OpenMP

Jan 7, 2020

Course outline (Pacheco; GGKK; Quinn)

- Motivation (1;1;1)
- How to quantify performance improvement (2.6; 5; 7)
- Parallel hardware architecture (2.2-2.3; 2,4; 2)
- Parallel programming frameworks
  - Pthreads for shared memory (4; 7; -)
  - **OpenMP for shared memory (5; 7.10; 17)**
  - MPI for distributed memory (3; 6; 4)
  - CUDA/OpenCL for GPU,
  - Hadoop/Spark/Mapreduce for distributed systems
- Parallel program verification
- Parallel algorithm design
- Some case studies

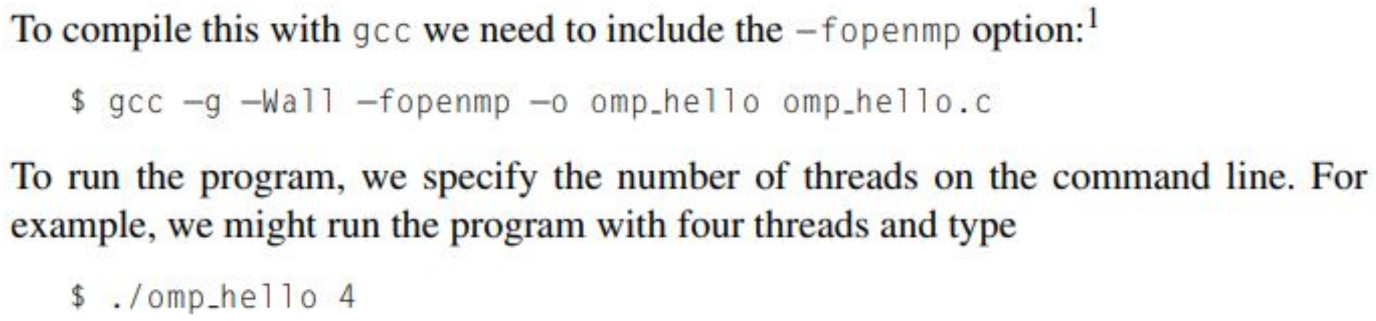
Discussion points

- Hello world program, compile, run
- Synchronization
  - For mutual exclusion on shared data - critical, atomic, lock
  - For work coordination - barrier
  - Prevent data dependencies
- Scope of variables
- Sharing work among threads
- Thread safety
- Task Parallelism
- Cache coherence, false sharing (during architecture discussion)
- Non parallelizable algorithms (during algorithm design discussion)

Hello World

```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 */
```

Compiling and running

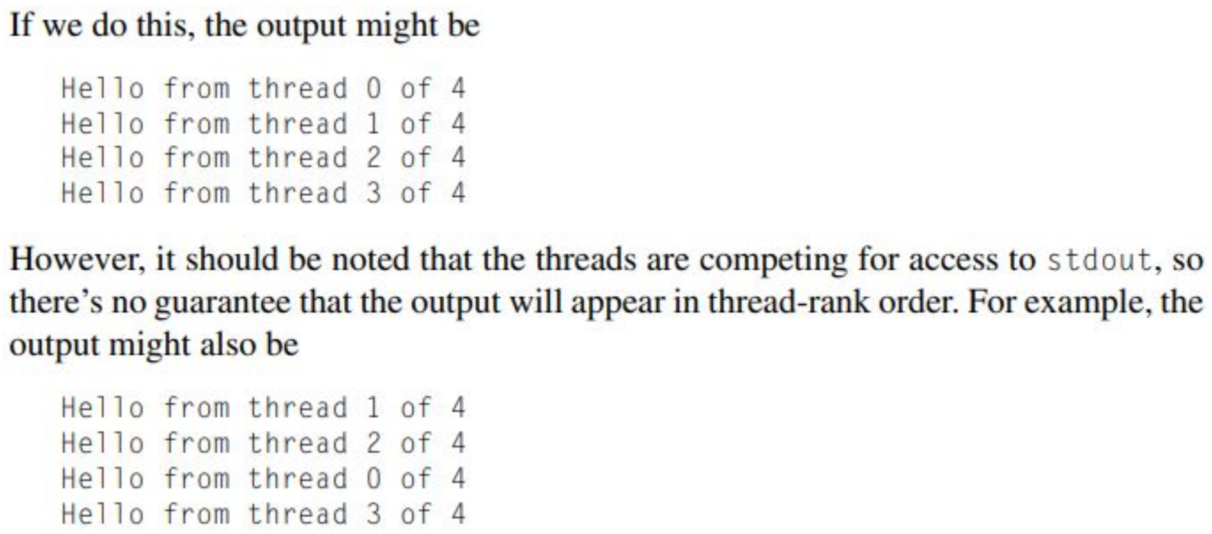


To compile this with `gcc` we need to include the `−fopenmp` option:[1]

```
$ gcc −g −Wall −fopenmp −o omp_hello omp_hello.c
```

To run the program, we specify the number of threads on the command line. For example, we might run the program with four threads and type

```
$ ./omp_hello 4
```



If we do this, the output might be

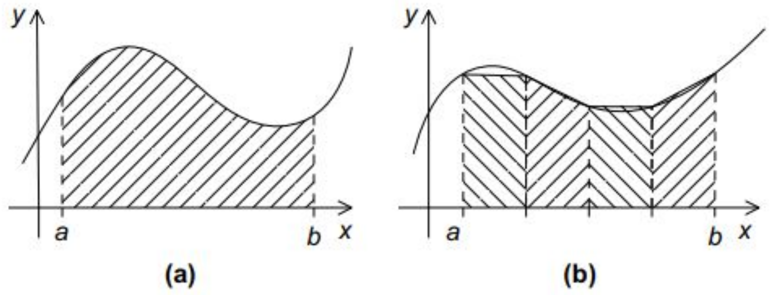
```
Hello from thread 0 of 4
Hello from thread 1 of 4
Hello from thread 2 of 4
Hello from thread 3 of 4
```

