Introduction to OpenMP

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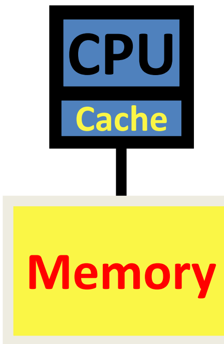
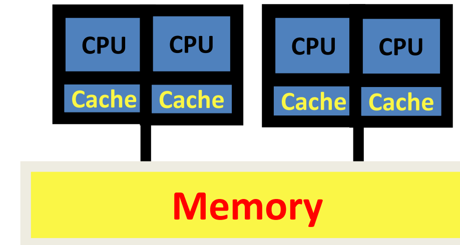
How to build faster computers – a survey

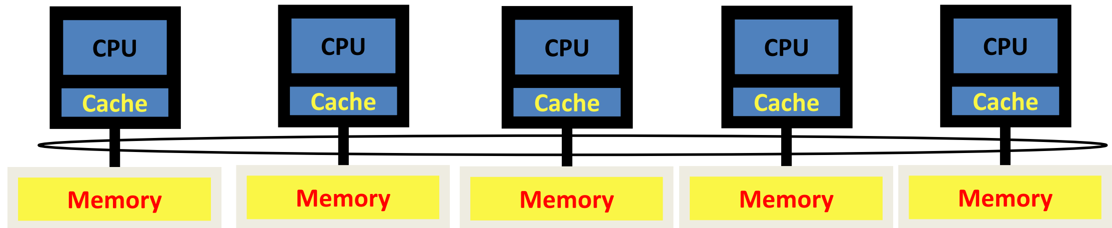
1. **Increase performance / throughput of CPU core**
   a) Reduce cycle time, i.e. increase clock speed (Moore)
   b) Increase throughput, i.e. superscalar + SIMD



2. **Improve data access time**
   a) Increase cache size
   b) Improve main memory access (bandwidth & latency)
3. **Use parallel computing (shared memory)**
   a) Requires shared-memory parallel programming
   b) Shared/separate caches
   c) Possible memory access bottlenecks



4. **Use parallel computing (distributed memory)**
   "Cluster" of computers tightly connected
   a) Almost unlimited scaling of memory and performance
   b) Distributed-memory parallel programming

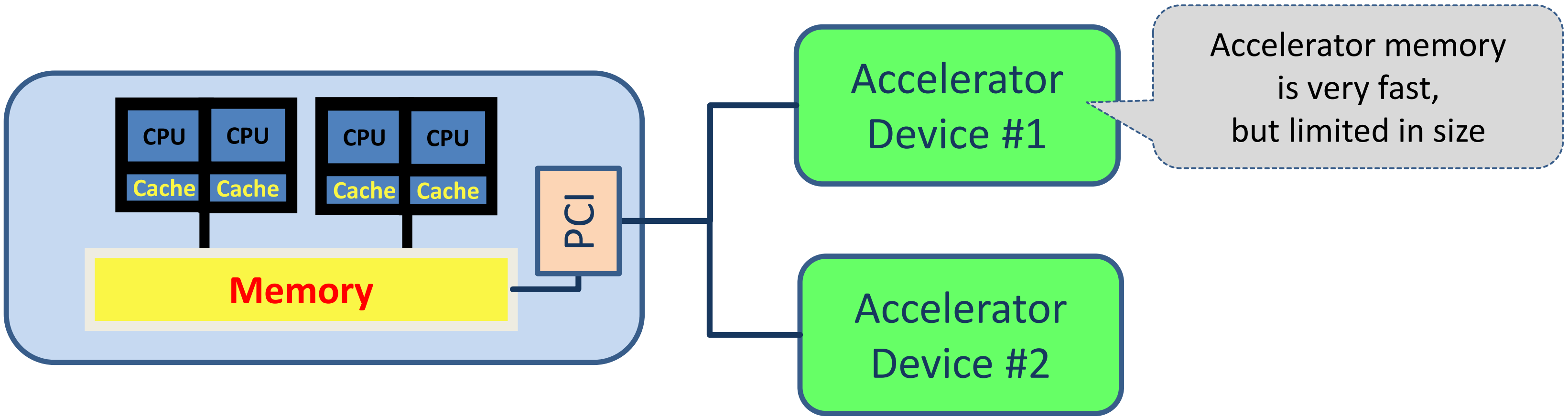


How to build faster computers (cont'd)

