OpenMP Overview

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- Christian Terboven (RWTH Aachen)
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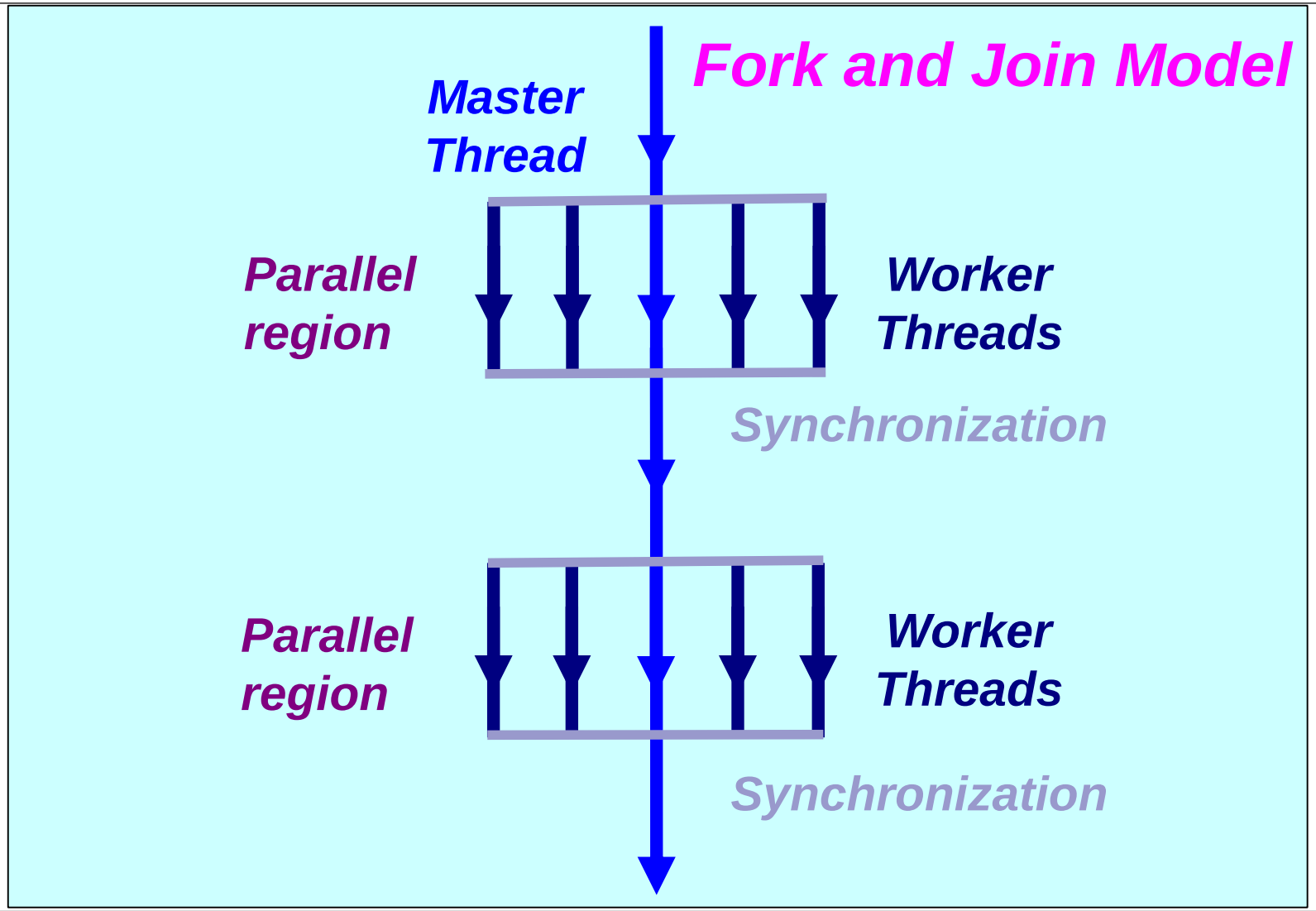
- Michael Klemm (Intel)

Core concept

The OpenMP Execution Model



Defining Parallelism in OpenMP

A parallel region is a block of code executed by all threads in the team

```
#pragma omp parallel [clause[[,] clause] ...]
{
    "this code is executed in parallel"

} // End of parallel section (note: implied barrier)
```

```
!$omp parallel [clause[[,] clause] ...]

    "this code is executed in parallel"

!$omp end parallel (note: implied barrier)
```