However, it should be noted that the threads are competing for access to `stdout`, so there’s no guarantee that the output will appear in thread-rank order. For example, the output might also be

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

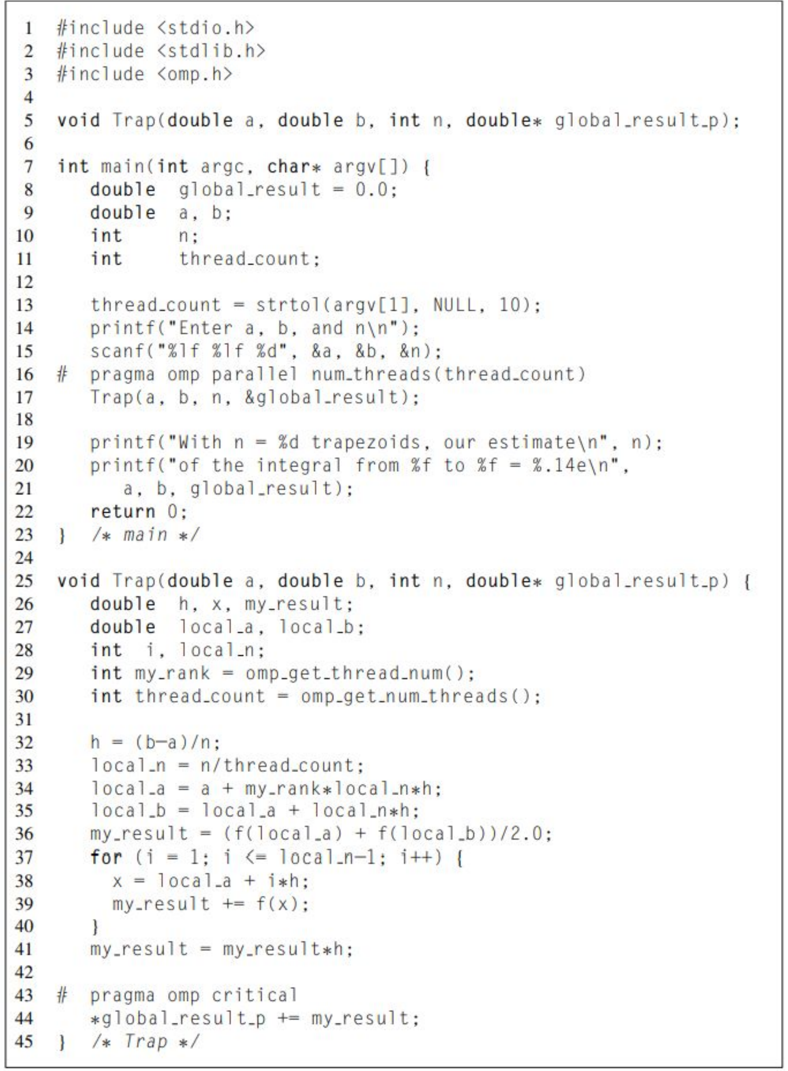
Race condition example: Trapezoidal rule example

```
/* 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;
```



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

Critical directive



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

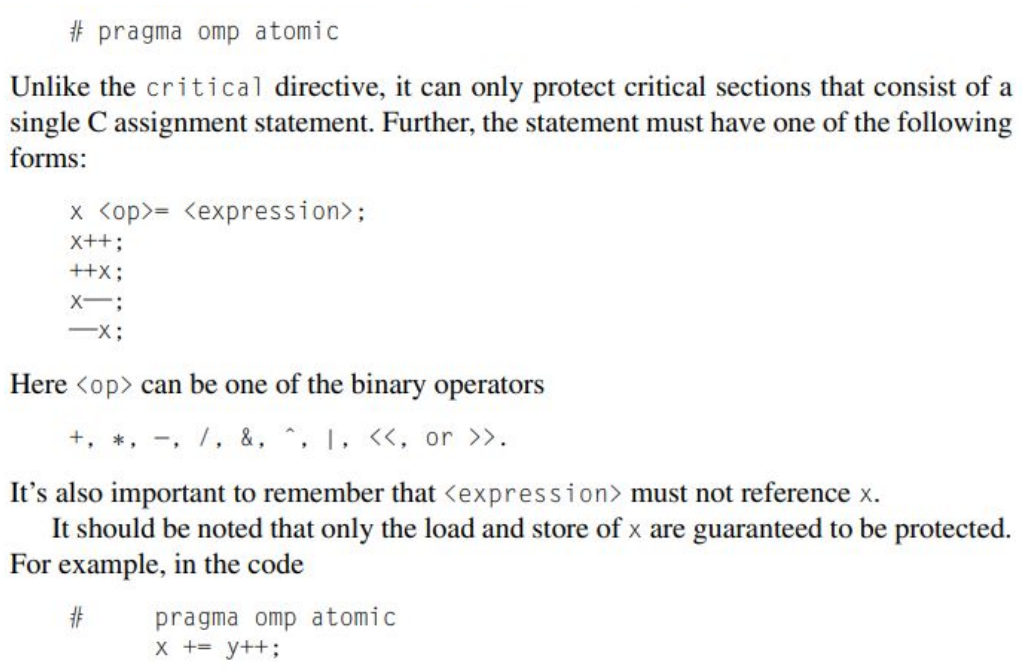
   printf("With n = %d trapezoids, our estimate\n", n);
   printf("of the integral from %f to %f = %.14e\n",
      a, b, global_result);
   return 0;
}  /* main */

