CME 213

SPRING 2019

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Homework 2

- Will be posted after class
- You can do most of the homework with your own computer, FarmShare, or the Google Compute Platform.
- See instructions in the homework assignment and on the class web page.

- Short demo of GCP

C++ threads, Pthreads

- Creating thread, thread join
- Mutex: locked/unlocked; used to protect access to shared variables; enforce order in read/write.
- Condition variables:
  - Used to allow threads to become idle and wake up when a condition becomes true.
  - `cond_wait`
  - `cond_signal`

OpenMP

Pthreads/OpenMP

- Pthreads gives you maximum flexibility.
- It's a low level API that allows you to implement pretty much any parallel computation exactly the way you want it.
- However, in many cases, the user only wants to parallelize certain common situations:
  - `For` loop: partition the loop into chunks and have each thread process one chunk.
  - Hand-off a block of code (computation) to a separate thread
- This is where OpenMP is useful. It simplifies the programming significantly.
- In some cases, adding **one line** in a C code is sufficient to make it run in parallel.
- As a result, OpenMP is the standard approach in scientific computing for multicore processors.

OpenMP

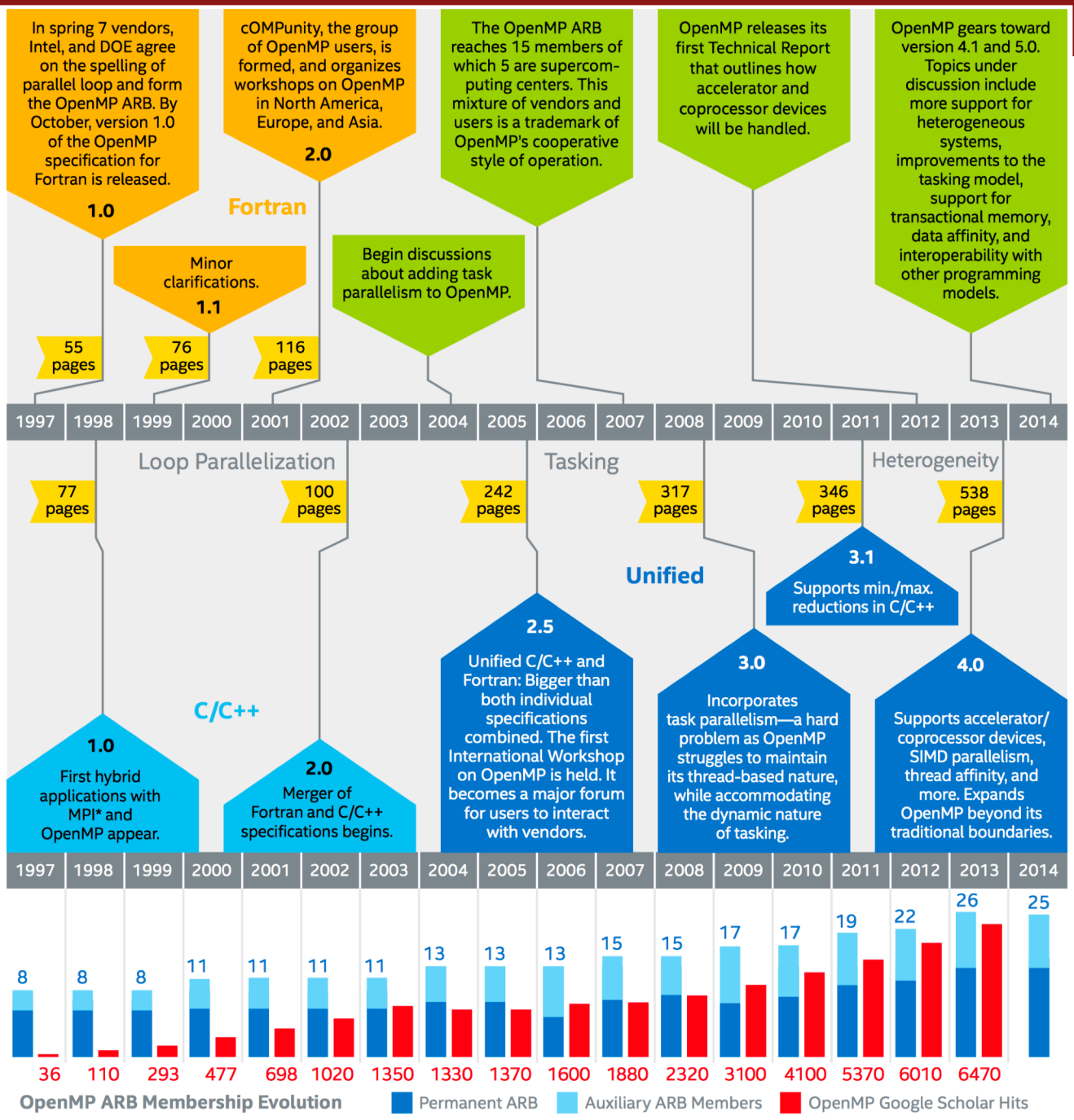
What is OpenMP?