The Worksharing Constructs

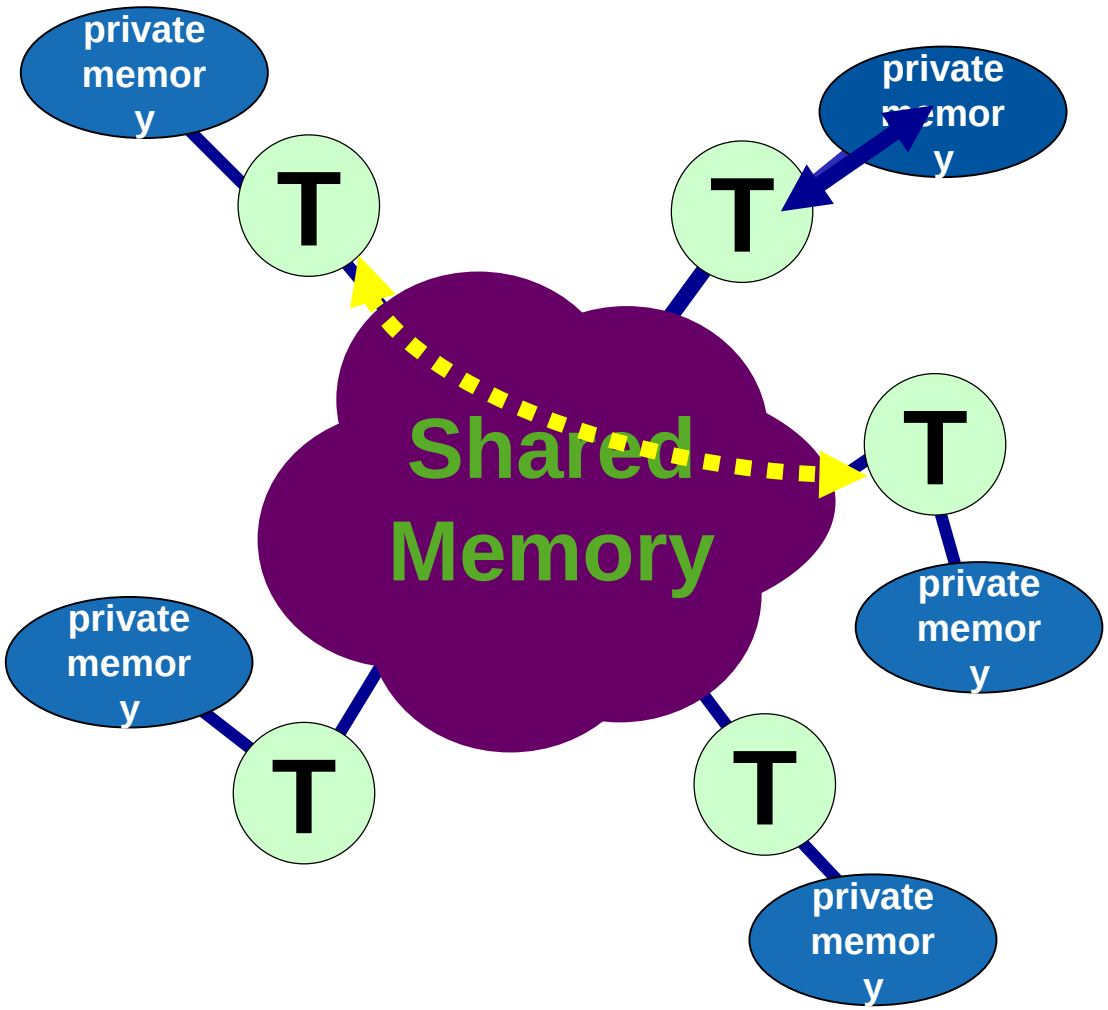
```
#pragma omp for
{
    ....
}

!$OMP DO
    ....
!$OMP END DO
```

```
#pragma omp sections
{
        ....
}

!$OMP SECTIONS
        ....
!$OMP END SECTIONS
```

```
#pragma omp single
{
        ....
}

!$OMP SINGLE
        ....
!$OMP END SINGLE
```

- ✓ *The work is distributed over the threads*
- ✓ *Must be enclosed in a parallel region*
- ✓ *Must be encountered by all threads in the team, or none at all*
- ✓ *No implied barrier on entry*
- ✓ *Implied barrier on exit (unless the nowait clause is specified)*
- ✓ *A work-sharing construct does not launch any new threads*

The OpenMP Memory Model



- *All threads have access to the same, globally shared memory*
- *Data in private memory is only accessible by the thread owning this memory*
- *No other thread sees the change(s) in private memory*
- *Data transfer is through shared memory and is 100% transparent to the application*

Scoping Rules

- Managing the Data Environment is the challenge of OpenMP.

- *Scoping* in OpenMP: Dividing variables in *shared* and *private*:
  - *private*-list and *shared*-list on Parallel Region
  - *private*-list and *shared*-list on Worksharing constructs
  - General default is *shared* for Parallel Region, *firstprivate* for Tasks.
  - Loop control variables on *for*-constructs are *private*
  - Non-static variables local to Parallel Regions are *private*
  - *private*: A new uninitialized instance is created for each thread
    - *firstprivate*: Initialization with Master‘s value
    - *lastprivate*: Value of last loop iteration is written back to Master
  - Static variables are *shared*

Privatization of Global/Static Variables

- Global / static variables can be privatized with the *threadprivate* directive
  - One instance is created for each thread
    - Before the first parallel region is encountered
    - Instance exists until the program ends
    - Does not work (well) with nested Parallel Region
  - Based on thread-local storage (TLS)
    - TlsAlloc (Win32-Threads), pthread_key_create (Posix-Threads), keyword `__thread` (GNU extension)

Really: try to avoid the use of threadprivate and static variables!

