OpenMP loops

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Outline

- Expressing parallelism
  - Understanding parallel threads
- Memory Data management
  - Data clauses
- Synchronization
  - Barriers, locks, critical sections
- Work partitioning
  - Loops, sections, single work, tasks…
- Execution devices
  - Target

What we saw so far..

- Threads
  - How to create and properly manage a team of threads
  - How to join them with barriers
- Memory
  - How to create private and shared ~~variables~~ storages
  - How to properly ensure memory consistency among parallel threads
- Data syncronization
  - How to create locks to implement, e.g., mutual exclusion
  - How to identify Critical Sections
  - How to ensure atomicity on single statements

Work sharing between threads

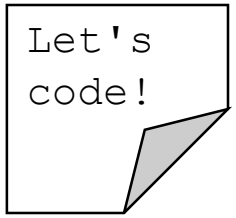
- But..how can we split an existing workload among parallel threads?
  - Say, a loop

- Typical $c€nario
  1. Analyze sequential code from customer/boss
  2. Parallelize it with OpenMP (for a "generic" parallel machine)
  3. Tune `num_threads` for specific machine
  4. Get money/congratulations from customer/boss

  - Might not be as easy as with PI Montecarlo!

How to do 2. without rewriting/re-engineering the code?

Exercise

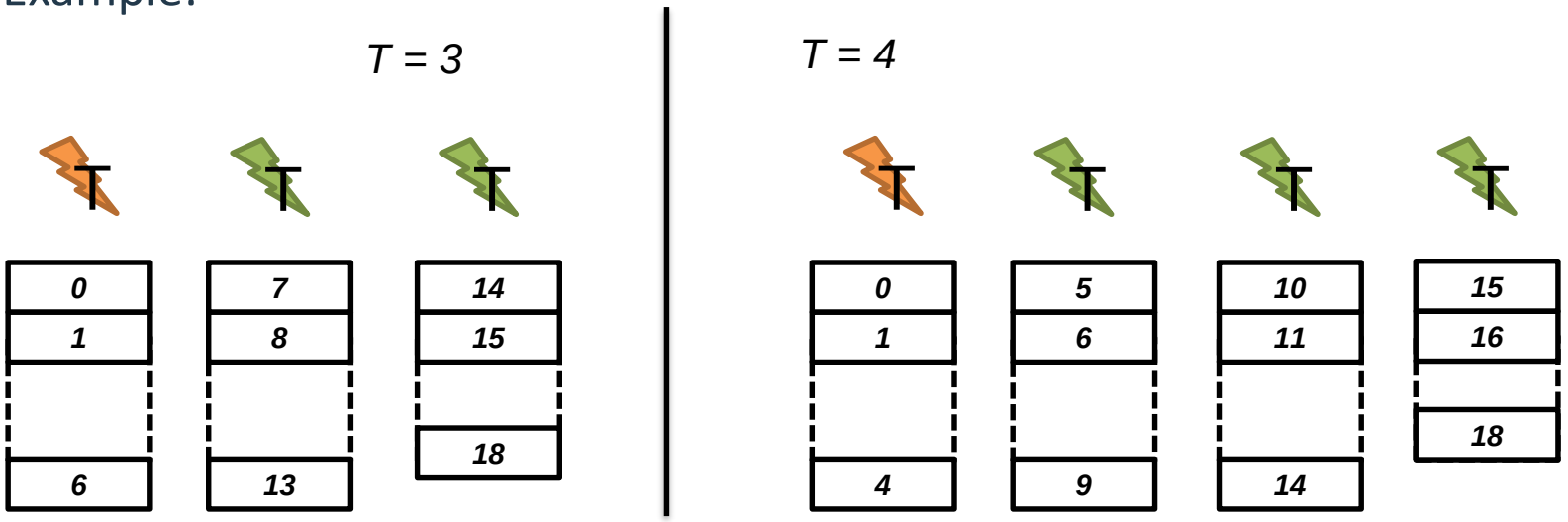


- Create an array of N elements
  - Put inside each array element its index, multiplied by '2'
  - `arr[0] = 0; arr[1] = 2; arr[2] = 4;` ...and so on

Exercise

Let's code!

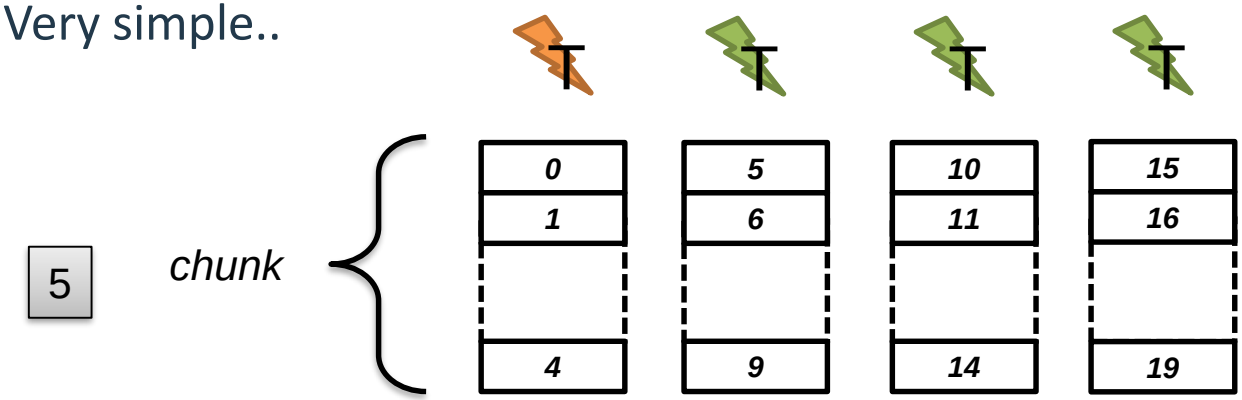
- Create an array of N elements
  - Put inside each array element its index, multiplied by '2'
  - `arr[0] = 0; arr[1] = 2; arr[2] = 4;` ...and so on
- Now, do it in parallel with a team of T threads
  - N = 19, T ≠ 19, N > T
  - Hint: Act on the boundaries of the loop
  - Hint #2: `omp_get_thread_num(), omp_get_num_threads()`
- Example:



Loop partitioning among threads

Let's code!