- OpenMP is an Application Programming Interface (API), jointly defined by a group of major computer hardware and software vendors.
- OpenMP provides a portable, scalable model for developers of shared memory parallel applications.
- The API supports C/C++ and Fortran on a wide variety of architectures.

Hence, it is more portable and general than threads.

- OpenMP website: `openmp.org`
- Wikipedia: `en.wikipedia.org/wiki/OpenMP`
- LLNL tutorial `https://computing.llnl.gov/tutorials/openMP/`

- The Parallel Universe
- ARB: Architecture Review Board



Compiling your code

First things first

- Header file:

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

- This is only needed if you explicitly use the OpenMP API.

- Compiler flags:

Compiler	Flag
icc **icpc** **ifort**	**-openmp**
gcc **g++** **g77** **gfortran**	**-fopenmp**

Parallel regions

For loop

For loops

- This is the most basic construct in OpenMP.
- You will need to use it for Homework Assignment 2.
- Let's go through an example together.
- Download the files from the class web page and open

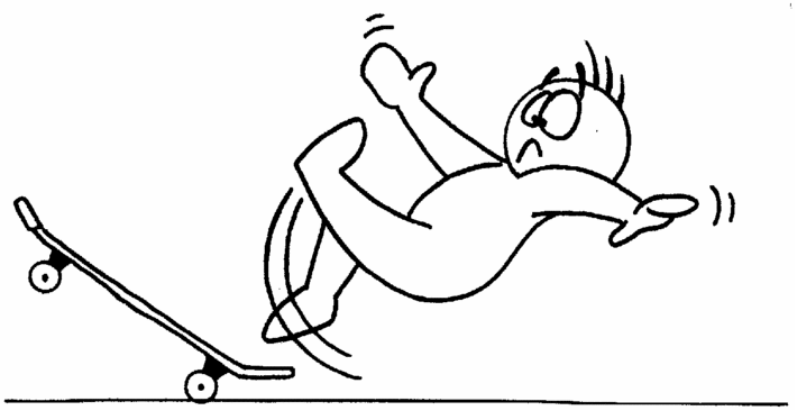
`for_loop.cpp`

- I will show you a demo on GCP.

```
#pragma omp parallel for
    for (int i = 0; i < n; ++i)
    {
        x[i] = i;
        y[i] = 2 * i;
    }

    print_vector(x);
    print_vector(y);

    /* todo: write your own omp parallel for loop here */

    print_vector(z);

    for (int i = 0; i < n; ++i)
        assert(z[i] == x[i] + y[i]);
    /* you must pass the test above if your for loop is correct. */
```

Directives

- OpenMP is based on directives.
- Powerful because of simple syntax.
- Dangerous because you may not understand exactly what the compiler is doing.