C/C++

```
static int i;
#pragma omp threadprivate(i)
```

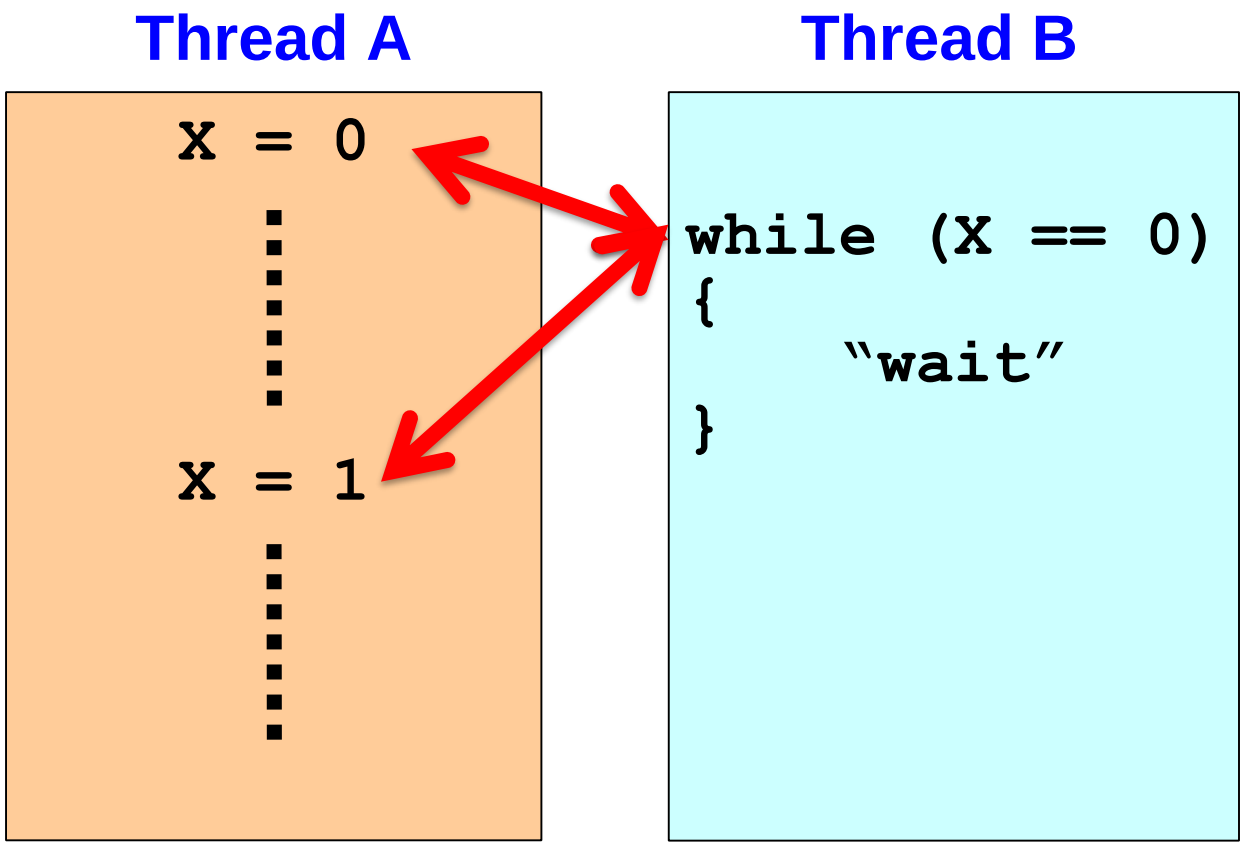
Fortran

```
SAVE INTEGER :: i
!$omp threadprivate(i)
```

Gotcha's

- Need to get this right
  - Part of the learning curve
- Private data is undefined on entry and exit
  - Can use firstprivate and lastprivate to address this
- Each thread has its own temporary view on the data
  - Applicable to shared data only
  - Means different threads may temporarily not see the same value for the same variable ...
  - Let me explain

The Flush Directive



If <u>shared</u> variable X is kept within a register, the modification may not be made visible to the other thread(s)

The Flush construct

```
#pragma omp flush [(list)]
```

```
!$omp flush [(list)]
```

- Strongly recommended: do **not** use this directive
  - … unless really necessary. Really ☺.
  - Could give very subtle interactions with compilers
  - If you insist on still doing so, be prepared to face the OpenMP language lawyers
- Implied on many constructs
  - A good thing
  - This is your safety net

The OpenMP Barrier

- Several constructs have an implied barrier
  - This is another safety net (has implied flush by the way)
- In some cases, the implied barrier can be left out through the “nowait” clause
- This can help fine tuning the application
  - But you’d better know what you’re doing
- The explicit barrier comes in quite handy then

```
#pragma omp barrier
```

```
!$omp barrier
```

The Nowait Clause

- To minimize synchronization, some directives support the optional nowait clause
  - If present, threads do not synchronize/wait at the end of that particular construct
- In C, it is one of the clauses on the pragma
- In Fortran, it is appended at the closing part of the construct

```
#pragma omp for nowait
{
        :
}
```

```
!$omp do
        :
        :
!$omp end do nowait
```

Mutual exclusion

- A *Critical Region* is executed by all threads, but by only one thread simultaneously (*Mutual Exclusion*).