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 */
```

Atomic directive



```
# pragma omp atomic
```

Unlike the `critical` directive, it can only protect critical sections that consist of a single C assignment statement. Further, the statement must have one of the following forms:

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

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

```
+, *, −, /, &, ^, |, <<, or >>.
```

It's also important to remember that `<expression>` must not reference `x`.

It should be noted that only the load and store of `x` are guaranteed to be protected. For example, in the code

```
#     pragma omp atomic
      x += y++;
```

The idea behind the atomic directive is that 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.

Fine grained synchronization: message queue example

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

while (!Done())
   Try_receive();
```

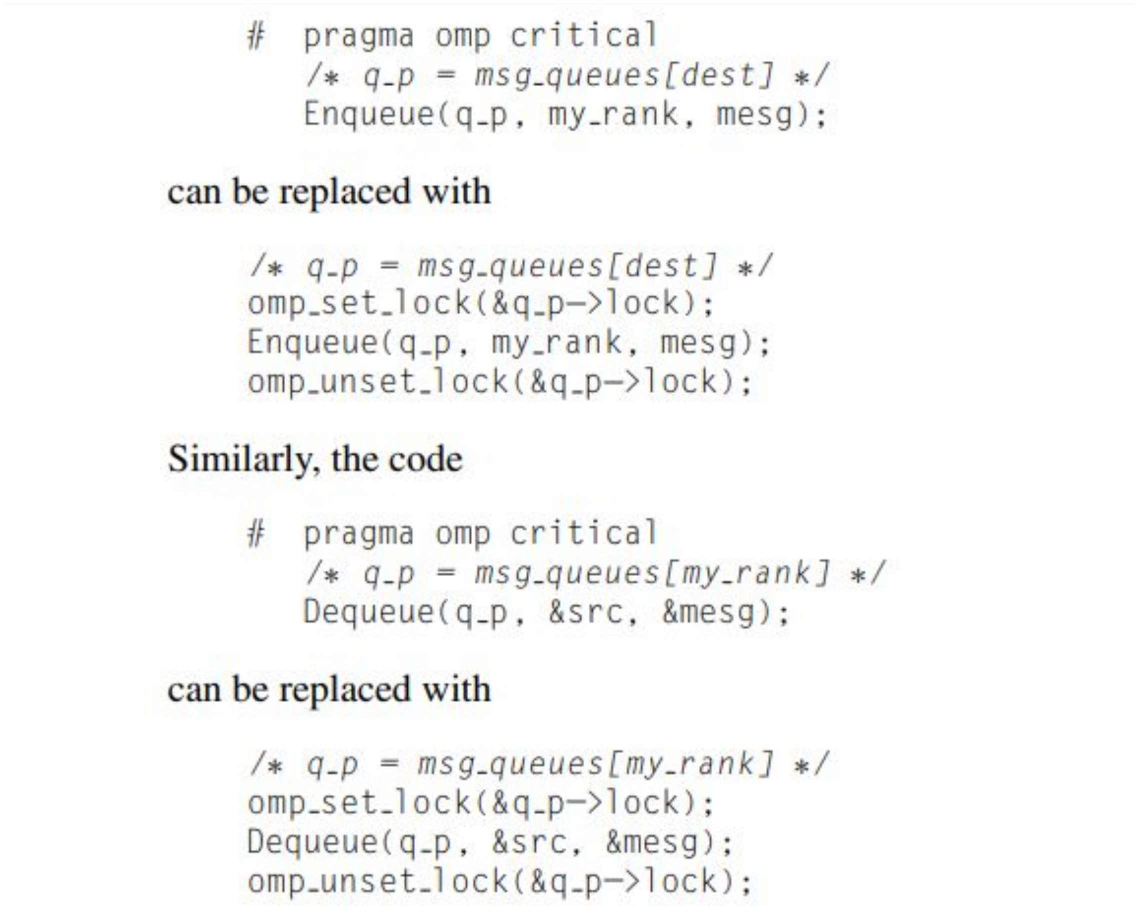
```
   mesg = random();
   dest = random() % thread_count;
#  pragma omp critical
   Enqueue(queue, dest, my_rank, mesg);
```

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

```
queue_size = enqueued - dequeued;
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);
```

Lock primitive



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

can be replaced with

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

Similarly, the code

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

can be replaced with

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

Synchronization caveats

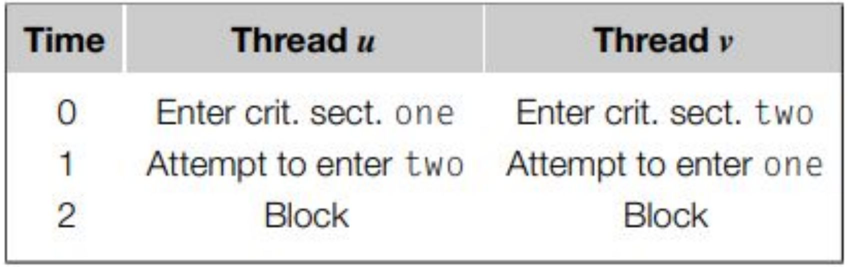
- Mixing different synchronization primitives