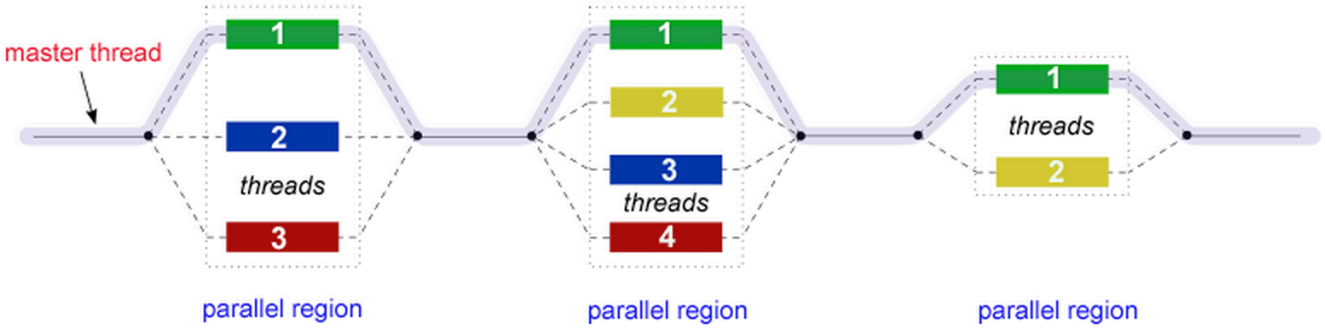


The most general concept: omp parallel region

The most basic directive is

```
#pragma omp parallel
{ // structured block ... }
```

This starts a new parallel region. OpenMP follows a fork-join model:



Upon entering a region, if there are no further directives, a team of threads is created and all threads execute the code in the parallel region.

Basic example

`hello_world_openmp.cpp`

Compilation:

```
g++ -o hello_world hello_world_openmp.cc -fopenmp
```

```
#pragma omp parallel
    {
        long tid = omp_get_thread_num();
        // Only thread 0 does this
        if (tid == 0)
        {
            int n_threads = omp_get_num_threads();
            printf("Number of threads = %d\n", n_threads);
        }
        // Print the thread ID
        printf("Hello World from thread = %ld\n", tid);
        // Compute some of the digits of pi
        DoWork(tid);
    } // All threads join master thread and terminate
```

3. 14159265358979323846264338327950288419716939937510582097494459
23078164062862089986280348253421170679821480865132823066470938
44609550582231725359408128481117450284102701938521105559644
62294895493038196442881097566593344612847564823378678316 52
71201909145648566923460348610454326648213393607260249 14127
37245870066063155881748815209209628292540917153643678 92590
36001133053054882046652138414695194151160943305727036 57595
91953092186117381932611793105118548074462379962749567351885 75
27248912279381830119491298336733624406566430860213949463952 24
73719070217986094370277053921717629317675238467481846766940513
20005681271452635608277857713427577896091736371787214684409012
24953430146549585371050792279689258923542019956112129021960864
03441815981362977477130996051870721134999999837297804995105973
17328160963185950245945534690830264252230825334465035261931 1
88171010003137838752886587533208381420617177669147303598253490
42875546873115956286388235378759375195778185778053217122680661
30019278766111959092164201989380952572010654858632788659361533
81827968230301952035301852968995773622599413891249721775283479
13151557485724245415069595082953311686172785588907509838175463
74649393192550604009277016711390098488240128583616035637076601
04710181942955596198946767837449448255379774726847104047534646
20804668425906949129331367702898915210475216205696602405803 81
50193511253382430035587640247496473263914199272604269922 79678
23547816360093417216412199245863150302861829745557067498385 05
49458858692699569092721079750930295532116534498720275596023 64
80665499119881834797753566369807426542527862551818417 5746728
90977772793800081647060016145249192173217214772350141441973 5
68548161361157352552133475741849468438523323907394143334547 7
62416862518983569485562099219222184272550254256887671790494 60
16534668049886272327917860857843838279679766814541009538837863
60950680064225125205117392984896084128488626945604241965285022 2
10661186306744278622039194945047123713786960956364371917287467 7