C/C++

```
#pragma omp critical (name)
{
    ... structured block ...
}
```

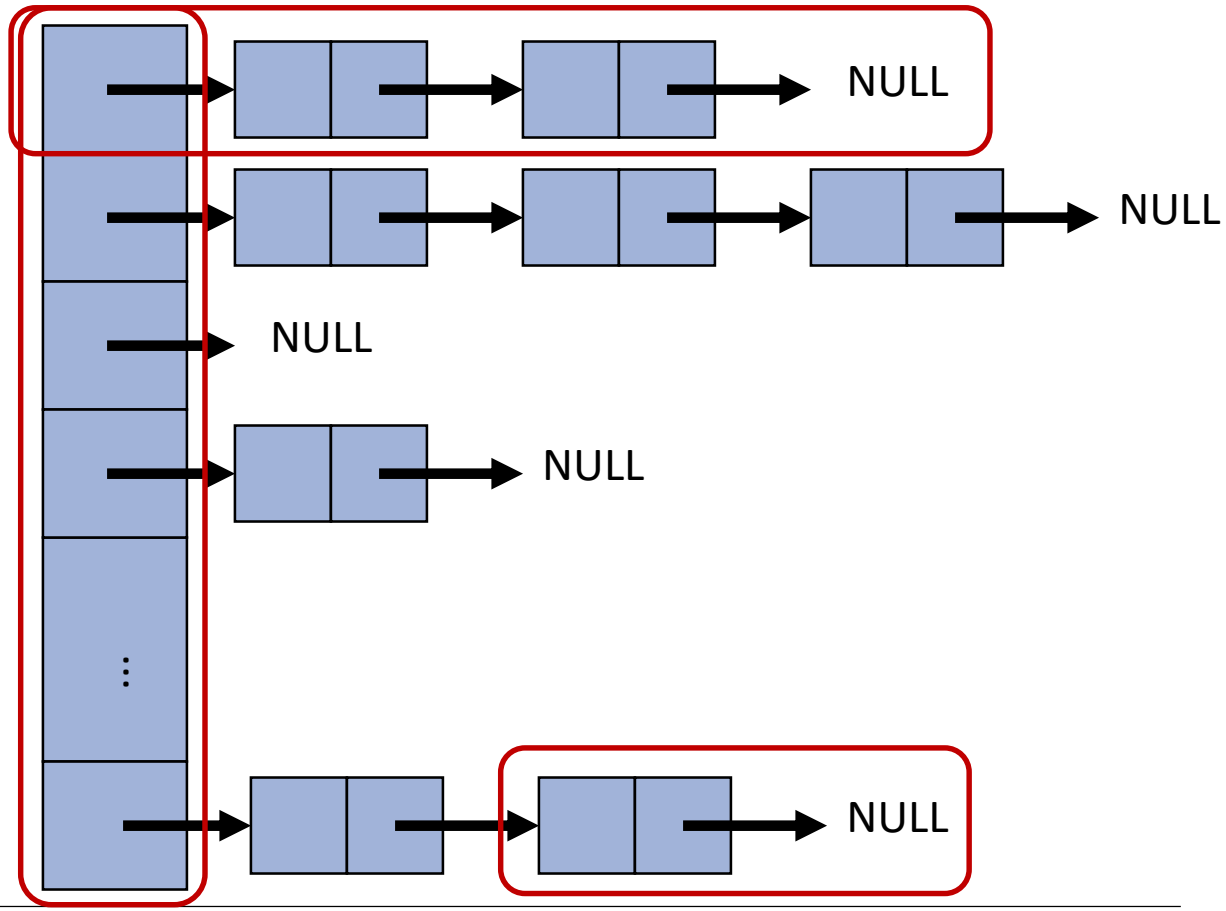
- OpenMP also provides locks und locking routines
  - omp_lock_t
  - omp_init_lock()
  - omp_set_lock()
  - omp_unset_lock()
  - omp_test_lock()
  - omp_init_lock()

Performance Optimization for Locking

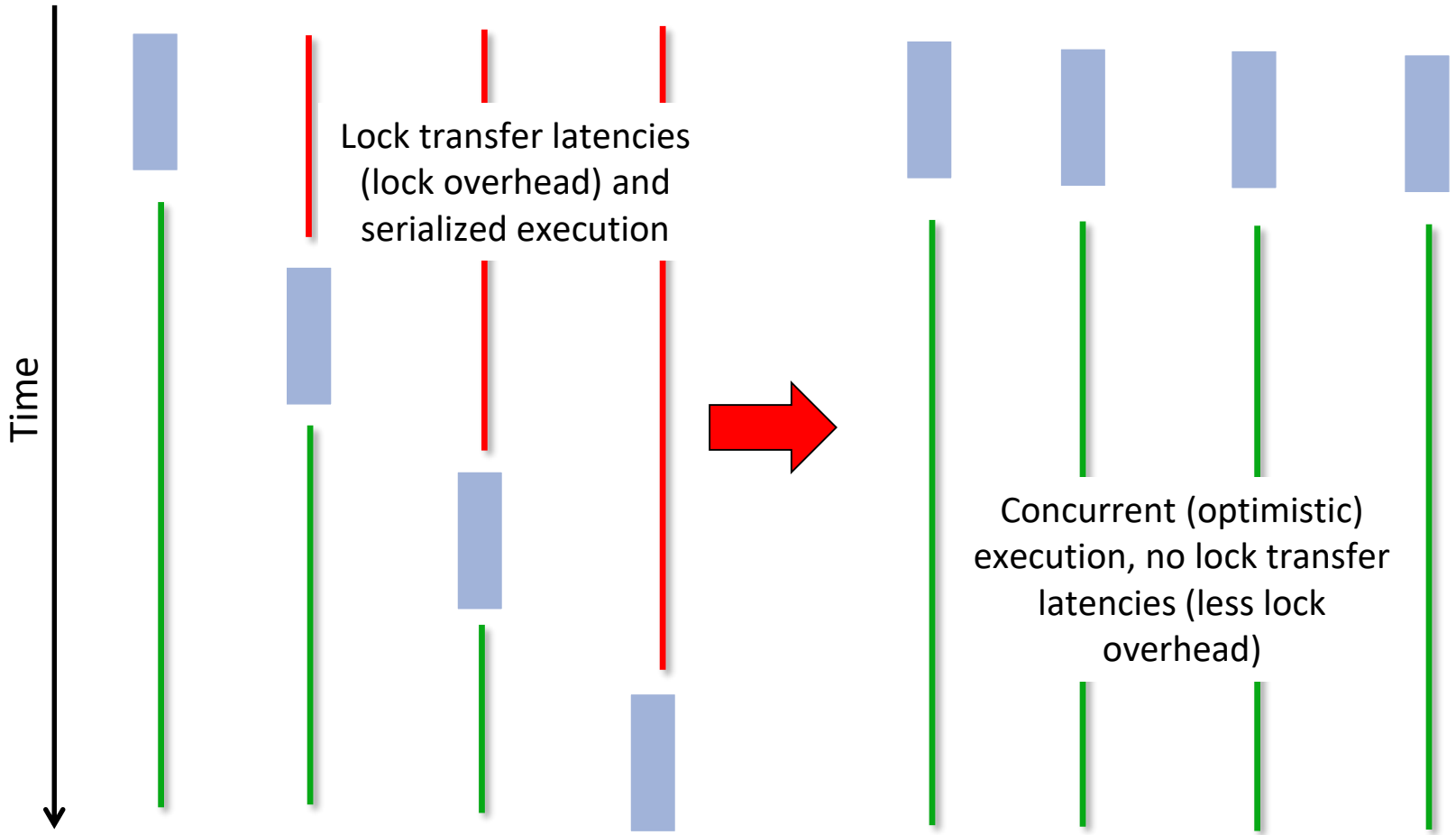
- Don’t use locks ☺
- Fine-grained locking
  - Push locks towards the finest granularity of data access (if possible)
  - May avoid mutual exclusion of lengthy sequences of execution
- Lock-free data structures
  - Don’t use locks, but use atomic instruction of the machine
  - Advice: do not attempt to implement such a data structure yourself
- Use transactional memory
  - Speculate on the mutual exclusion (increased parallelism if no conflicts)
  - Pay extra if a conflict happens