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

- Issue of fairness

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

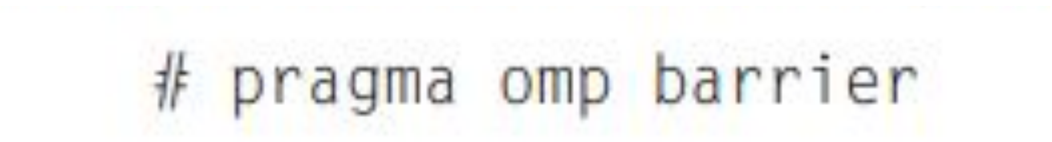
- Issue of deadlock, especially if threads enter different critical sections in different orders



Time	Thread *u*	Thread *v*
0	Enter crit. sect. one	Enter crit. sect. two
1	Attempt to enter two	Attempt to enter one
2	Block	Block

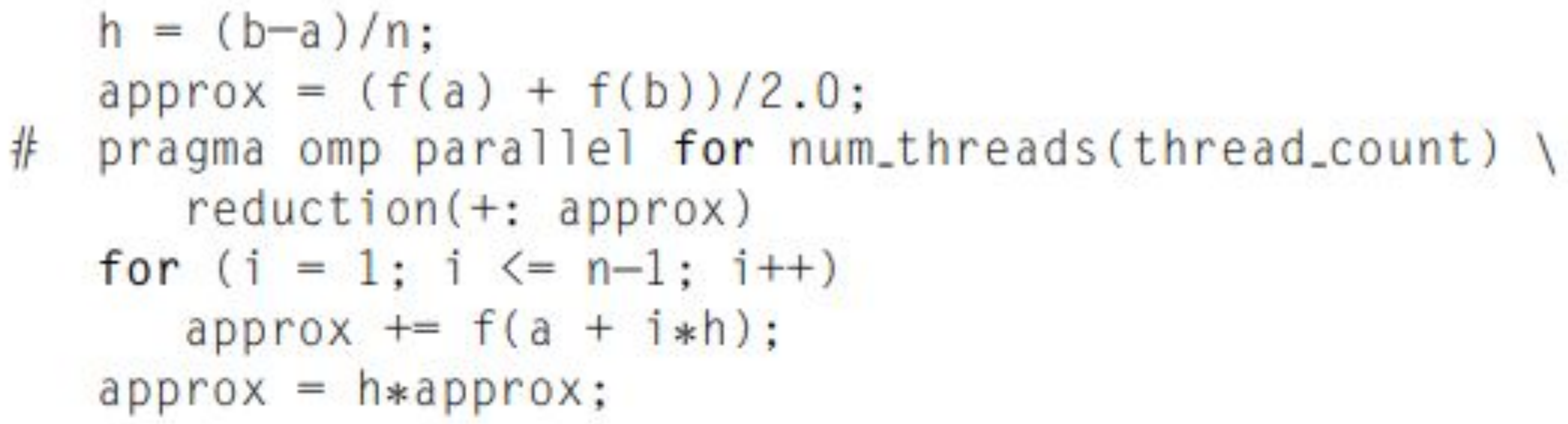
Work synchronization: Barrier primitive

- One or more threads might finish allocating their queues before some other threads
- If this happens, the threads that finish first could start trying to enqueue messages in a queue that hasn’t been allocated
- Program will crash
- In middle of parallel block, so implicit barriers will not work
- Use explicit barrier to make sure none of the threads start sending messages until all the queues are allocated.



```
# pragma omp barrier
```

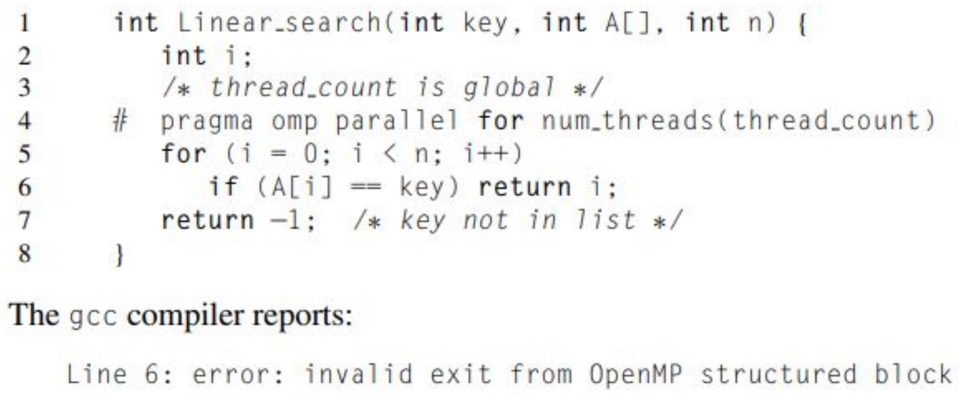
Parallel for



```
    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;
```

For loop restrictions

- Only loops for which the number of iterations can be determined . from the for statement itself and prior to execution of the loop.
- 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.
- 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.