5. Use an accelerator with your compute node

a) Requires offload of program regions
(semantics may be limited)

b) Host and accelerator memory are connected, but separate



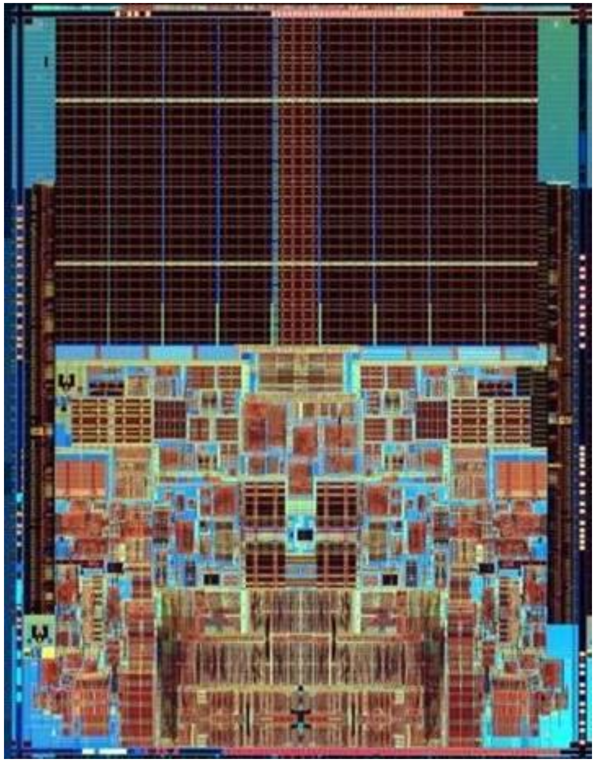
(Improvements are under way)

c) Programming complexity is higher than for shared memory systems
(„heterogeneous parallel computing")

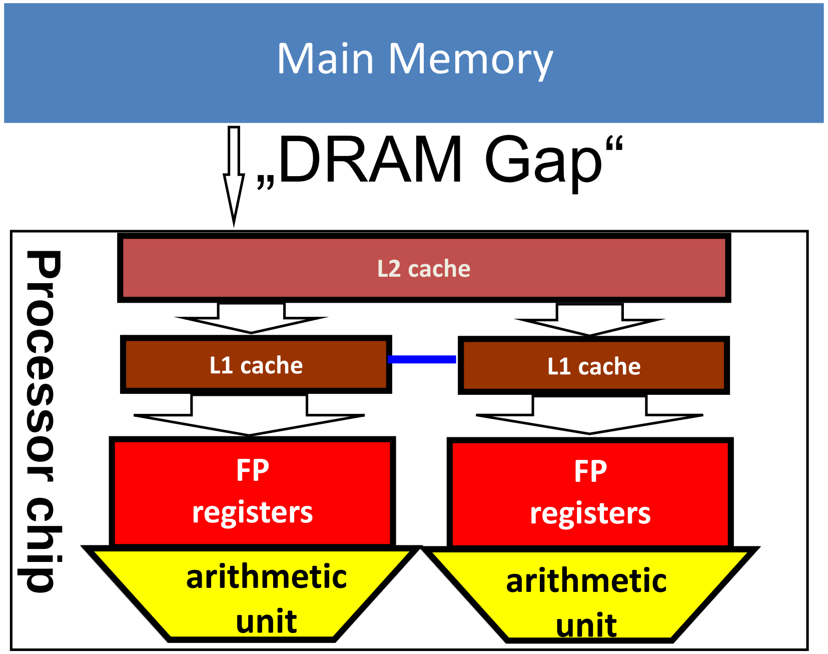
It is not a faster CPU – it is a parallel computer on a chip.

Put multiple processors ("cores") on a chip which share resources
(example shows a dual core that shares L2 cache and memory bandwidth)