- Case #1: N multiple of T
  - Say, N = 20, T = 4
- chunk = #iterations for each thread
- Very simple..



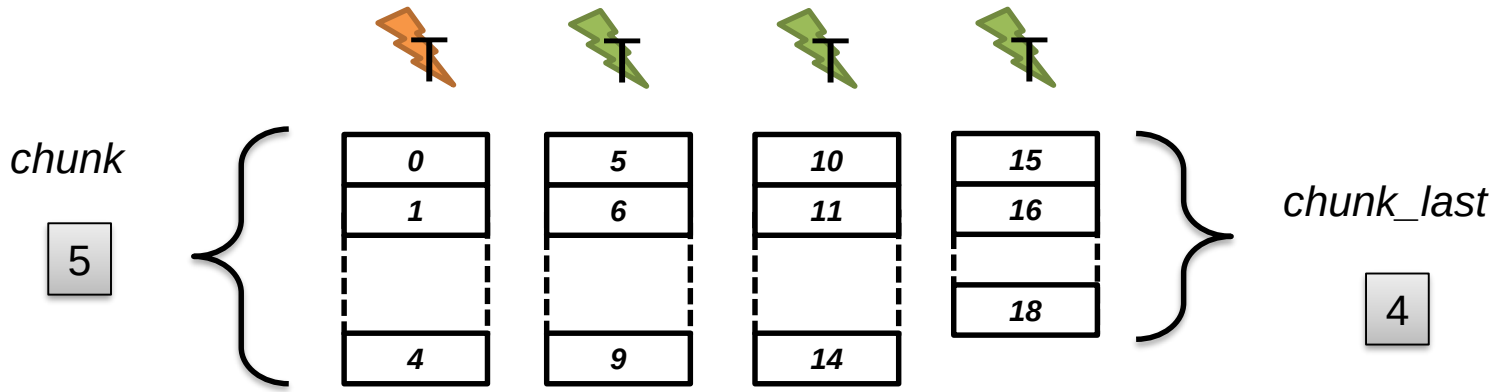
$$chunk = \frac{N}{T};$$

$$i_{start} = thread_{ID} * \ chunk; \qquad i_{end} = i_{start} + chunk + 1$$

Loop partitioning among threads

Let's code!

- Case #2: N not multiple of T
  - Say, N = 19, T = 4
- chunk = #iterations for each thread (but last)
  - Last thread has less! ($chunk_{last}$)



$$chunk = \frac{N}{T} + 1\,; \qquad chunk_{last} = N\ \%\ chunk$$

$$i_{start} = thread_{ID} * \ chunk; \qquad i_{end} = \begin{cases} i_{start} + chunk & if\ not\ last\ thread \\ i_{start} + chunk_{last} & if\ last\ thread \end{cases}$$

"Last thread"

- Unfortunately, we don't know which thread will be "last" in time
- But…we don't actually care the order in which iterations are executed
  - If there are not depenencies..
  - And..we do know that

0 <= `omp_get_thread_num()< omp_get_num_threads()`

- We choose that last thread as highest number

Let's put them together!

› Case #1 (*N* multiple of *T*)

$$chunk = \frac{N}{T} \qquad i_{start} = thread_{ID} * \ chunk; \qquad i_{end} = i_{start} + chunk$$

› Case #2 (*N* not multiple of *T*)

$$chunk = \frac{N}{T} + 1\ ; \qquad chunk_{last} = N\ \%\ chunk$$

$$i_{start} = thread_{ID} * \ chunk; \qquad i_{end} = \begin{cases} i_{start} + chunk & if\ not\ last\ thread \\ i_{start} + chunk_{last} & if\ last\ thread \end{cases}$$

Work sharing constructs

- A way to distribute work among parallel threads
  - In a simple, and "elegant" manner
  - Using pragmas
- OpenMP was born for this
  - OpeMP 2.5 targets regular, loop-based parallelism
- OpenMP 3.x targets irregular/dynamic parallelism
  - We will see it later

The `for` construct

```
#pragma omp for [clause [[,] clause]...] new-line
  for-loops
```

Where clauses can be:

```
private(list)
firstprivate(list)
lastprivate(list)
linear(list[ : linear-step])
reduction(reduction-identifier : list)
schedule([modifier [, modifier]:]kind[, chunk_size])
collapse(n)
ordered[(n)]
nowait
```

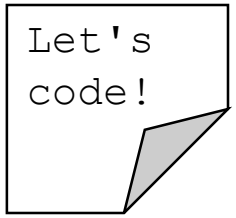
- The iterations will be executed in parallel by threads in the team
- The iterations are distributed across threads executing the parallel region to which the loop region binds
- for-loops must have Canonical loop form

Canonical loop form

```
for (init-expr; test-expr; incr-expr)
  structured-block
```

- `init-expr; test-expr; incr-expr` not void
- Eases programmers' life
  - More structured
  - Recommended also for "sequential programmers"
- Preferrable to `while` and `do..while`
  - If possible

Exercise



- Create an array of *N* elements
  - Put inside each array element its index, multiplied by '2'
  - `arr[0] = 0; arr[1] = 2; arr[2] = 4;` ...and so on..