Pi algorithm

In our code, Pi is computed using:

$$\frac{\pi}{2} = 1 + \frac{1}{3}\left(1 + \frac{2}{5}\left(1 + \frac{3}{7}\left(1 + \frac{4}{9}\left(1 + \cdots\right)\right)\right)\right)$$

Using this expansion, can you show that the code computes the digits of Pi, 4 at a time, assuming that:

```
carry + sum / SCALE < 10,000
```

- Is the previous algorithm parallel?
- Is this a good multicore implementation?
- How would you improve it?

- Computing pi in parallel is difficult.
- Many algorithms use sequential calculations using high-precisions arithmetic, that is you compute using numbers with a lot of digits.
- This leads to the natural question:

Is it possible to compute the
n-th digit of π independently from the
others?

Bailey–Borwein–Plouffe formula

$$\pi = \sum_{k=0}^{\infty} \frac{1}{16^k} \left(\frac{4}{8k+1} - \frac{2}{8k+4} - \frac{1}{8k+5} - \frac{1}{8k+6} \right)$$

Computing the *n*-th bit

This problem can now be reformulated as:
Can we compute the fractional part of

$$16^n \pi$$

Take:

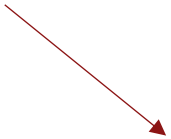
$$\sum_{k=0}^{\infty} \frac{16^{n-k}}{8k+1} = \sum_{k=0}^{n} \frac{16^{n-k}}{8k+1} + \sum_{k=n+1}^{\infty} \frac{16^{n-k}}{8k+1}$$

Only a few terms are needed

whole numbers can be removed

Computing the first sum

$$\sum_{k=0}^{n} \frac{16^{n-k}}{8k+1}$$



$$\sum_{k=0}^{n} \frac{16^{n-k} \bmod (8k+1)}{8k+1}$$

This can be easily computed

Clause

- This is one of the tricky points of OpenMP.
- Recall in Pthreads that:
  - Variables passed as argument to a thread are **shared** (they might be pointers in a `struct` for example)
  - Variables inside the function that a thread is executing are **private** to the thread.
- OpenMP needs a similar mechanism: some variables are going to be shared (all threads can read and write), others need to be private.
- There are “complicated” rules to figure out whether a variable is private or shared.