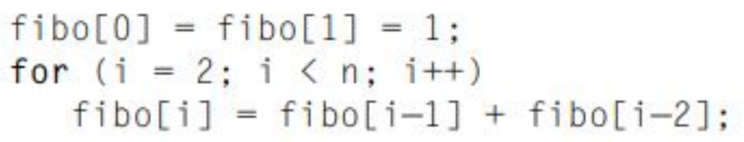
```
1     int Linear_search(int key, int A[], int n) {
2        int i;
3        /* thread_count is global */
4     #  pragma omp parallel for num_threads(thread_count)
5        for (i = 0; i < n; i++)
6           if (A[i] == key) return i;
7        return -1;  /* key not in list */
8     }
```

The gcc compiler reports:

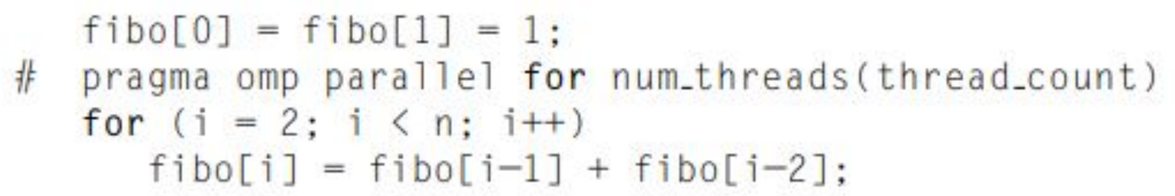
```
Line 6: error: invalid exit from OpenMP structured block
```

Loop carried dependencies

- OpenMP compilers don’t check for dependences among iterations in a loop that’s being parallelized with a parallel for directive. It’s up to us, the programmers, to identify these dependencies.
- A loop in which the results of one or more iterations depend on other iterations cannot, in general, be correctly parallelized by OpenMP.
- Example: 1 1 2 3 5 8 13 21 34 55 or 1 1 2 3 5 8 0 0 0 0 can both be output from parallelizing the Fibonacci for loop

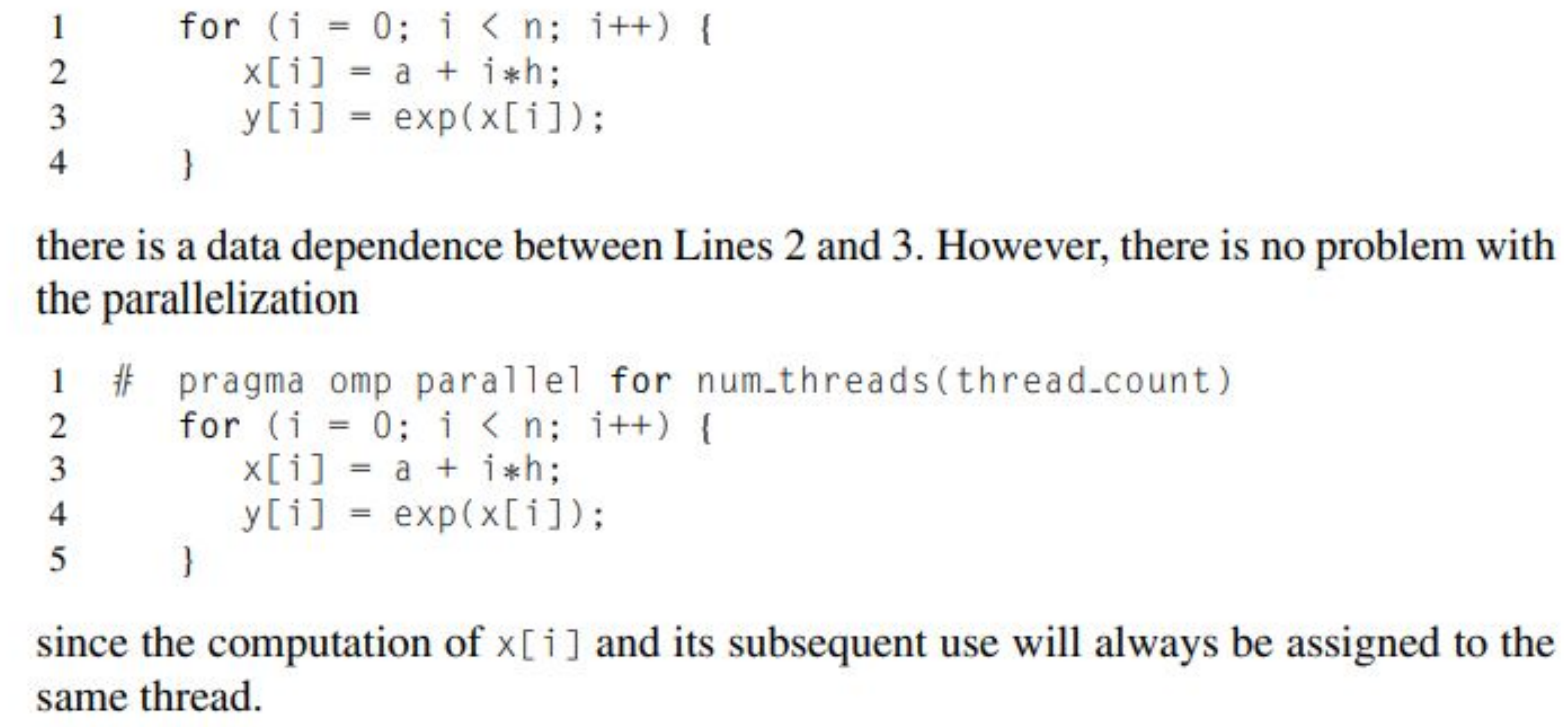


```
fibo[0] = fibo[1] = 1;
for (i = 2; i < n; i++)
   fibo[i] = fibo[i-1] + fibo[i-2];
```



