm thread %d!\n",get_thread_num());
    #pragma omp for
      for (i=0;i<1000;i++) printf("%d ",i);
  }
  return 0;
}
```

No barrier

Directive **omp master**

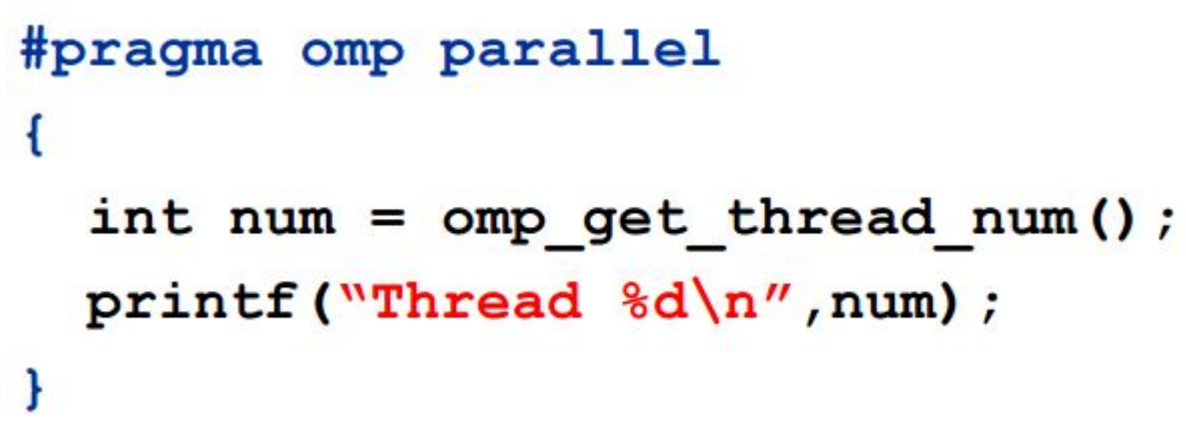


```
#include <stdio.h>
#include <omp.h>
int main()
{ int i;
  #pragma omp parallel private(i)
  {
    #pragma omp for
      for (i=0;i<1000;i++) printf(“%d ”,i);
    #pragma omp master
      printf(“I’m Master!\n”)
    #pragma omp for
      for (i=0;i<1000;i++) printf(“%d ”,i);
  }
  return 0;
}
```

No barrier

The scope of variables

Variables declared inside a parallel block are local to the thread:



```
#pragma omp parallel
{
  int num = omp_get_thread_num();
  printf("Thread %d\n",num);
}
```

The scope of variables

Variables declared outside the parallel block **are shared by default** across all threads:

```
int n = 10;
#pragma omp parallel
{
  for (int i=0;i<n;i++)
    printf("%d\n",i);
}
```

```
int num;
#pragma omp parallel
{
  num = omp_get_thread_num();
  printf("Thread %d\n",num);
}
```

The scope of variables

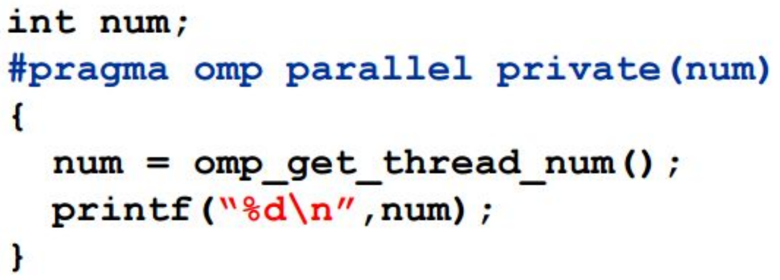
The scope of variables declared outside the parallel block is determined by the Directive parameters:

- private
- firstprivate
- lastprivate
- shared
- default
- reduction
- threadprivate
- copyin

The scope of variables

The scope of variables declared outside the parallel block is determined by the Directive parameters:

- **private - Own local variable in each thread**
- firstprivate
- lastprivate
- shared
- reduction

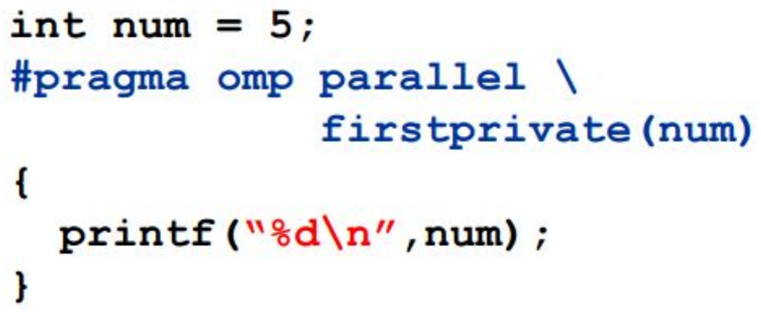