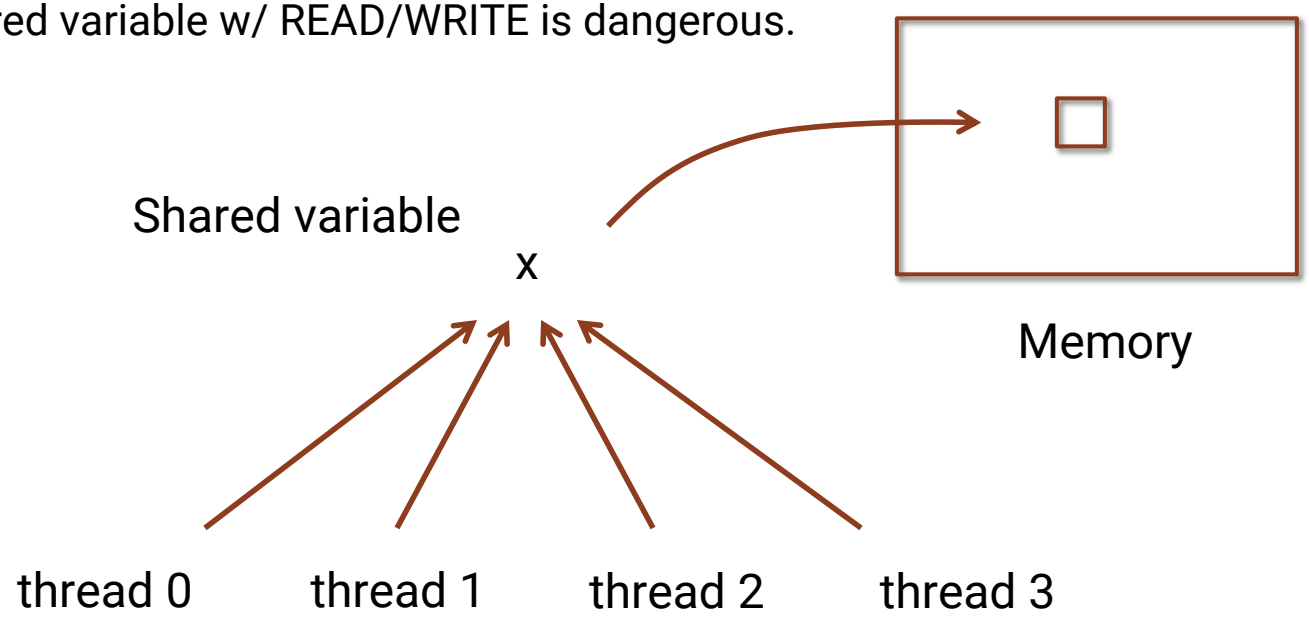
Shared/private

- See `shared_private_openmp.cpp`
- In a `parallel` construct, variables defined outside are shared by default.
- You can declare explicitly whether a variable is shared or private using

```
private(variable_name)
shared(variable_name)
```