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

General data dependencies are fine



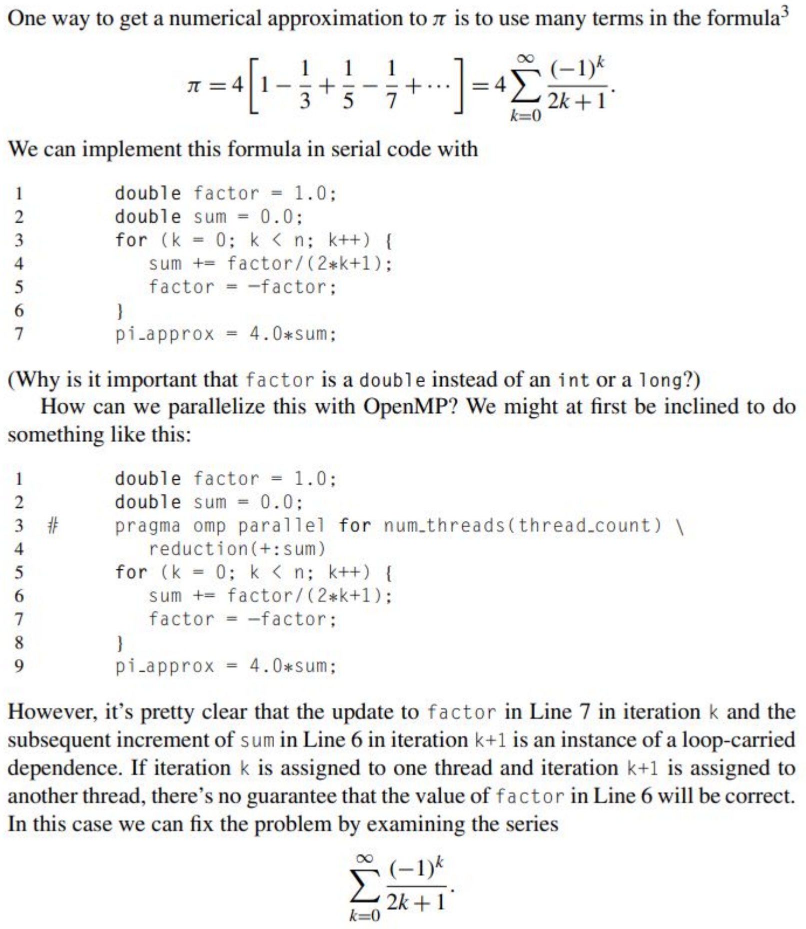
```
1     for (i = 0; i < n; i++) {
2        x[i] = a + i*h;
3        y[i] = exp(x[i]);
4     }
```

there is a data dependence between Lines 2 and 3. However, there is no problem with the parallelization

```
#  pragma omp parallel for num_threads(thread_count)
   for (i = 0; i < n; i++) {
      x[i] = a + i*h;
      y[i] = exp(x[i]);
   }
```

since the computation of `x[i]` and its subsequent use will always be assigned to the same thread.

Dealing with loop carried dependencies



One way to get a numerical approximation to π is to use many terms in the formula[3]

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

We can implement this formula in serial code with

```
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;
```

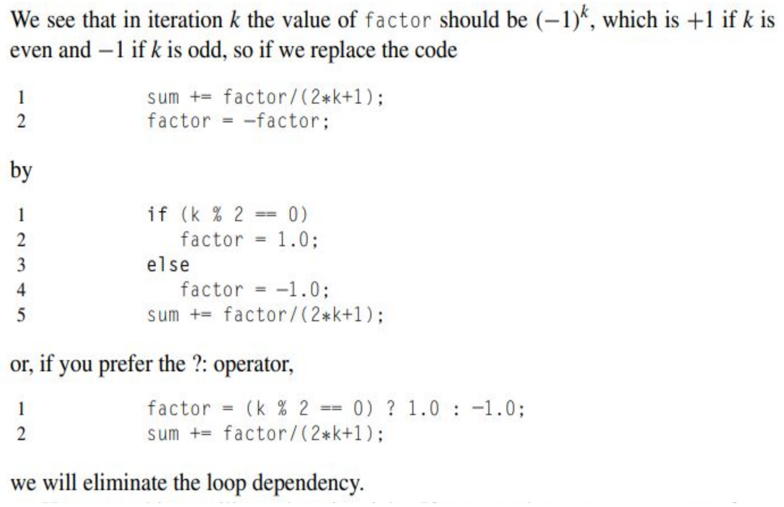
(Why is it important that `factor` is a `double` instead of an `int` or a `long`?)

How can we parallelize this with OpenMP? We might at first be inclined to do something like this:

```
1        double factor = 1.0;
2        double sum = 0.0;
3  #     pragma omp parallel for num_threads(thread_count) \
4           reduction(+:sum)
5        for (k = 0; k < n; k++) {
6           sum += factor/(2*k+1);
7           factor = -factor;
8        }
9        pi_approx = 4.0*sum;
```

However, it's pretty clear that the update to `factor` in Line 7 in iteration `k` and the subsequent increment of `sum` in Line 6 in iteration `k+1` is an instance of a loop-carried dependence. If iteration `k` is assigned to one thread and iteration `k+1` is assigned to another thread, there's no guarantee that the value of `factor` in Line 6 will be correct. In this case we can fix the problem by examining the series

$$\sum_{k=0}^{\infty}\frac{(-1)^k}{2k+1}.$$



We see that in iteration k the value of `factor` should be $(-1)^k$, which is $+1$ if k is even and -1 if k is odd, so if we replace the code

```
sum += factor/(2*k+1);
factor = -factor;
```

by

```
if (k % 2 == 0)
   factor = 1.0;
else
   factor = -1.0;
sum += factor/(2*k+1);
```

or, if you prefer the ?: operator,

```
factor = (k % 2 == 0) ? 1.0 : -1.0;
sum += factor/(2*k+1);
```

we will eliminate the loop dependency.