- Now, do it in parallel with a team of *T* threads
  - Using the `for` construct

Data sharing clauses

```
#pragma omp for [clause [[,] clause]...] new-line
  for-loops
```

Where clauses can be:

```
private(list)
firstprivate(list)
lastprivate(list)
linear(list[ : linear-step])
reduction(reduction-identifier : list)
schedule([modifier [, modifier]:]kind[, chunk_size])
collapse(n)
ordered[(n)]
nowait
```

- `first/private, reduction` we already know…
  - Private storage, w/ or w/o initialization
- `linear`, we won't see

The `lastprivate` clause

- A list item that appears in a `lastprivate` clause is subject to the `private` clause semantics

- Also, the value is updated with the one from the sequentially last iteration of the associated loops

`lastprivate` variables and memory

› Create a new storage for the variables, local to threads, and initialize

```
int a = 11;


#pragma omp for        lastprivate(a) \
                       num_threads(4)
{

    a = ...

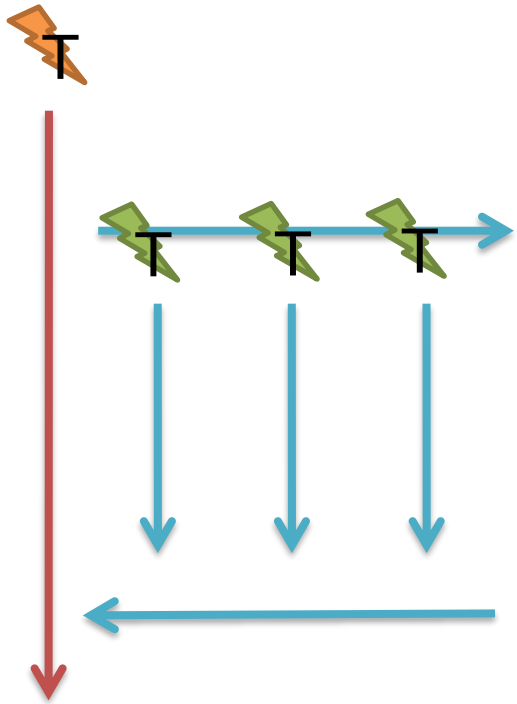








}
```



Process memory

`lastprivate` variables and memory

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}
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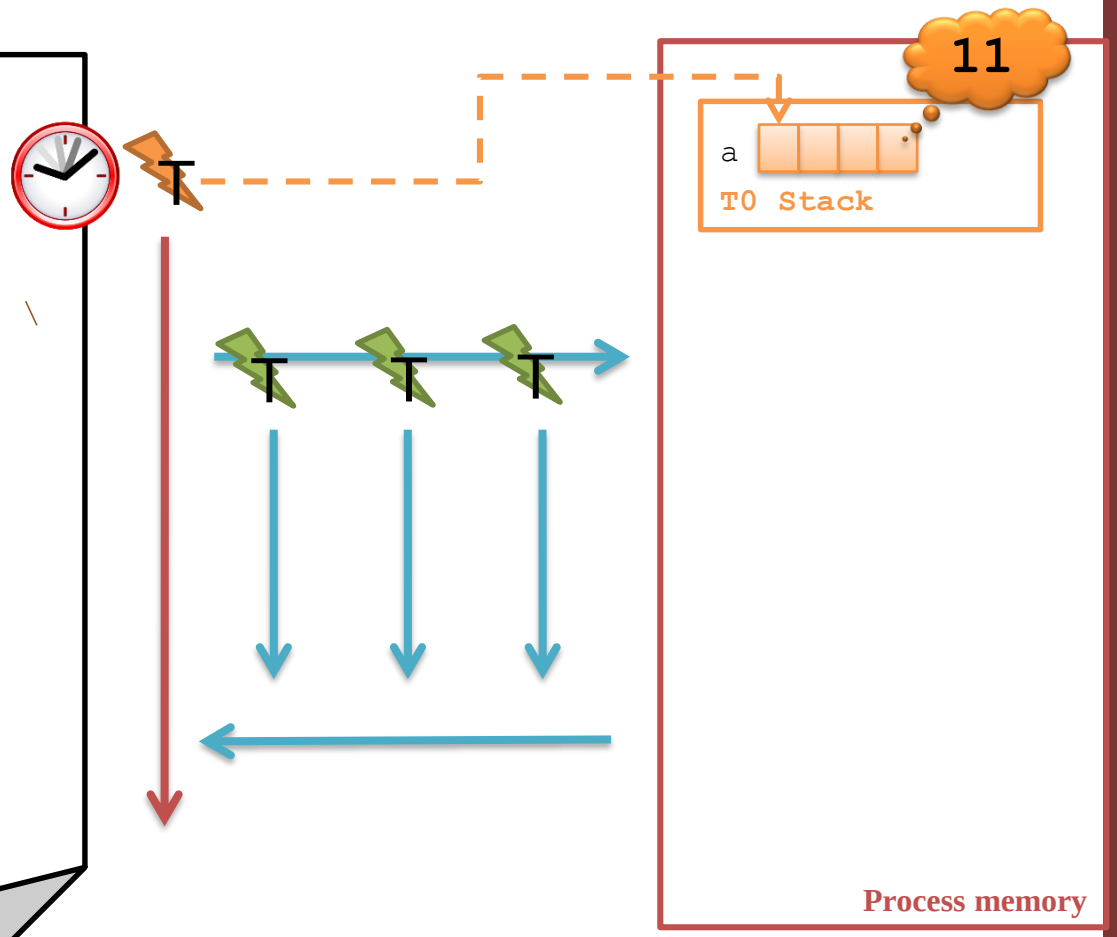