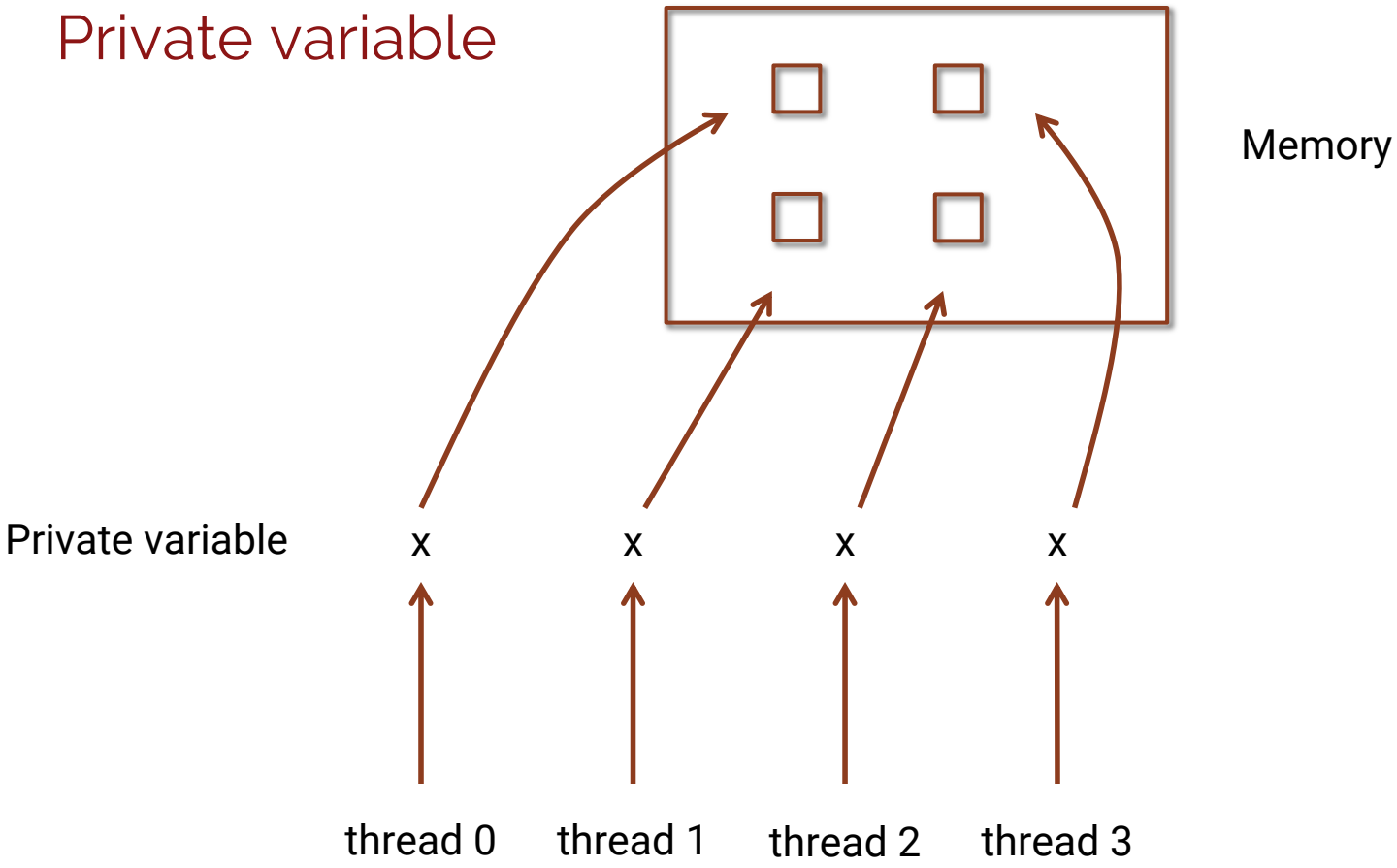
Shared variable

- Those are typically READ ONLY.
- Using a shared variable w/ READ/WRITE is dangerous.



Variable refers to the same memory location for all threads.

Private variable



Variable refers to a different memory location for each thread. Those variables are typically READ/WRITE.

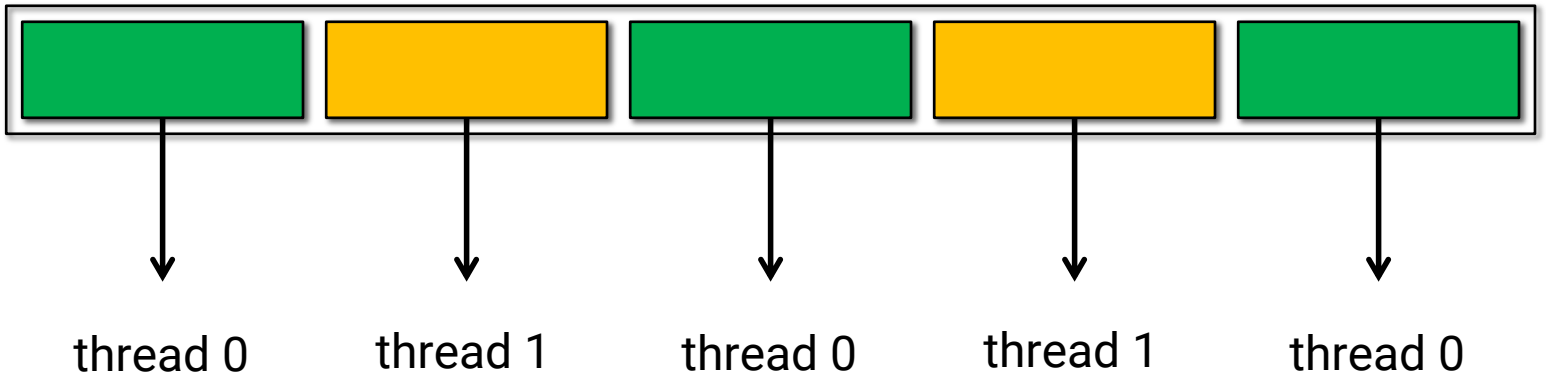
Worksharing constructs

Parallel for loop

The most common approach to parallelize a computation on a multicore processor is to parallelize a `for` loop.