Efficient use of all cores for a single application → programmer

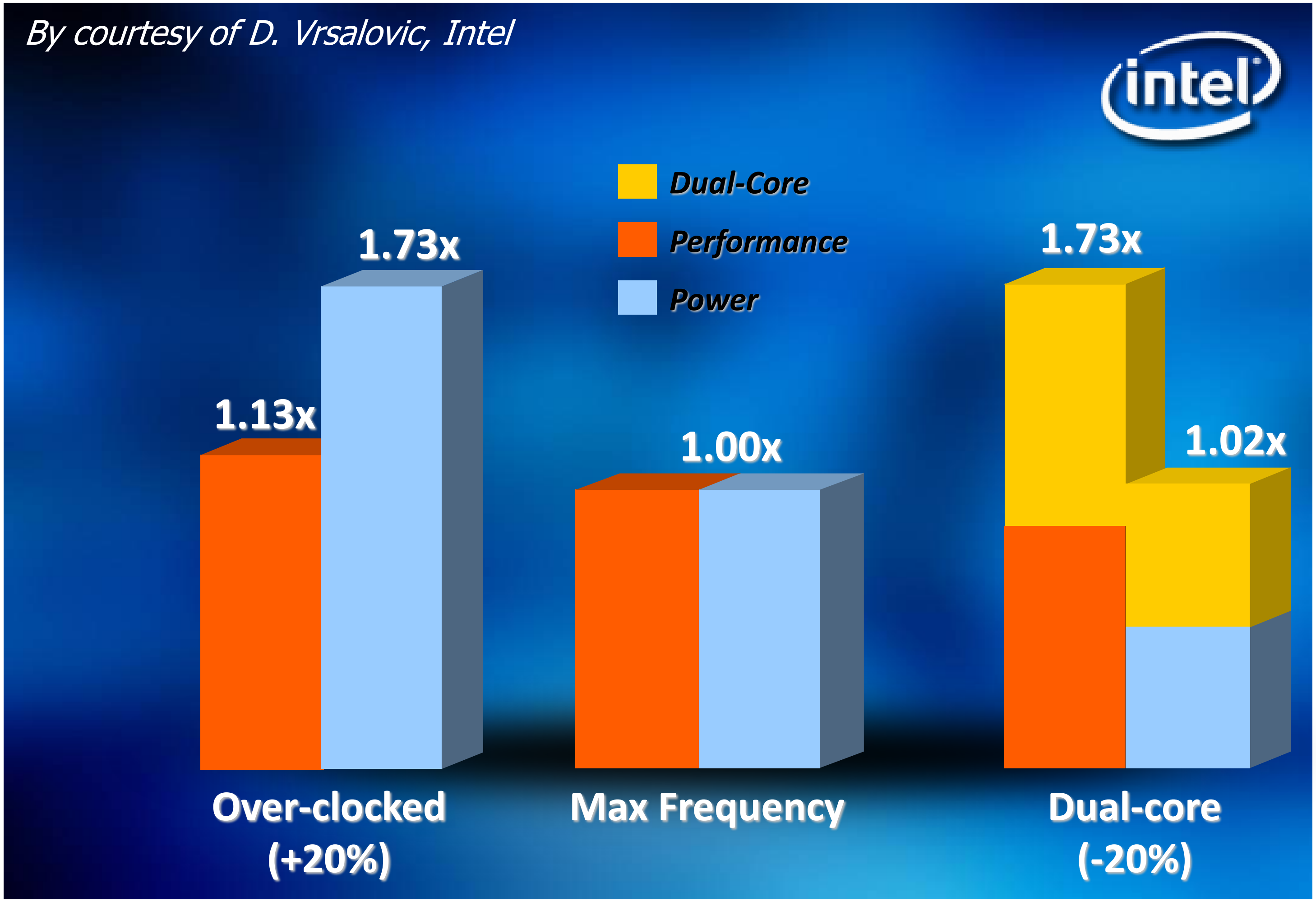


Intel Xeon (Woodcrest)