```
int num;
#pragma omp parallel private(num)
{
  num = omp_get_thread_num();
  printf("%d\n",num);
}
```

The scope of variables

The scope of variables declared outside the parallel block is determined by the Directive parameters:

- private
- **firstprivate - Local variable with initialization**
- lastprivate
- shared
- reduction



```c
int num = 5;
#pragma omp parallel \
            firstprivate(num)
{
  printf("%d\n",num);
}
```

The scope of variables

The scope of variables declared outside the parallel block is determined by the Directive parameters:

- private
- firstprivate
- **lastprivate**
- shared
- reduction

Local variable with the last value saved (in sequential execution)

```
int i,j;
#pragma omp parallel for \
            lastprivate(j)
for (i=0;i<100;i++) j = i;

printf("Последний j = %d\n",j);
```

The scope of variables

The scope of variables declared outside the parallel block is determined by the Directive parameters:

- private
- firstprivate
- lastprivate
- **shared**
- reduction

Shared (shared) variable

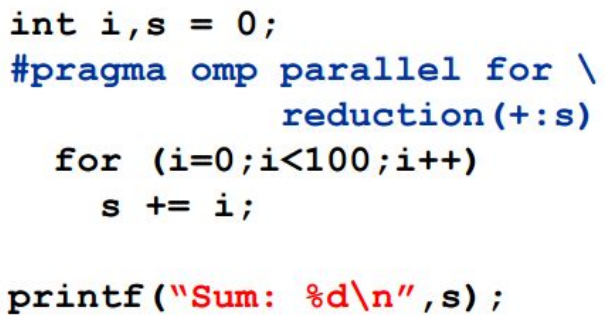
```
int i,j;

#pragma omp parallel for \
                shared(j)
for (i=0;i<100;i++) j = i;

printf("j = %d\n",j);
```

The scope of variables

The scope of variables declared outside the parallel block is determined by the Directive parameters:

- private
- firstprivate
- lastprivate
- shared
- **reduction**

The variable to perform the reducing operation



```
int i,s = 0;
#pragma omp parallel for \
            reduction(+:s)
  for (i=0;i<100;i++)
    s += i;

printf("Sum: %d\n",s);
```

Synchronizing threads

Thread synchronization directives:

- master
- barrier
- critical
- atomic

Locks:

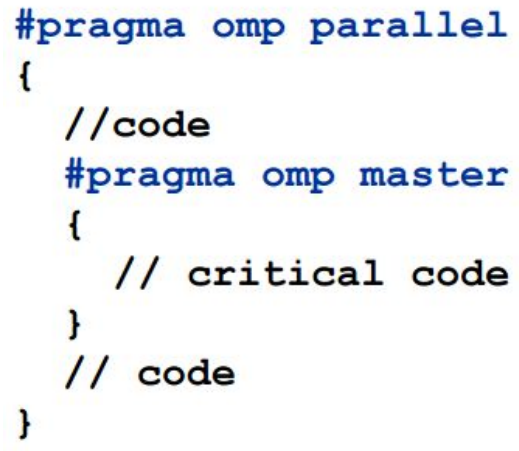
- omp_lock_t

Synchronizing threads

Thread synchronization directives:

- **master**
- barrier
- critical
- atomic

Выполнение кода только главным потоком

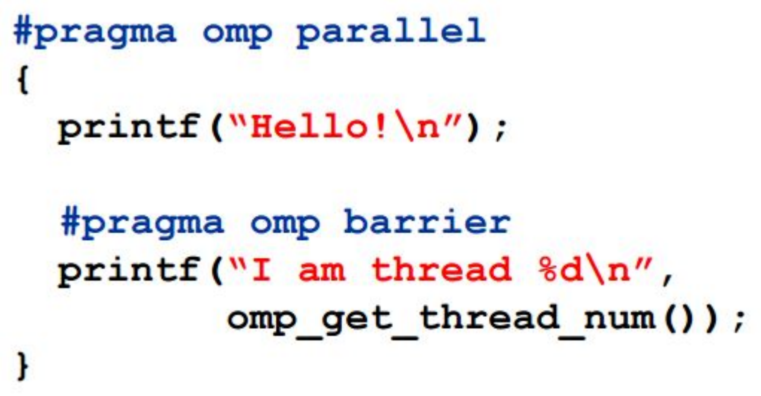