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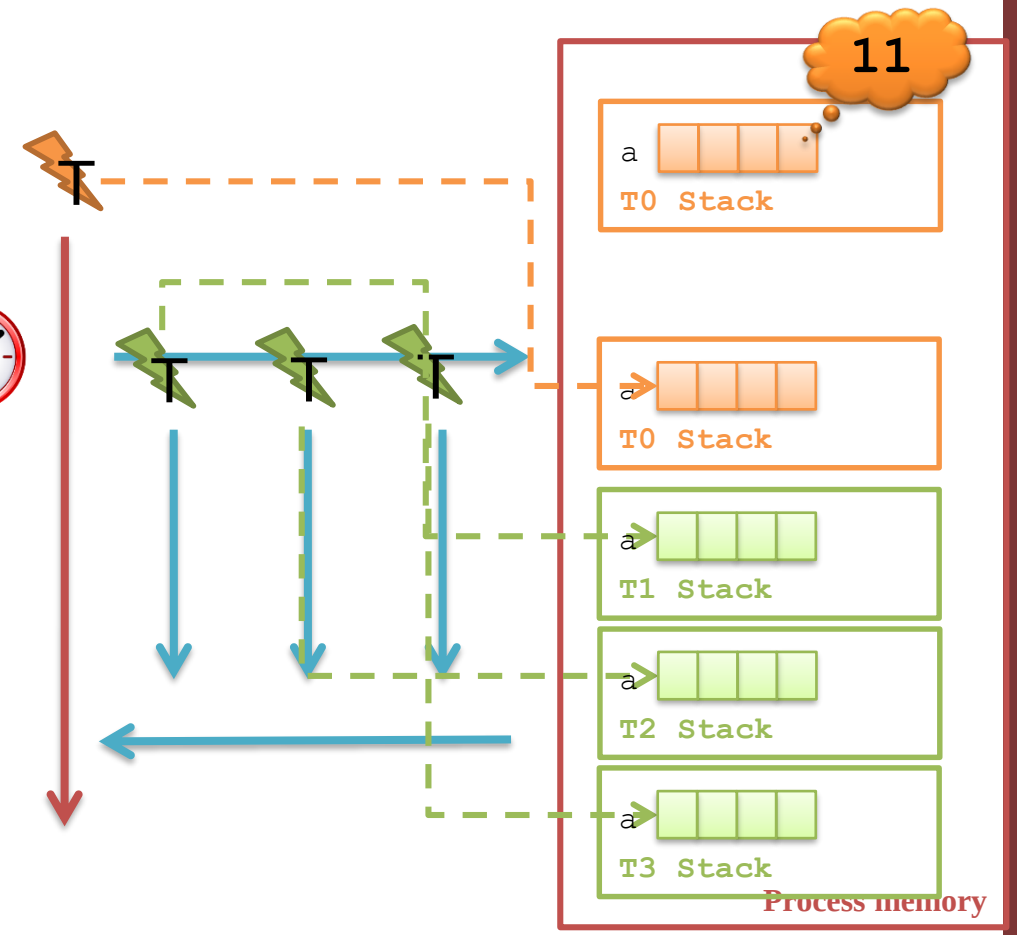

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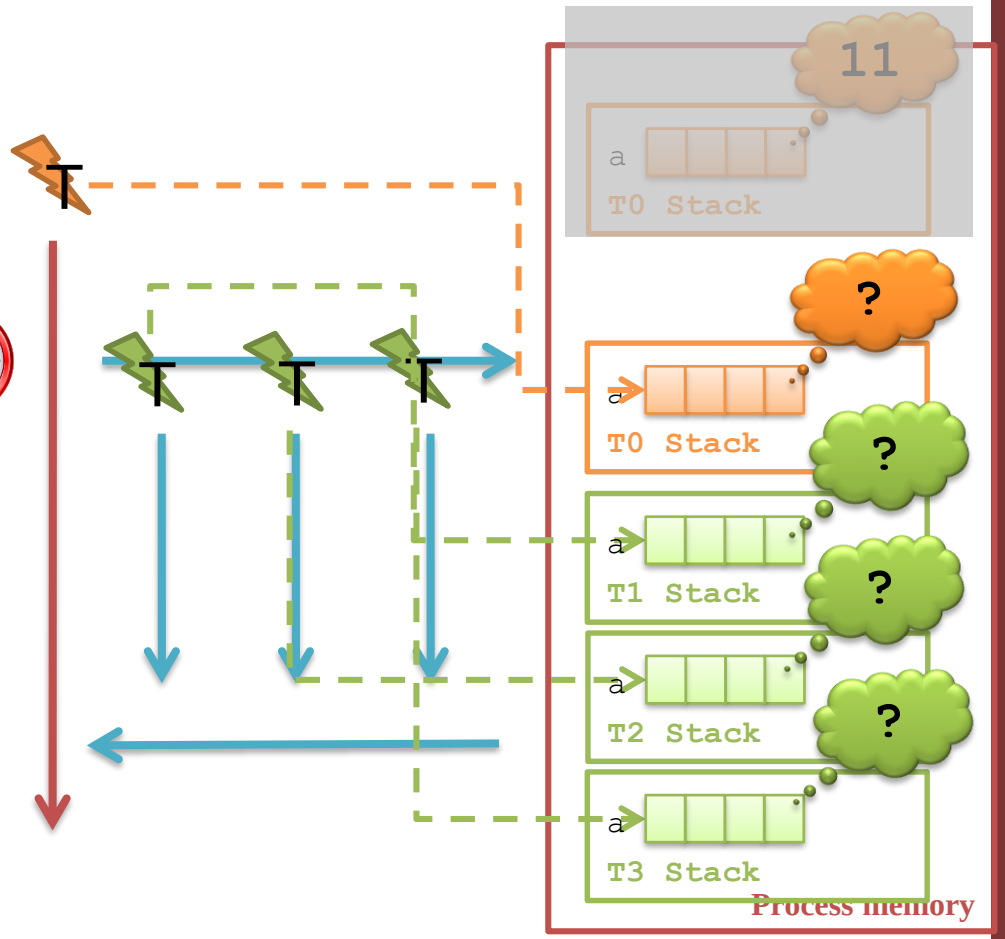