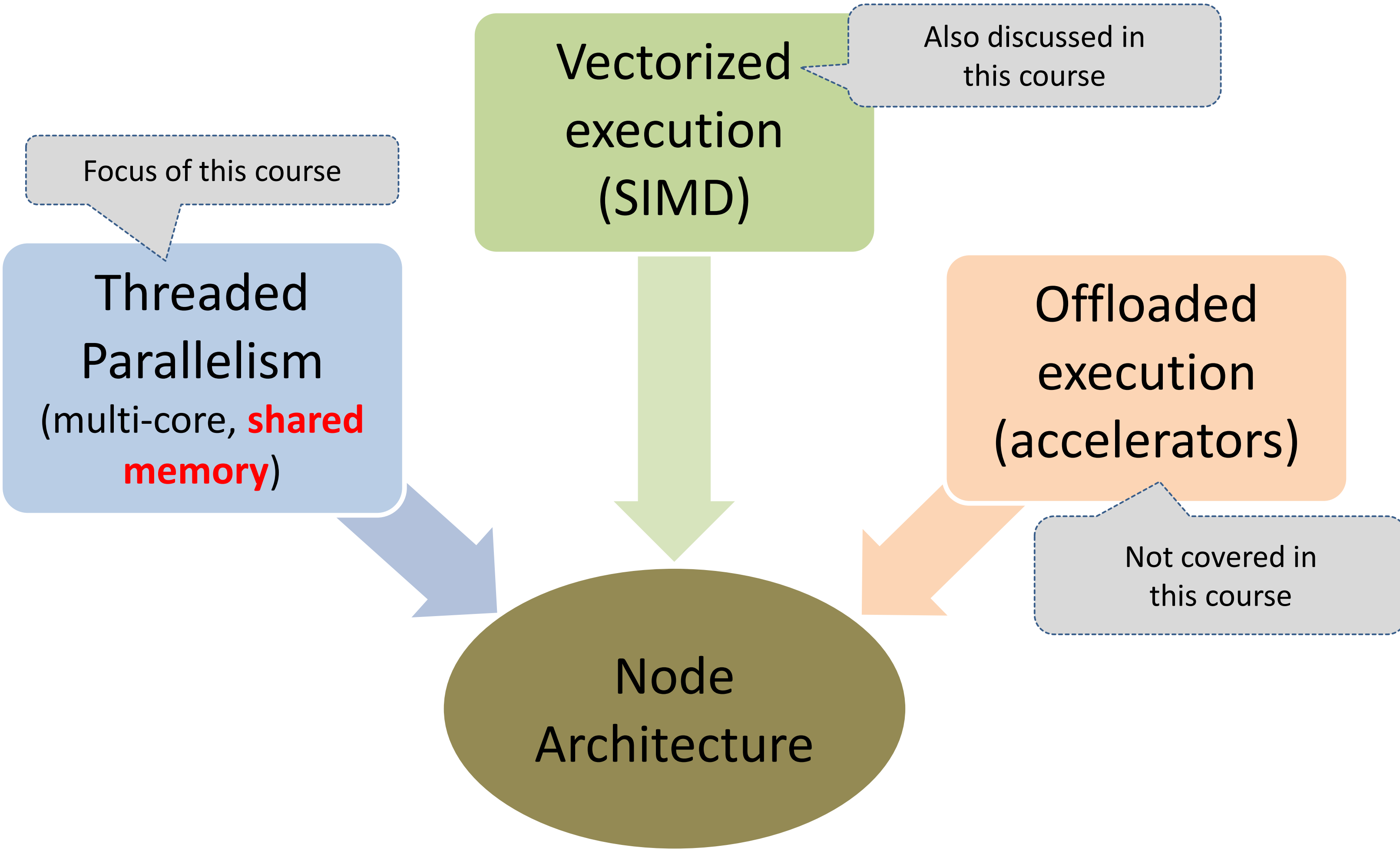


… the party is over!

- **Option 1 a) is not feasible any more, option 2 only in small increments**



Paradigms supported by OpenMP – three faces of parallelism



OpenMP and portability

- **Syntactic portability**
  - Directives / pragmas
  - Conditional compilation permits to masks API calls
- **Semantic portability**
  - Standardized across platforms → safe-to-use interface
  - Unsupported/unavailable hardware features → irrelevant directives will be ignored (you might need a special compiler for your devices …)
- **Performance portability**
  - Unfortunately performance is not necessarily portable
  - Has traditionally been a problem (partly due to differences in hardware/architectural properties)

Compatibility with Sequential Execution

Are semantics for sequential execution retained?

- yes, due to directive concept
- programmer may **choose** not to

Do memory accesses occur in the same order?

- no, due to **relaxed** memory consistency (performance feature!)

Are the same numeric results obtained for parallel execution?

- **no associativity** for model number operations
- parallel execution might reorder operations
  (programmer may need to enforce ordering for reproducibility and/or numeric stability)

OpenMP Standard

- **Responsible body:** OpenMP Architecture Review Board
  - Published OpenMP **4.5** in November 2015
  - Development continues