Discussion points

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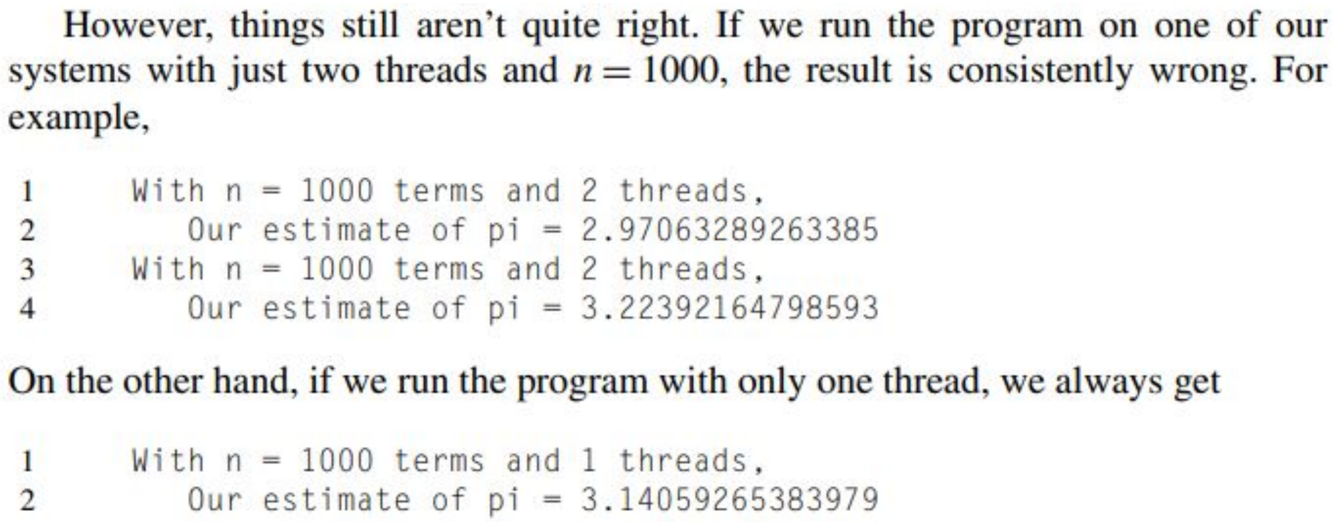
Scope of variables



However, things still aren't quite right. If we run the program on one of our systems with just two threads and $n = 1000$, the result is consistently wrong. For example,

```
With n = 1000 terms and 2 threads,
   Our estimate of pi = 2.97063289263385
With n = 1000 terms and 2 threads,
   Our estimate of pi = 3.22392164798593
```

On the other hand, if we run the program with only one thread, we always get

```
With n = 1000 terms and 1 threads,
   Our estimate of pi = 3.14059265383979
```

Use default(none) and private for correctness

```
      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);
      }
```

Reduction clause

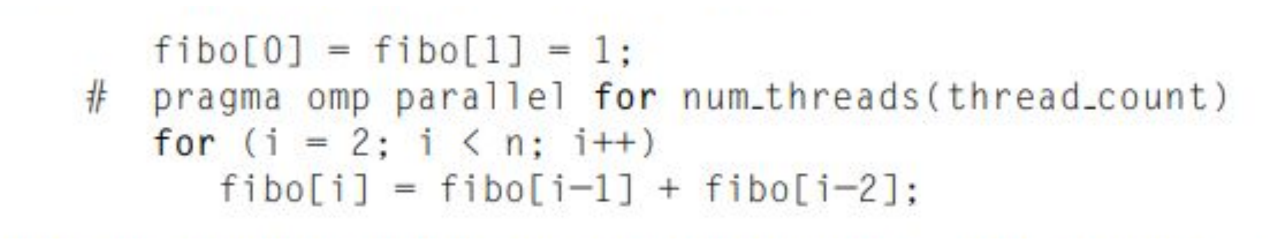
```
   global_result = 0.0;
#  pragma omp parallel num_threads(thread_count)
   {
#     pragma omp critical
      global_result += Local_trap(double a, double b, int n);
   }
```

```
   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;
   }
```

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

How is work divided among threads?

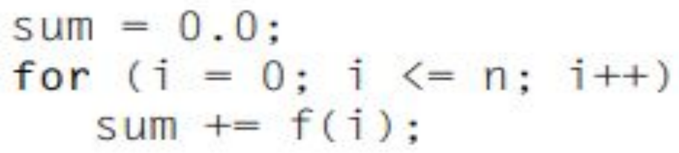
Most OpenMP implementations use roughly a block partitioning: if there are n iterations in the serial loop, then in the parallel loop the first n/thread count are assigned to thread 0, the next n/thread count are assigned to thread 1, and so on.