Fine-grained Locking

- Example: hash table with linked lists for buckets
- Tradeoff:
  - (Expected) degree of parallelism
  - Number of individual locks required
  - Implementation complexity
- Can be combined with TM
  - See next slide



Transactional memory



Lock hints in OpenMP

- Lock hints can help the Runtime to choose the best implementation of a lock.
- Hints are:
  - omp_lock_hint_none
  - omp_lock_hint_uncontended
  - omp_lock_hint_contended
  - omp_lock_hint_nonspeculative
  - omp_lock_hint_speculative
- Hints can be combined with + or | .

C/C++

```
omp_lock_t lck;
omp_init_lock_with_hint(&lck);
#pragma omp parallel
{
        omp_set_lock(&lck);
        /* mutual exclusion here...*/
        ...
        omp_unset_lock(&lck);
}
omp_destroy_lock(&lck);
```

C/C++

```
#pragma omp critical hint(...)
{
        ...
}
```

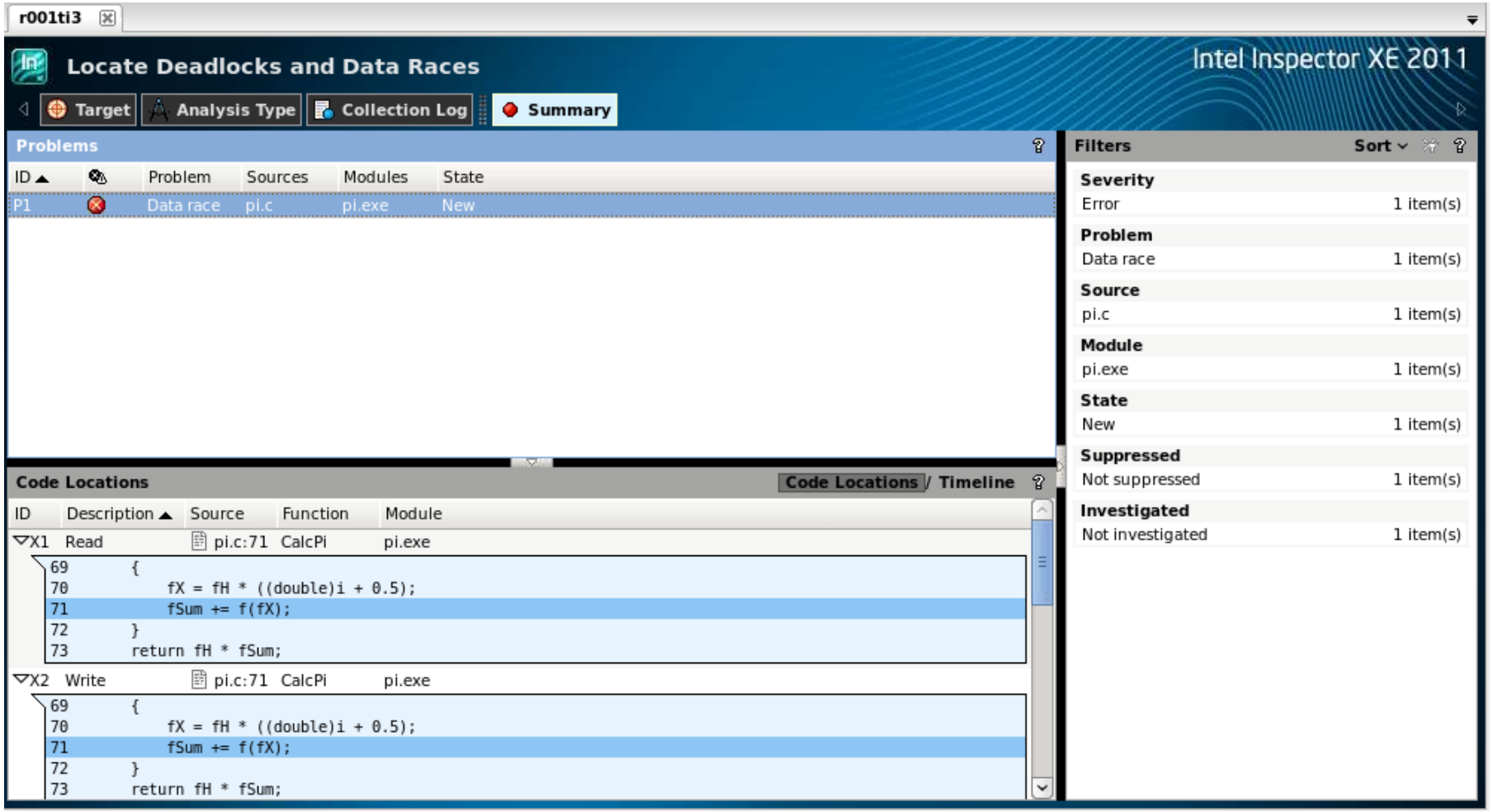
Tools for OpenMP

Data race

- Data Race: the typical OpenMP programming error, when:
  - two or more threads access the same memory location, and
  - at least one of these accesses is a write, and
  - the accesses are not protected by locks or critical regions, and
  - the accesses are not synchronized, e.g. by a barrier.
- Non-deterministic occurrence: e.g. the sequence of the execution of parallel loop iterations is non-deterministic and may change from run to run
- In many cases *private* clauses, *barriers* or *critical regions* are missing
- Data races are hard to find using a traditional debugger
  - Use the *Intel Inspector XE* or similar tool