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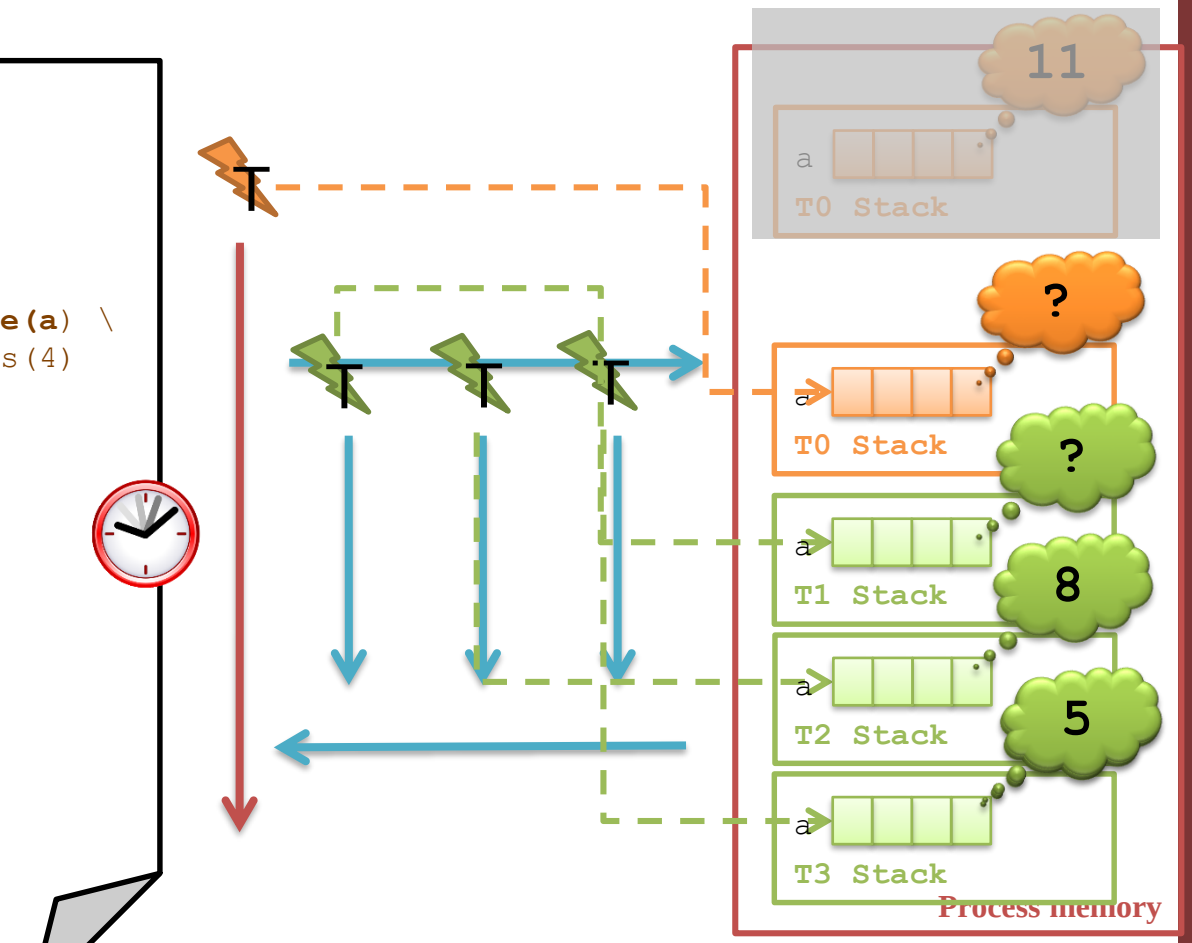
}
```



`lastprivate` variables and memory

› Create a new storage for the variables, local to threads, and initialize

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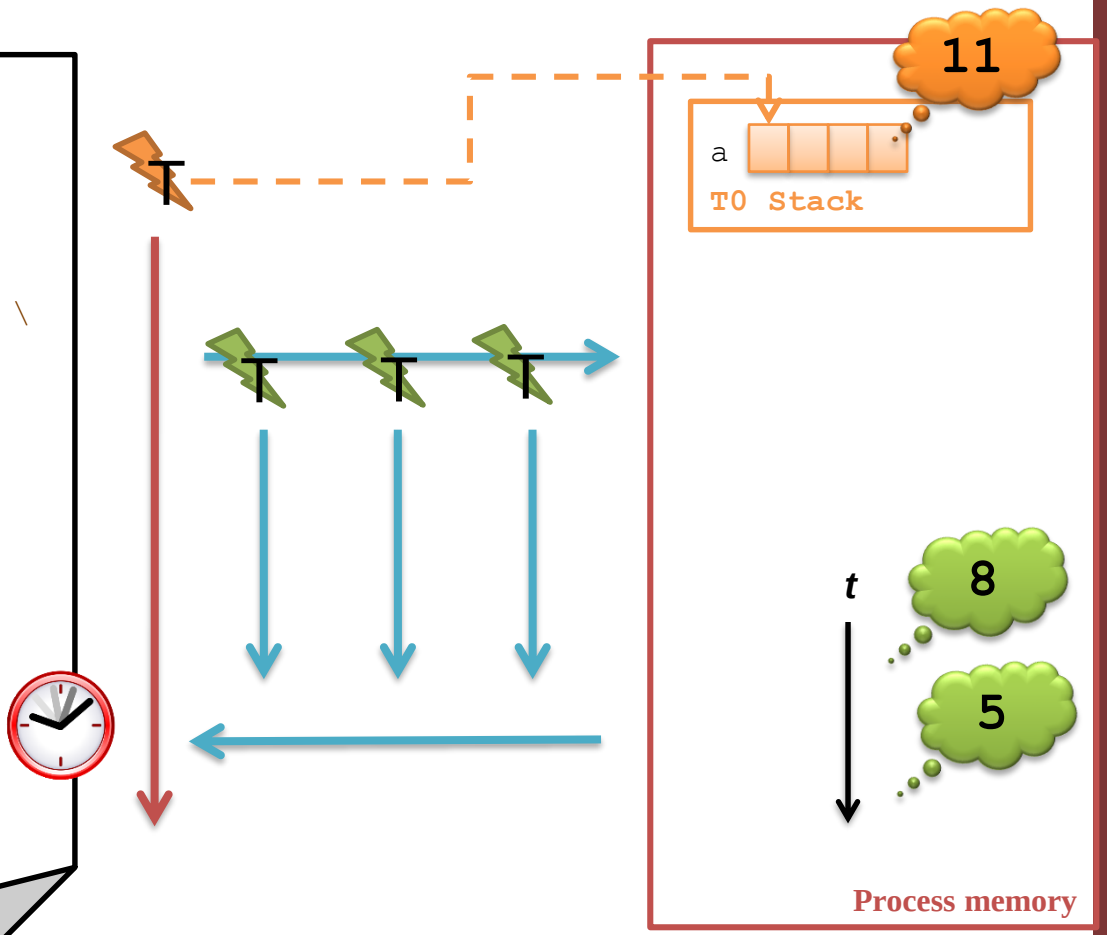

`lastprivate` variables and memory

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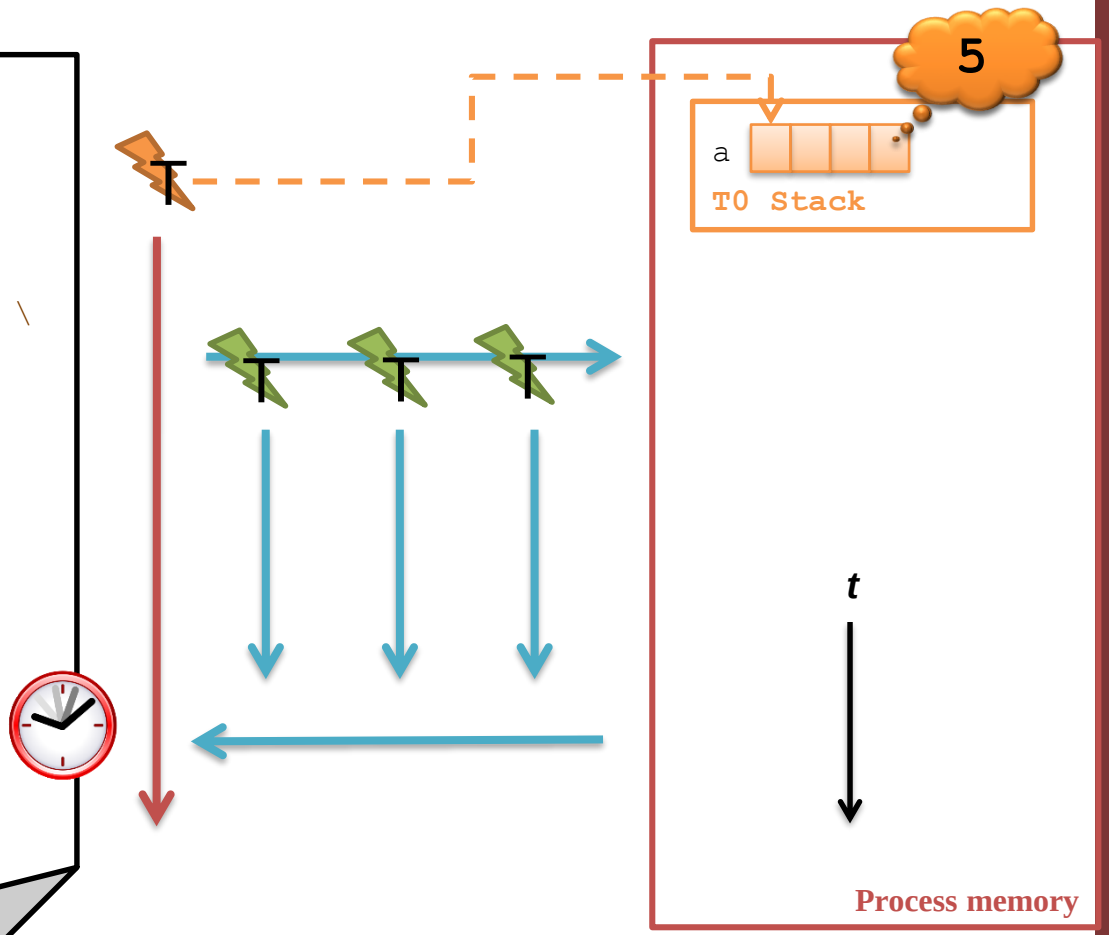
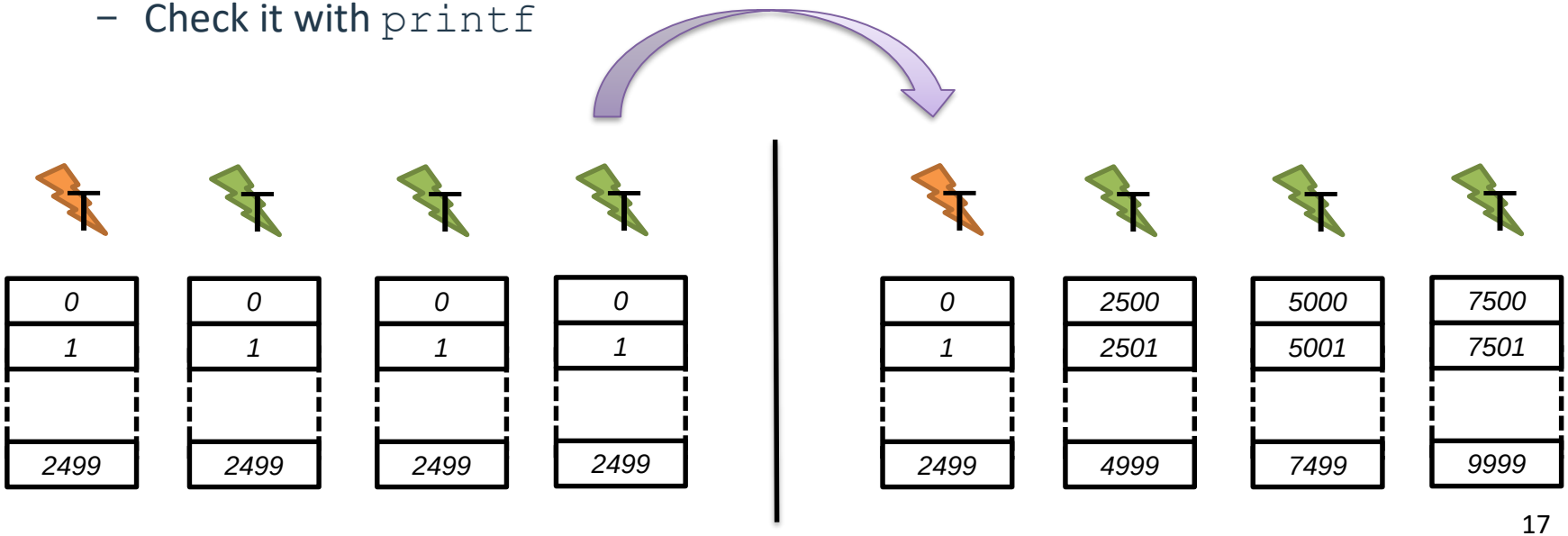


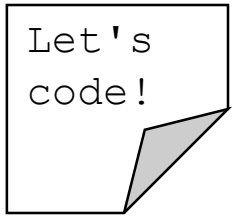
Exercise

Let's code!

- Modify the "PI Montecarlo" exercise
  - Use the `for` construct
- Up to now, each threads executes its "own" loop
  - `i` from 0 to 2499
- Using the `for` construct, they actually share the loop
  - No need to modify the boundary!!!
  - Check it with `printf`



Exercise



- Create an array of *N* elements
  - Put inside each array element its index, multiplied by '2'
  - `arr[0] = 0; arr[1] = 2; arr[2] = 4;` ...and so on..

- Declare the array as `lastprivate`
  - So you can print its value after the parreg, in the sequential zone
  - Do this at home

OpenMP 2.5

- OpenMP provides three work-sharing constructs
  - Loops
  - Single
  - Sections

The `single` construct