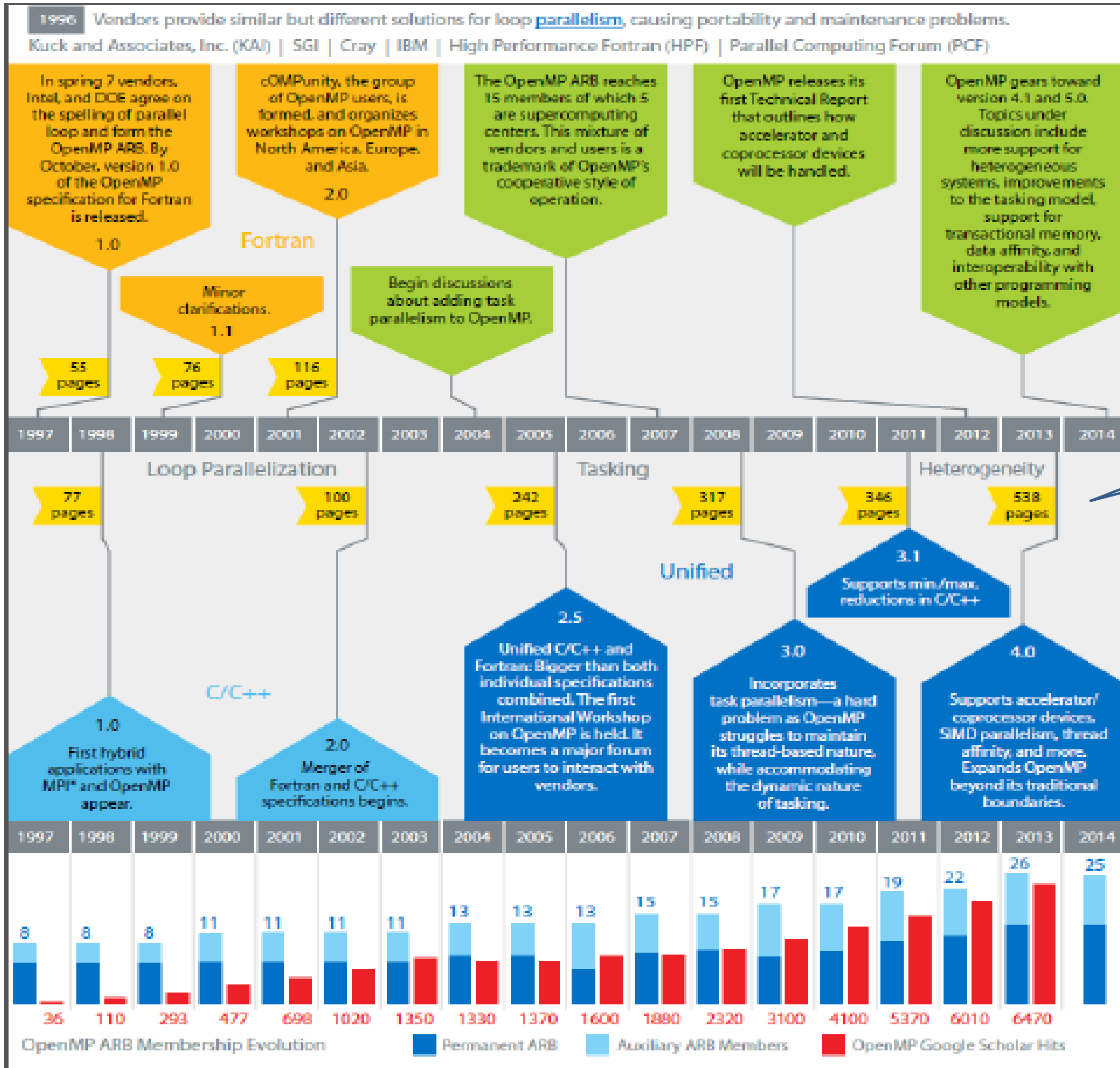
History of OpenMP starts in 1997

- **Base languages**
  - Fortran (77, 95, 2003)
  - C, C++
  - (Java is not a base language)

Fortran and C examples will be displayed

- **Resources:**
  - http://www.openmp.org (including standard documents)
  - http://www.compunity.org

OpenMP history
(courtesy Intel „The Parallel Universe“, issue 18)