Inspector XE

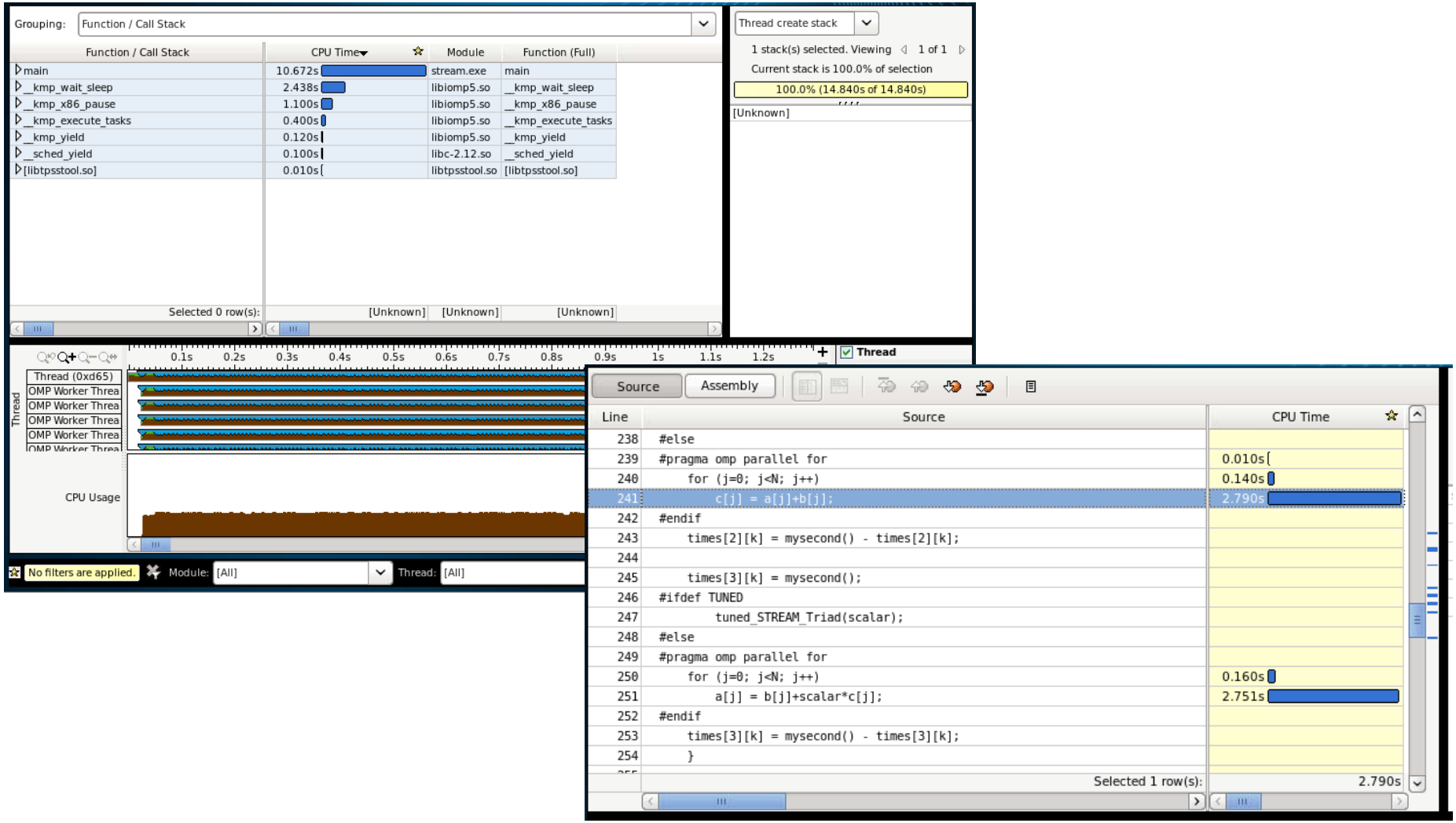
- Runtime detection of data races



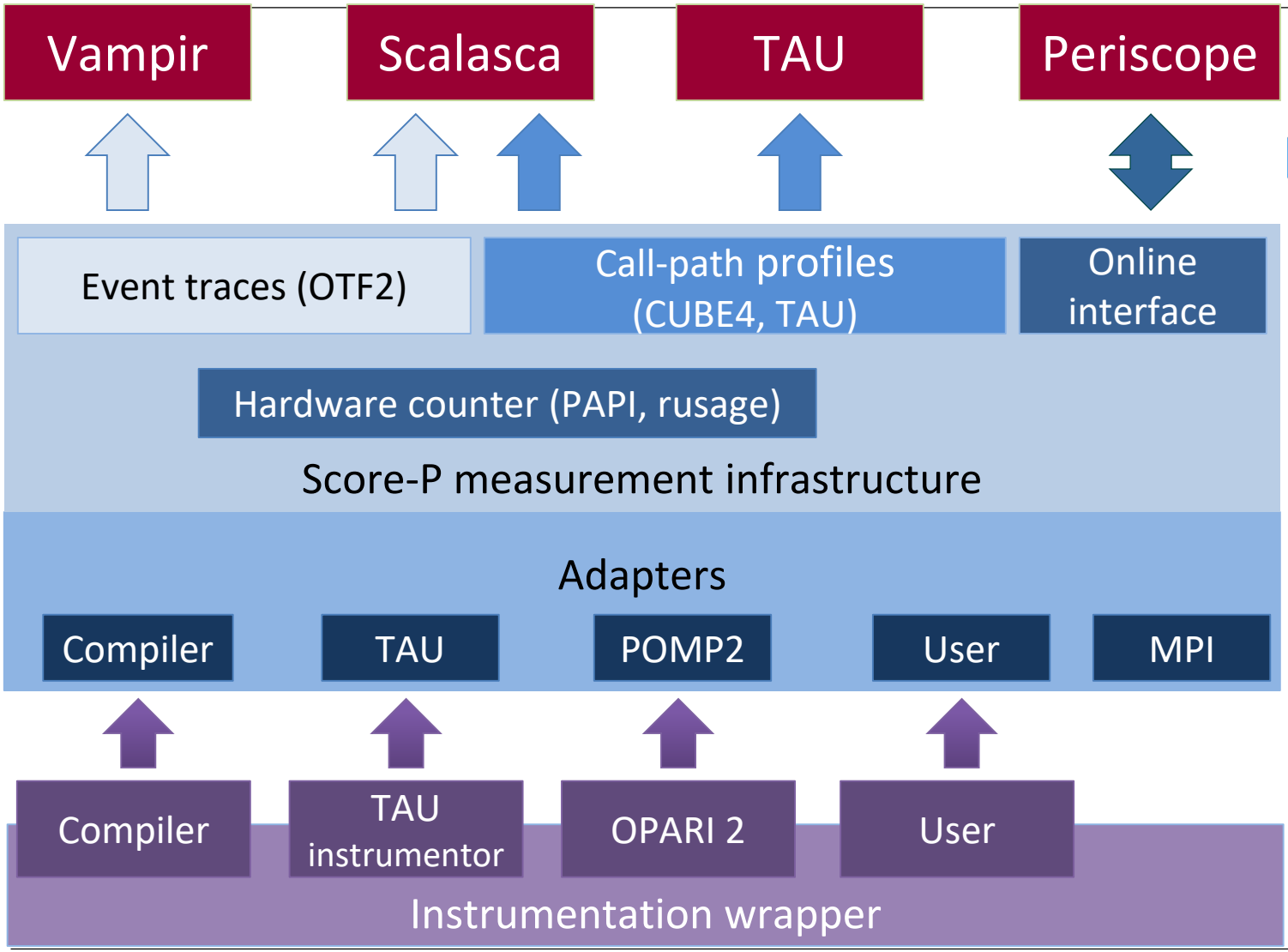
Intel VTune Amplifier XE

- Performance Analyses for
  - Serial Applications
  - Shared Memory Parallel Applications
- Sampling Based measurements
- Features:
  - Hot Spot Analysis
  - Concurrency Analysis
  - Wait
  - Hardware Performance Counter Support