```
#pragma omp single [clause [[,] clause]...] new-line
  structured-block
```

Where clauses can be:

```
private(list)
firstprivate(list)
copyprivate(list)
nowait
```

- The enclosed block is executed by only one threads in the team
- ..and what about the other threads?

Worksharing constructs and barriers

- Each worksharing construct has an implicit barrier at its end
  - Example: a loop
  - If one thread is delayed, it prevents other threads to do useful work!!
  - Remember: barrier = consistent view of the sh memory

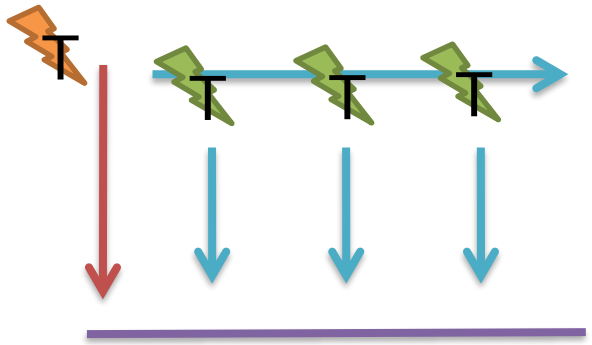
```
#pragma omp parallel num_threads(4)
{
  #pragma omp for
  for(int i=0; i<N; i++)
  {

    ...

  } // (implicit) barrier


  // USEFUL WORK!!

} // (implicit) barrier
```



Worksharing constructs and barriers

- Each worksharing construct has an implicit barrier at its end
  - Example: a loop
  - If one thread is delayed, it prevents other threads to do useful work!!
  - Remember: barrier = consistent view of the sh memory

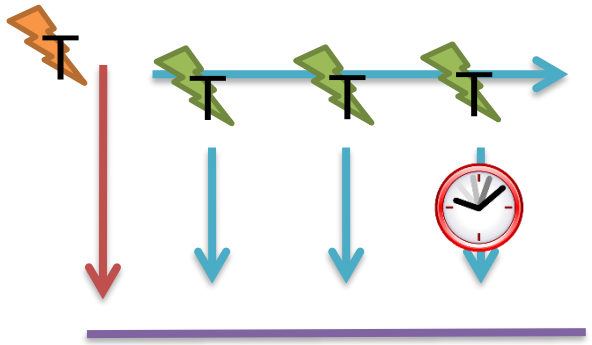
```
#pragma omp parallel num_threads(4)
{
  #pragma omp for
  for(int i=0; i<N; i++)
  {

    ...

  } // (implicit) barrier


  // USEFUL WORK!!