OpenMP has some special constructs to do that.

```
#pragma omp for [clause [clause] ... ]
   for (i = lower bound; i op upper bound; incr expr) {
   ...
}
```



Example

- Let's consider again the matrix-matrix example we used for Pthreads.
- See `matrix_prod_openmp.cpp`
- One line of code is sufficient to parallelize the calculation! This is the power of OpenMP.

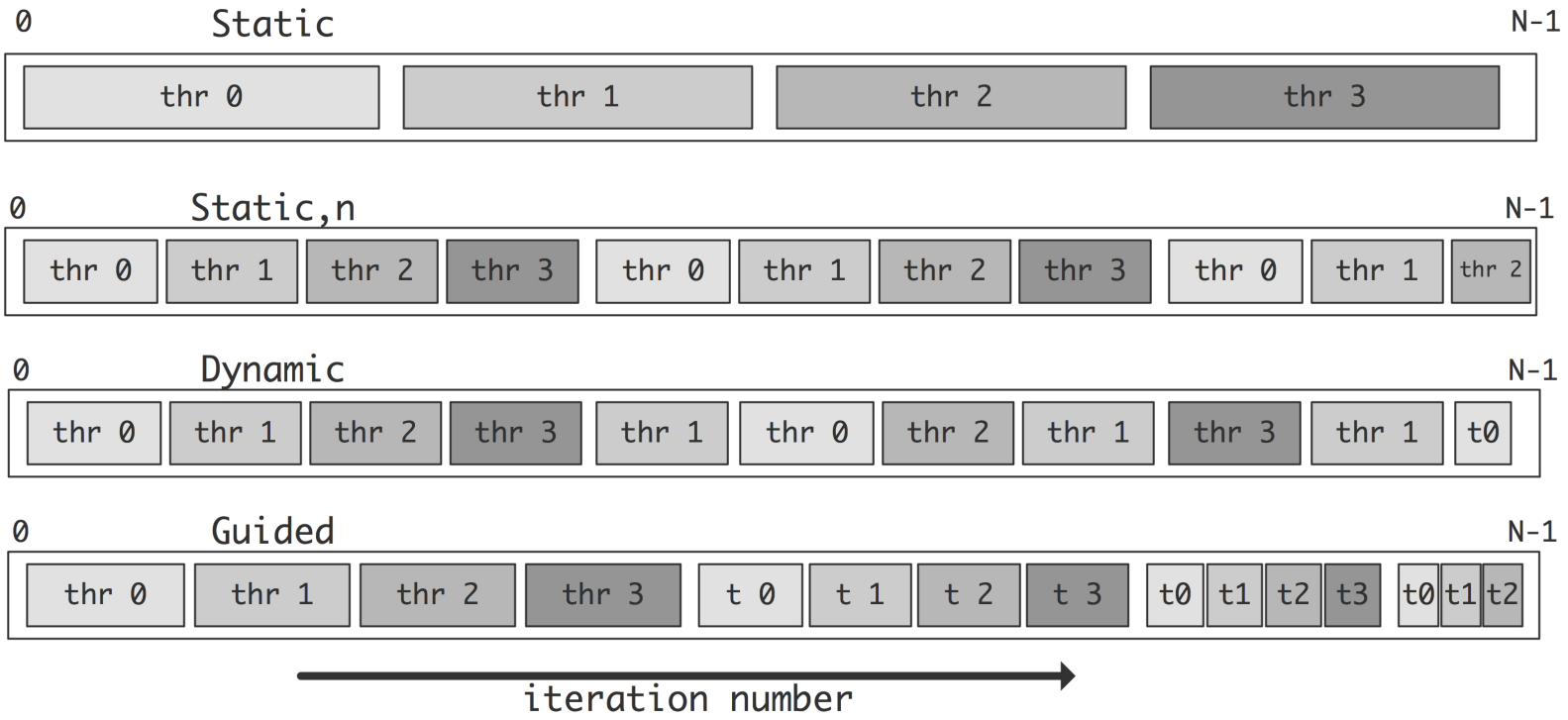
```
$ ./matrix_prod_openmp -n 4000 -p 16
$ top
```

```
#pragma omp parallel for
    for (int i = 0; i < size; ++i)
        for (int j = 0; j < size; ++j)
        {
            float c_ij = 0;
            for (int k = 0; k < size; ++k)
            {
                c_ij += MatA(i, k) * MatB(k, j);
            }
            mat_c[i * size + j] = c_ij;
        }
```