```
#pragma omp parallel
{
  //code
  #pragma omp master
  {
    // critical code
  }
  // code
}
```

Synchronizing threads

Thread synchronization directives:

- master
- **barrier**
- critical
- atomic

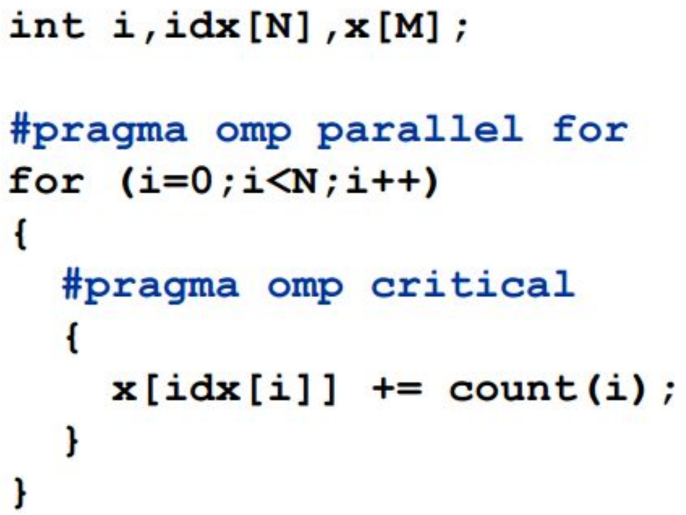


```
#pragma omp parallel
{
  printf("Hello!\n");

  #pragma omp barrier
  printf("I am thread %d\n",
         omp_get_thread_num());
}
```

Synchronizing threads

Thread synchronization directives:

- master
- barrier
- **critical**
- atomic

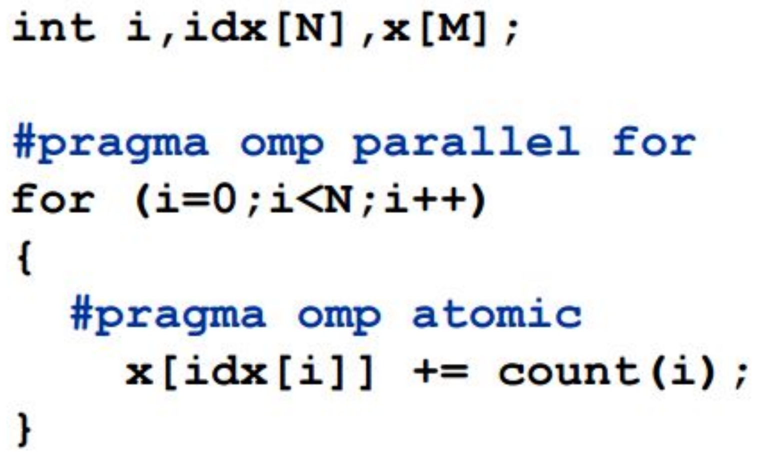


```
int i,idx[N],x[M];

#pragma omp parallel for
for (i=0;i<N;i++)
{
  #pragma omp critical
  {
    x[idx[i]] += count(i);
  }
}
```

Synchronizing threads

Thread synchronization directives:

- master
- barrier
- critical
- **atomic**



```
int i,idx[N],x[M];