} // (implicit) barrier
```



Worksharing constructs and barriers

- Each worksharing construct has an implicit barrier at its end
  - Example: a loop
  - If one thread is delayed, it prevents other threads to do useful work!!
  - Remember: barrier = consistent view of the sh memory

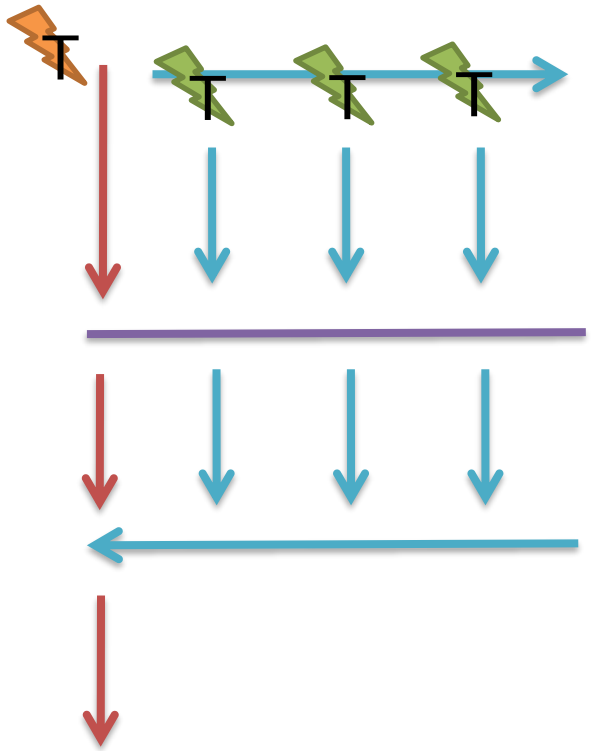
```
#pragma omp parallel num_threads(4)
{
  #pragma omp for
  for(int i=0; i<N; i++)
  {

    ...

  } // (implicit) barrier


  // USEFUL WORK!!

} // (implicit) barrier
```



Nowait clause in the for construct

```
#pragma omp for [clause [[,] clause]...] new-line
  for-loops
```

Where clauses can be:

```
private(list)
firstprivate(list)
lastprivate(list)
linear(list[ : linear-step])
reduction(reduction-identifier : list)
schedule([modifier [, modifier]:]kind[, chunk_size])
collapse(n)
ordered[(n)]
nowait
```

- The `nowait` clause removes the barrier at the end of a worksharing (WS) construct
  - Applies to all of WS constructs
  - Does not apply to parregs!

Worksharing constructs and barriers

- Removed the barrier at the end of WS construct
  - Still, there is a barrier at the end of parreg

```
#pragma omp parallel num_threads(4)

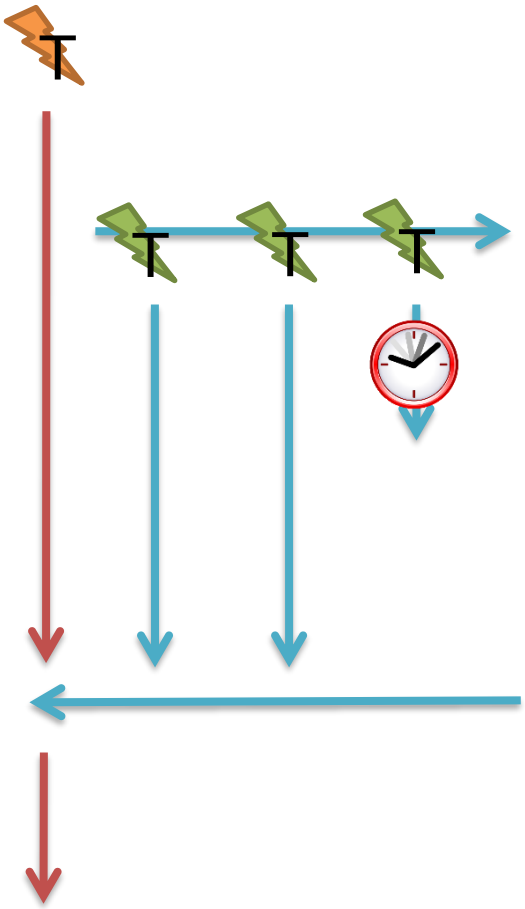
{
  #pragma omp for nowait
  for(int i=0; i<N; i++)
  {

    ...

  } // no barrier

  // USEFUL WORK!!


} // (implicit) barrier
```



The `sections` construct

```
#pragma omp sections [clause[ [,] clause] ... ] new-line
{
  [#pragma omp section new-line]
    structured-block
  [#pragma omp section new-line]
    structured-block
  ...
}
```

Where clauses can be:

```
private(list)
firstprivate(list)
lastprivate(list)
reduction(reduction-identifier : list)
nowait
```

- Each `section` contains code that is executed by a single thread
  - A "switch" for threads
- Clauses, we already know..
  - `lastprivate` items are updated by the `section` executing last (in time)

Sections vs. loops

- Loops implement data-parallel paradigm
  - Same work, on different data
  - Aka: data decomposition, SIMD, SPMD
- Sections implement task-based paradigm
  - Different work, on the same or different data
  - Aka: task decomposition, MPSD, MPMD

The `master` construct

```
#pragma omp master new-line
  structured-block
```

No clauses

- The structured block is executed only by master thread
  - "Similar" to the `single` construct

- It is not a work-sharing construct
  - There is no barrier implied!!

Combined parreg+ws

- For each WS construct, there is also a compact form
  - In this case, clauses to both constructs apply

```
#pragma omp parallel
{
  #pragma omp for
  for(int i=0; i<N; i++)
  {
    ...
  }
} // (implicit) barrier
```

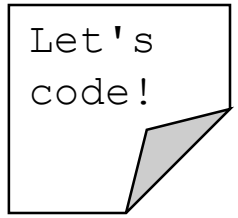
=

```
#pragma omp parallel
#pragma omp for
for(int i=0; i<N; i++)
{
  ...
} // (implicit) barrier
```

=

```
#pragma omp parallel for
for(int i=0; i<N; i++)
{
  ...
} // (implicit) barrier
```

How to run the examples



- Download the `Code/` folder from the course website

- Compile
- `$ gcc -fopenmp code.c -o code`

- Run (Unix/Linux)

```
$ ./code
```

- Run (Win/Cygwin)

```
$ ./code.exe
```

References

- "Calcolo parallelo" website
  - http://hipert.unimore.it/people/paolob/pub/Calcolo_Parallelo/
- My contacts
  - paolo.burgio@unimore.it
  - http://hipert.mat.unimore.it/people/paolob/
- Useful links
  - http://www.openmp.org
  - http://www.google.com