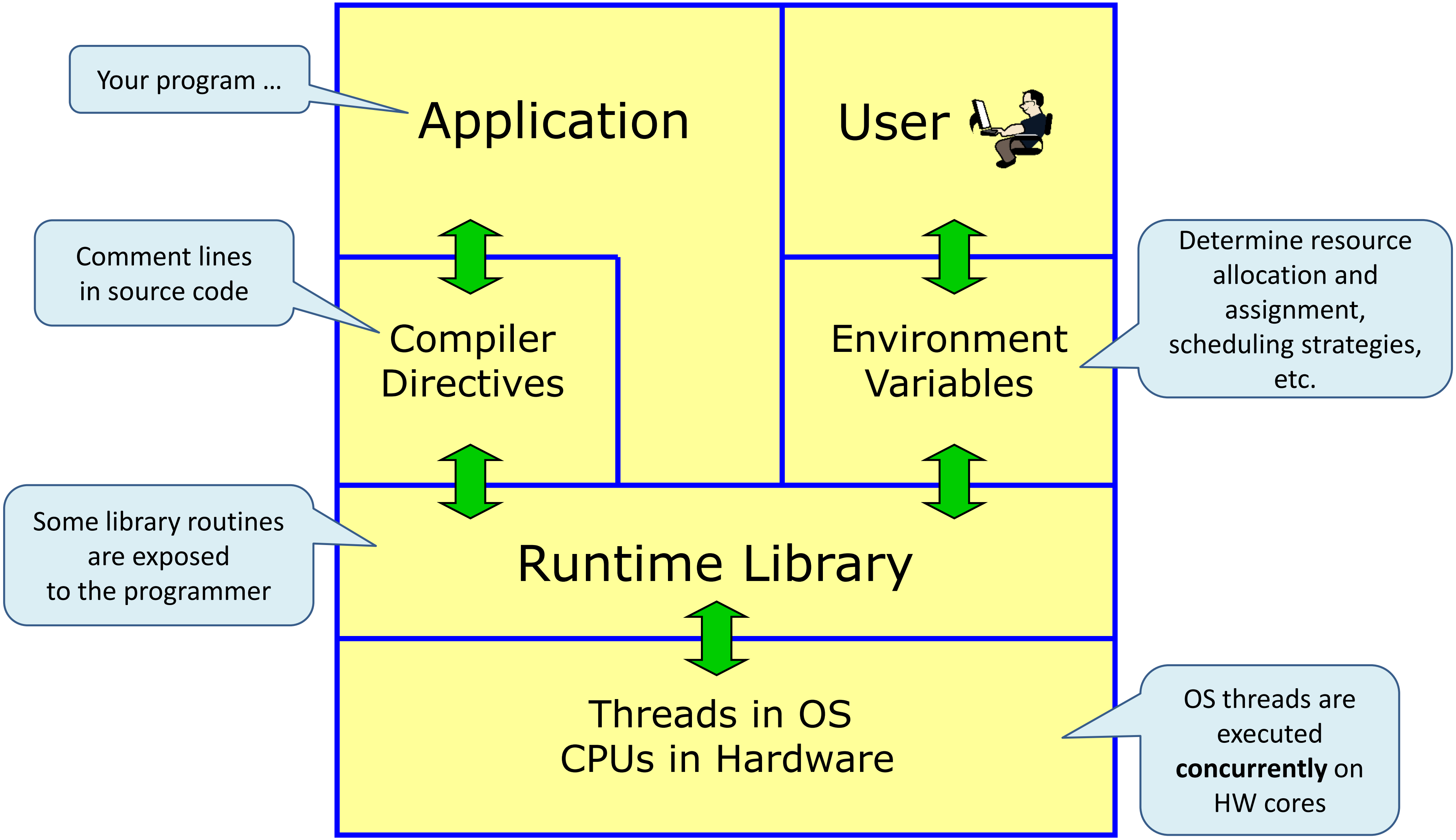


Note the increase in the standard's size

Course Target:

Learn the most useful and therefore most commonly used features of OpenMP

OpenMP Architecture



A simple application

Fortran

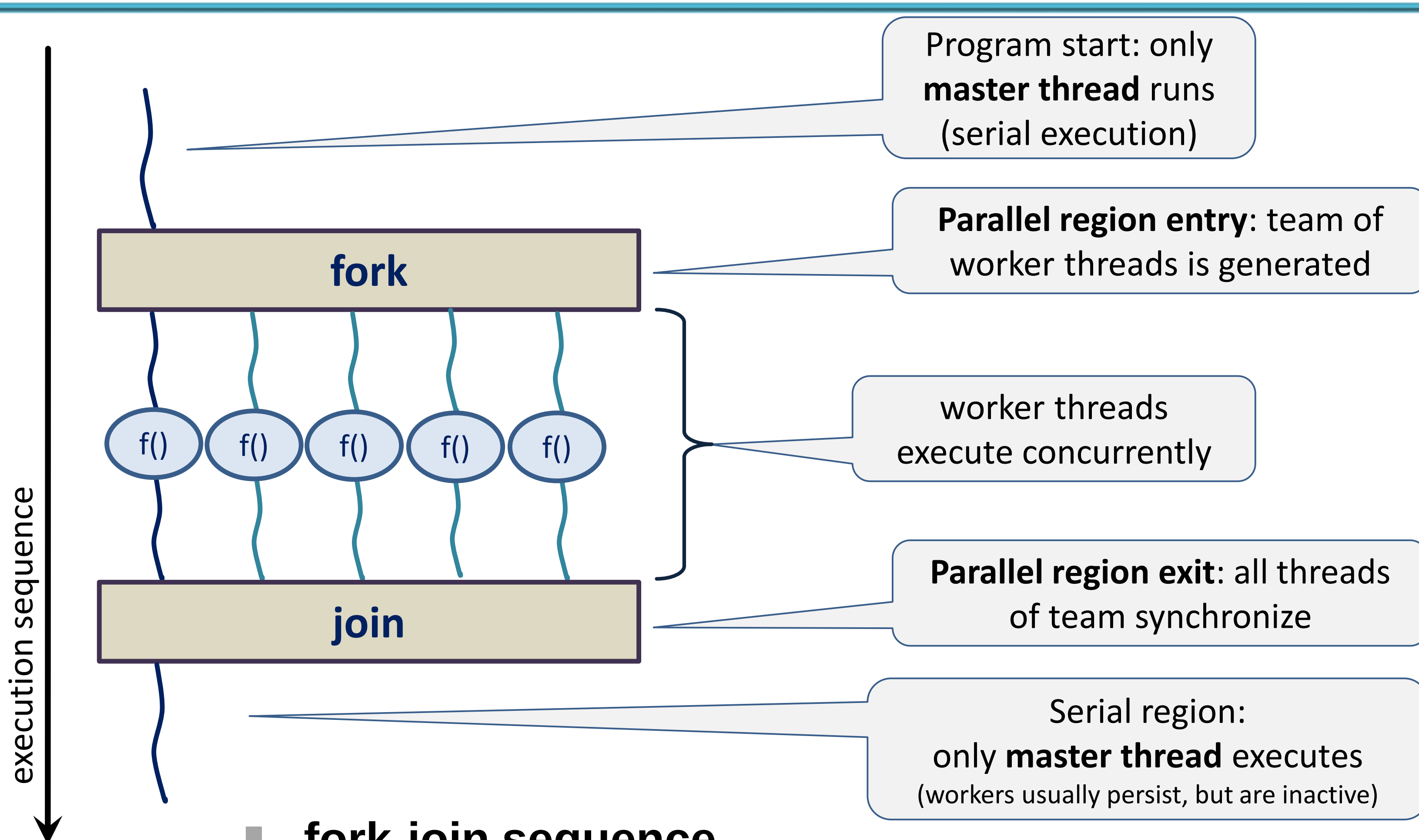
```
program
  use m
  implicit none

  call f()

end program

module m
  implicit none
contains
  subroutine f()
    print *, 'Hello'
  end subroutine
end module
```

C

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


  f();

  return 0;
}



void f() {
  printf("Hello\n");
}
```

Aim is to execute **f()** in parallel

Parallel execution model



- **fork-join sequence**
  - can repeat, with differing thread counts

Adding a parallel region

Fortran

```
program
  use m
  implicit none
!$omp parallel
  call f()
!$omp end parallel
end program
```

enclosed lexical block

C

```
#include <stdio.h>
int main() {
#pragma omp parallel
  {
    f();
  }
  return 0;
}
```

- **General form of directives:**

```
!$omp <directive> [<clause>]
```

sentinel

```
#pragma omp <directive> [<clause>]
```

sentinel

- clauses, if present, modify a directive‘s semantics
- multiple clauses per directive are possible
- continuation lines are supported for long directives:

	Fortran	C
continuation	&	\

OpenMP structured block rules

Fortran

- statements between a beginning and ending directive pair

C / C++

- delineated by braces following a directive

single point of entry

- GOTO into block is prohibited
- setjmp() into block is prohibited

single point of exit

- GOTO, RETURN, EXIT outside block are prohibited
- longjmp() and throw() outside block are prohibited

permitted: program termination

- STOP, ERROR STOP
- exit()

Using library calls

Fortran