Scheduling for loops

- How are the iterates in a for loop split among threads? This is important to fine-tune the optimization of your code.
- This is a problem of load-balancing: how should we distribute the work so that we minimize the total execution time?

1. schedule(static, block_size): iterations are divided into pieces of size block_size and then statically assigned to threads. This is the best default option.
2. schedule(dynamic, block_size): iterations are divided into pieces of size block_size, and dynamically scheduled among the threads; when a thread finishes one chunk, it is dynamically assigned another. This is useful when the work per iteration is irregular.
3. schedule(guided, block_size): specifies a dynamic scheduling of blocks but with decreasing size. It is appropriate for the case in which the threads arrive at varying times at a for construct (with each iteration requiring about the same amount of work).


0
Static
N-1
thr 0
thr 1
thr 2
thr 3
0
Static,n
N-1
thr 0
thr 1
thr 2
thr 3
thr 0
thr 1
thr 2
thr 3
thr 0
thr 1
thr 2
0
Dynamic
N-1
thr 0
thr 1
thr 2
thr 3
thr 1
thr 0
thr 2
thr 1
thr 3
thr 1
t0
0
Guided
N-1
thr 0
thr 1
thr 2
thr 3
t 0
t 1
t 2
t 3
t0
t1
t2
t3
t0
t1
t2
iteration number

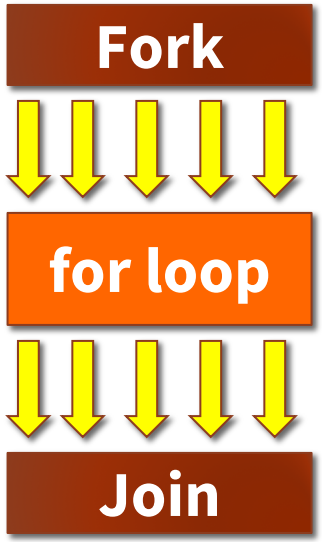
Other worksharing constructs: sections

- There are situations where two independent pieces of work can be executed concurrently. For example, we may need to update two vectors independently.
- In that case, we would like to assign one thread to do each operation in parallel.
- This can be done using sections.
- The compiler is allowed to schedule the execution of the code inside each section concurrently.

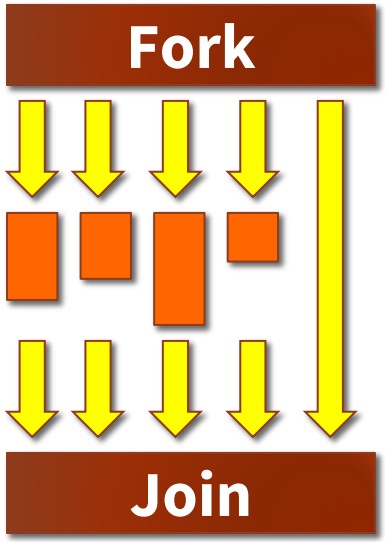
See `section.cpp`

```
#pragma omp parallel
    {
#pragma omp sections
        {
#pragma omp section
            for (unsigned i(0); i < size; i++)
                for (unsigned k(0); k < inner; k++)
                    c[i] += a[(i * k) % size];
#pragma omp section
            for (unsigned i(0); i < size; i++)
                for (unsigned k(0); k < inner; k++)
                    d[i] += a[(b[i] + i * k) % size];
        } // end of sections
    }     // end of parallel block
```

Summary



Large number of iterates.
Parallel for loop



Small and fixed number of independent tasks.
Parallel sections