Performance tools - VTune



Performance tools - Score-P

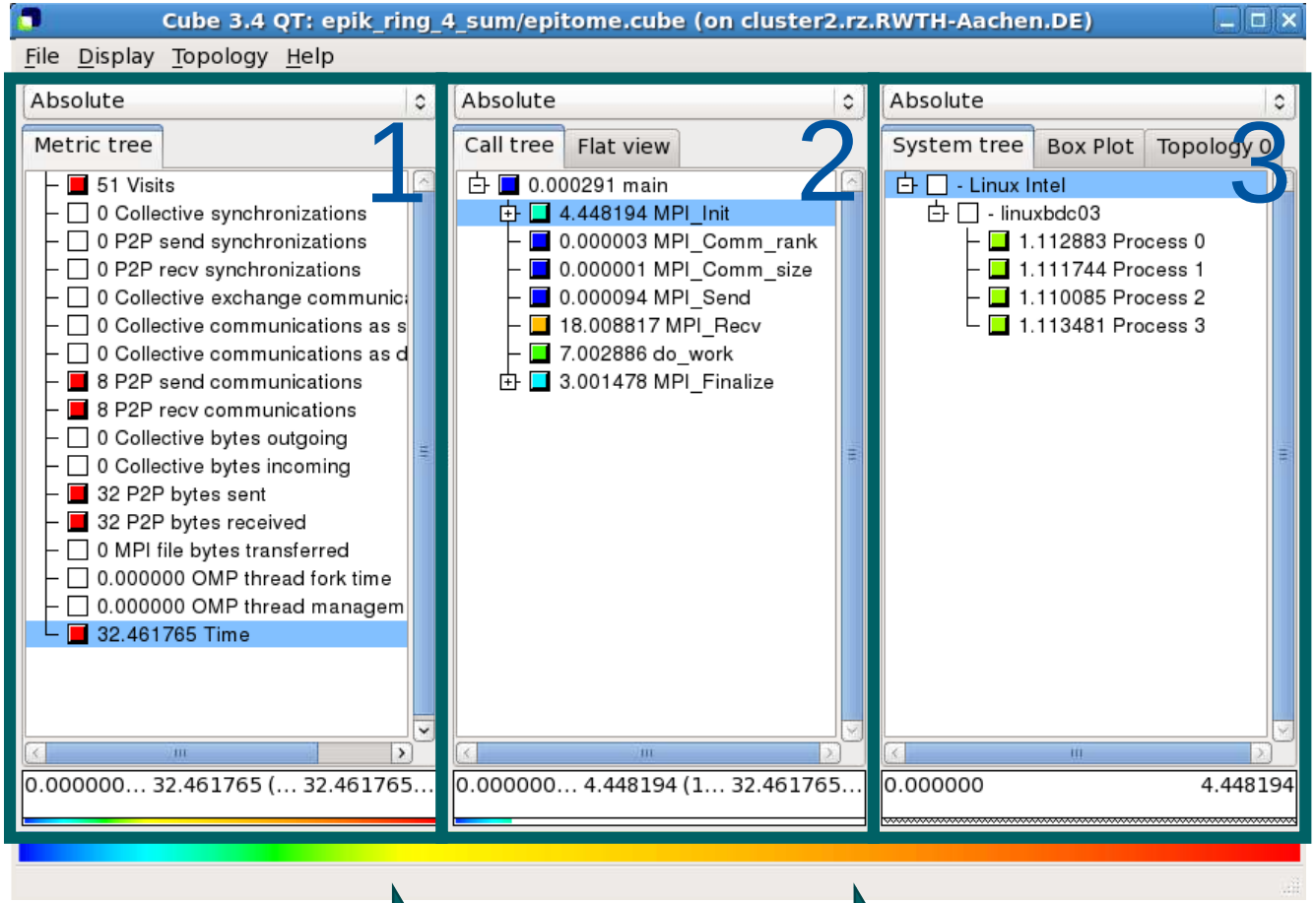


Performance Tools Score-P / Cube

1. Metric tree
2. Call tree
3. Topology tree

- All views are coupled from left to right:

1. choose a metric
- -> this metric is shown for all functions
2. choose a function
- -> the right view shows the distribution over processes



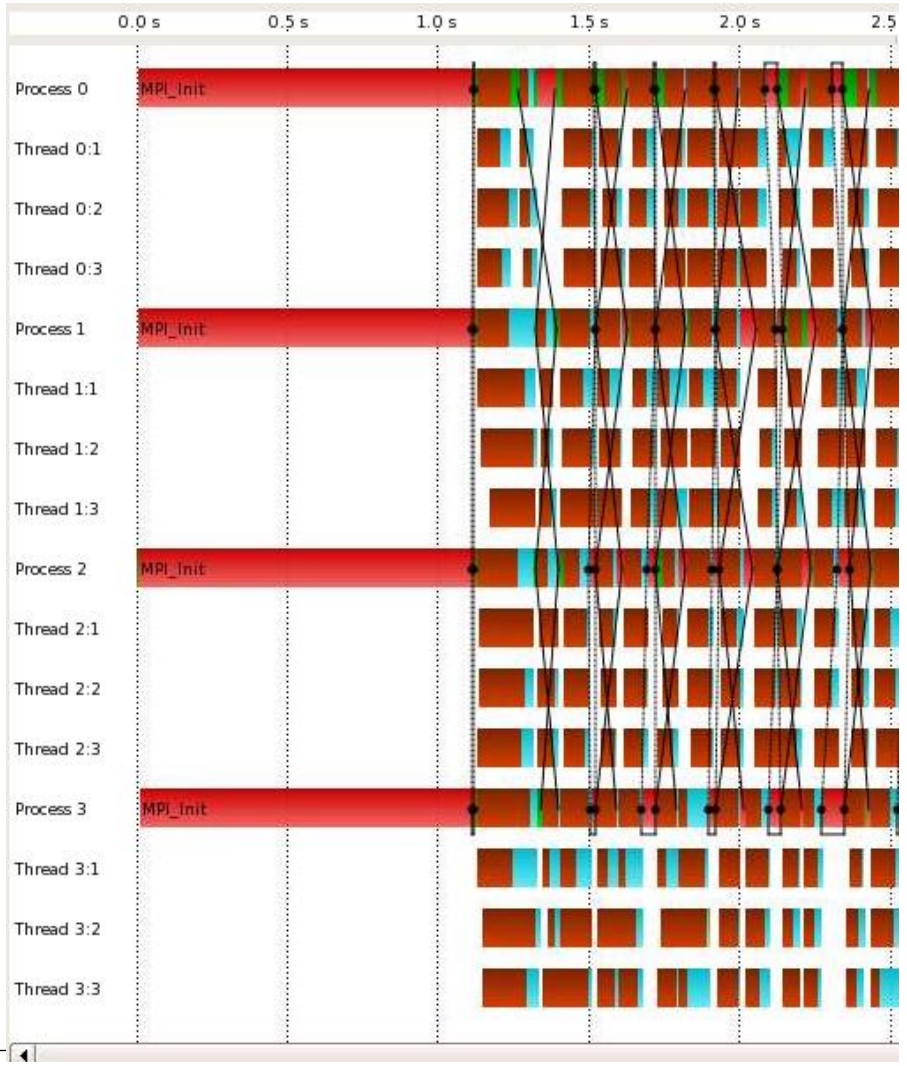
Total execution time is 32 sec.

Out of these 4.4 sec. are spent in MPI_Init().

Out of these 1.1 sec is spent by every process.

Performance Tools Score-P / Vampir

- The Timeline gives a detailed view of all events.
- Regions and Messages of all Processes and Threads are shown.
- Zoom horizontal or vertical for more detailed information.
- Click on a message or region for specific details.



Thank you for your attention!

Questions?