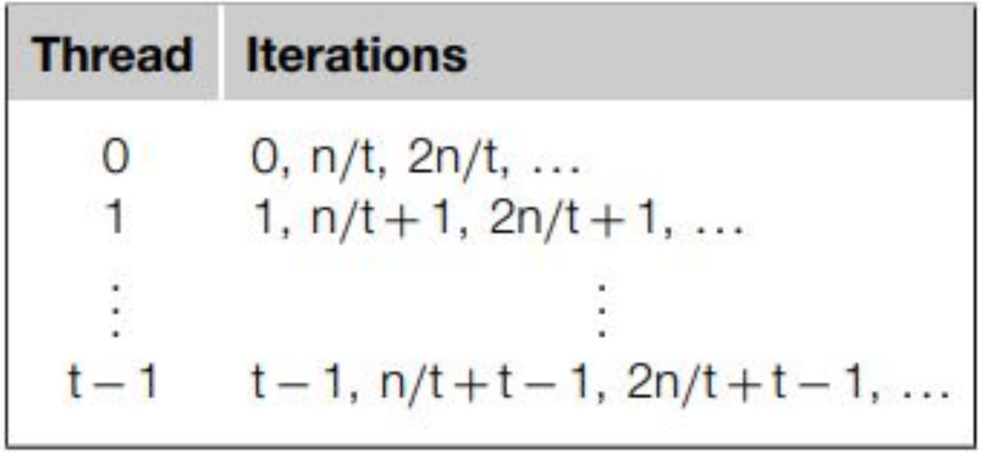
```
   fibo[0] = fibo[1] = 1;
#  pragma omp parallel for num_threads(thread_count)
   for (i = 2; i < n; i++)
      fibo[i] = fibo[i-1] + fibo[i-2];
```

In addition to correctness issues due to loop carried dependencies, there can be load balancing issues.

Load balancing issue



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



Thread	Iterations
0	0, n/t, 2n/t, ...
1	1, n/t+1, 2n/t+1, ...
⋮	⋮
t−1	t−1, n/t+t−1, 2n/t+t−1, ...

Schedule clause

Schedule clause has the form schedule(<type>[,<chunksize>])

- Type can be any one of the following:
  - **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, so after a thread completes its current set of iterations, it can request more from the run-time system.
  - **auto:** The compiler and/or the run-time system determine the schedule.
  - **runtime:** The schedule is determined at run-time.
- Chunksize is a positive integer.
  - A chunk of iterations is a block of iterations that would be executed consecutively in the serial loop. The number of iterations in the block is the chunksize.
  - Only static, dynamic, and guided schedules can have a chunksize. This determines the details of the schedule, but its exact interpretation depends on the type.

Static schedule with chunksizes 1, 2, 4

Thread 0:	0, 3, 6, 9
Thread 1:	1, 4, 7, 10
Thread 2:	2, 5, 8, 11

Thread 0:	0, 1, 6, 7
Thread 1:	2, 3, 8, 9
Thread 2:	4, 5, 10, 11

Thread 0:	0, 1, 2, 3
Thread 1:	4, 5, 6, 7
Thread 2:	8, 9, 10, 11

Guided schedule

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

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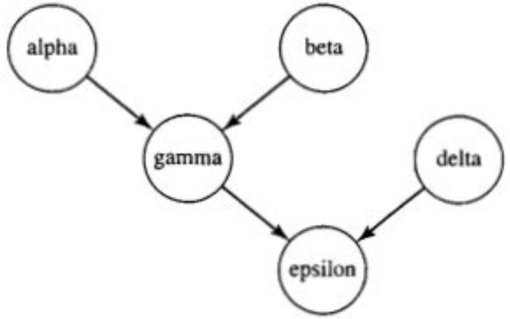
Task parallelism

```
v = alpha();
w = beta();
x = gamma(v, w);
y = delta();
printf ("%6.2f\n", epsilon(x,y));
```



Task parallelism

```
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printf ("%6.2f\n", epsilon(x,y));
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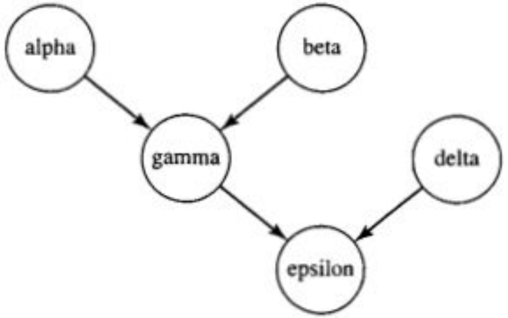

```
#pragma omp parallel sections
    {
#pragma omp section       /* This pragma optional */
       v = alpha();
#pragma omp section
       w = beta();
#pragma omp section
       y = delta();
    }
   x = gamma(v, w);
   printf ("%6.2f\n", epsilon(x,y));
```

```
#pragma omp parallel
   {
   #pragma omp sections
      {
      #pragma omp section      /* This pragma optional */
         v = alpha();
      #pragma omp section
         w = beta();
      }
   #pragma omp sections
      {
      #pragma omp section     /* This pragma optional */
         x = gamma(v, w);
      #pragma omp section
         y = delta();
      }
   }
   printf ("%6.2f\n", epsilon(x,y));
```

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- **Hello world program, compile, run**
- **Synchronization**
  - **For mutual exclusion on shared data - critical, atomic, lock**
  - **For work coordination - barrier**
  - **Prevent data dependencies**
- **Scope of variables**
- **Sharing work among threads**
- **Thread safety**
- **Task Parallelism**
- Cache coherence, false sharing (during architecture discussion)
- Non parallelizable algorithms (during algorithm design discussion)

Course outline (Pacheco; GGKK; Quinn)

- Motivation (1;1;1)
- How to quantify performance improvement (2.6; 5; 7)
- **Parallel hardware architecture (2.2-2.3; 2,4; 2)**
- Parallel programming frameworks
  - Pthreads for shared memory (4; 7; -)
  - OpenMP for shared memory (5; 7.10; 17)
  - MPI for distributed memory (3; 6; 4)
  - CUDA/OpenCL for GPU,
  - Hadoop/Spark/Mapreduce for distributed systems
- Parallel program verification
- Parallel algorithm design
- Some case studies