#pragma omp parallel for
for (i=0;i<N;i++)
{
  #pragma omp atomic
    x[idx[i]] += count(i);
}
```

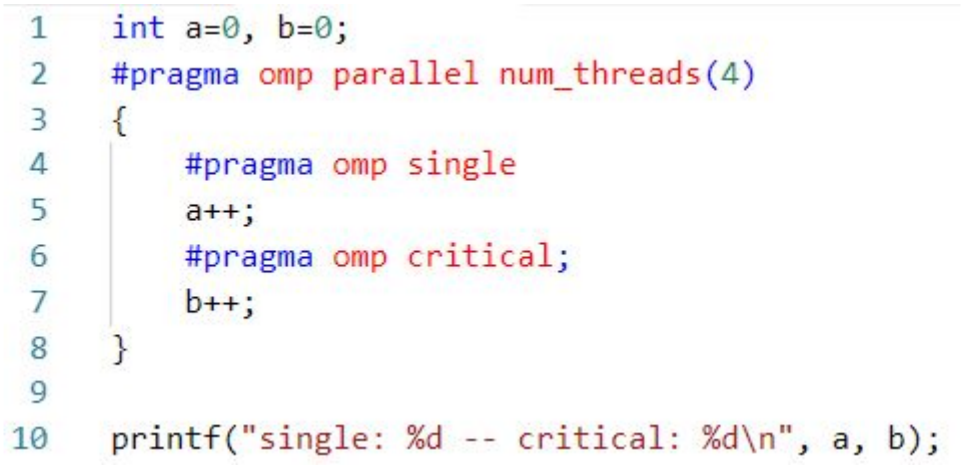
Locks

- Lock-a special object common to threads
- Threads can capture (lock) and release (unlock) a lock
- Only one thread at a time can capture a lock
- When attempting to capture a lock, threads wait for the lock to be released
- Using locks, you can control access to shared resources

An example of using the lock

```
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>
int x[1000];
int main()
{ int i,max;
  omp_lock_t lock;
  omp_init_lock(&lock);
  for (i=0;i<1000;i++) x[i]=rand();
  max = x[0];
  #pragma omp parallel for
    for(i=0;i<1000;i++)
    { omp_set_lock(&lock);
      if (x[i]>max) max = x[i];
      omp_set_unlock(&lock);
    }
  omp_destroy_lock(&lock);
  return 0;
}
```

Example: single vs critical



```c
int a=0, b=0;
#pragma omp parallel num_threads(4)
{
    #pragma omp single
    a++;
    #pragma omp critical;
    b++;
}

printf("single: %d -- critical: %d\n", a, b);
```

Example: single vs critical

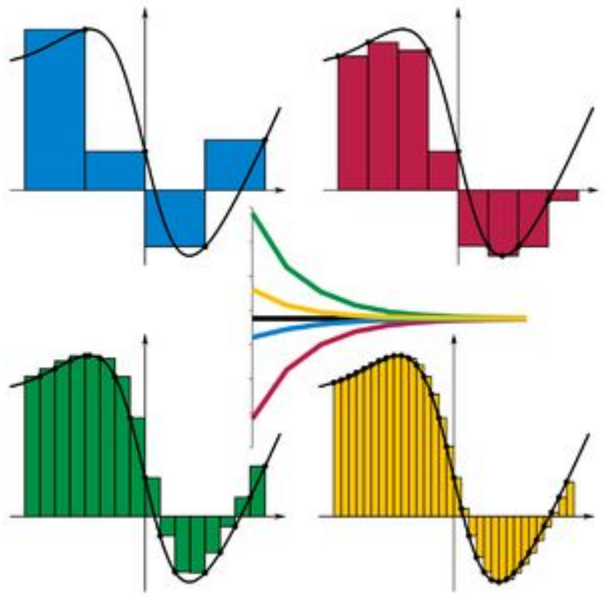
Output:

```
single: 1 -- critical: 4
```

Example

Numerical integration (Riemann sum)

Numerical integration is the approximate computation of an integral using numerical techniques



Source: omp_integral_0.c

Exercise 5b

Create program for Pi calculation based on OpenMP. Implement two versions:

1. Without reduction
2. Use reduction attribute

Questions:

Compare execution time of two versions.

Exercise 5c

Create program for multithreaded Prime number search based on OpenMP.

Question:

1. Compare time consummation with different for loop scheduler type.
2. Compare with PThread implementation.

Sample code: find_prime_number_seq_4.c