```
subroutine f()
!$  use omp_lib
  integer :: me
  me = 0
!$  me = omp_get_thread_num()
  print *, 'Hello from thread ', me
end subroutine
```

OpenMP module: explicit interfaces for API

returns an integer (avoid implicit typing!)

!$ indicates statement should be compiled **conditionally**

C

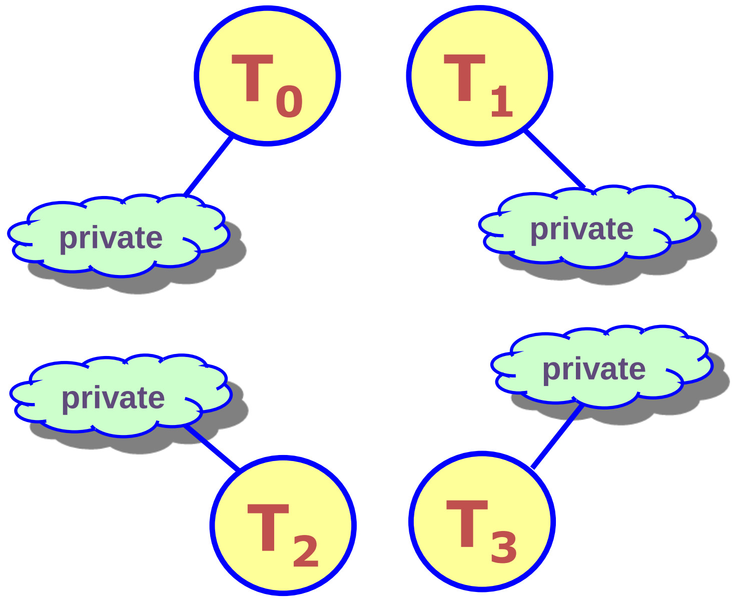
```
#include <stdio.h>
#include <omp.h>
void f() {
  int me = 0;
#ifdef _OPENMP
  me = omp_get_thread_num();
#endif
  printf("Hello from thread %i\n",me);
}
```

OpenMP include file: prototypes for API

OpenMP-specific macro for conditional compilation

Independent execution contexts

- **As many independent function calls as there are threads**
- **Thread-individual memory management within function call**
  - local variables ("me") are created in the thread-specific stack
  - malloc() or ALLOCATE create memory in the heap separately for each thread



- **Private variables**
  - associated with a particular thread are **inaccessible** by any other thread
  - **pro: safe** to use
  - **con: communication** is not possible (it is needed by many parallel algorithms), unnecessary replication of objects may happen.
- **Thread-individual stack limit**
  - control via environment variable (example: 100 MByte)

```
export OMP_STACKSIZE=100M
```

OpenMP API

- **Classes of routines:**
  - Execution environment (36), Locking (12), Timing (2), Device Memory (7)

most commonly used subset

Name	Result type	Purpose
`omp_set_num_threads (int num_threads)`	none	number of threads to be created for subsequent parallel region
`omp_get_num_threads()`	int	number of threads in **currently executing** region
`omp_get_max_threads()`	int	maximum number of threads that can be created for a subsequent parallel region
`omp_get_thread_num()`	int	thread number of calling thread (zero based) in **currently executing** region
`omp_get_num_procs()`	int	number of processors available
`omp_get_wtime()`	double	return wall clock time in seconds since some (fixed) time in the past
`omp_get_wtick()`	double	resolution of timer in seconds

Compiling and Running

- **Compilation:**

Fortran

```
f90 -fopenmp -o hello.exe hello.f90
```

generic instructions ...

C

```
cc -fopenmp -o hello.exe hello.c
```

- **Switch for OpenMP**
  - specific spelling is compiler-dependent
  - toggles both directives and conditional compilation
  - generates threaded code and links against OpenMP run time

serial compilation may require stub library

- **Execution:**

```
export OMP_NUM_THREADS=4
./hello.exe
```

by default, parallel regions generate a team with 4 threads

- **Output for example program:**

```
Hello from 1
Hello from 3
Hello from 0
Hello from 2
```

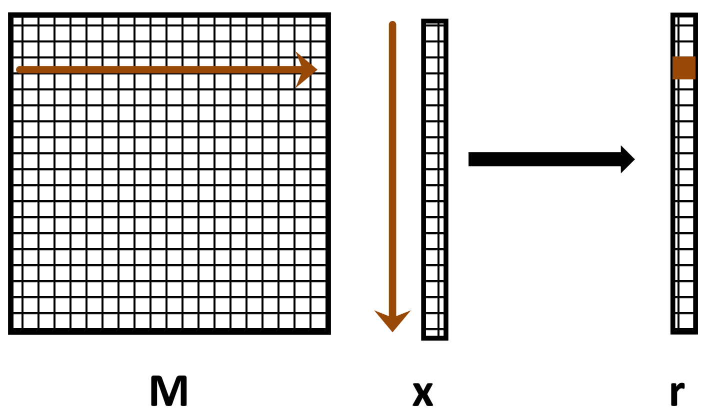
ordering will vary between runs (asynchronous execution)

Now: First exercise session

Simple work sharing, Scoping of Data, and Synchronization

Questions that now arise ...

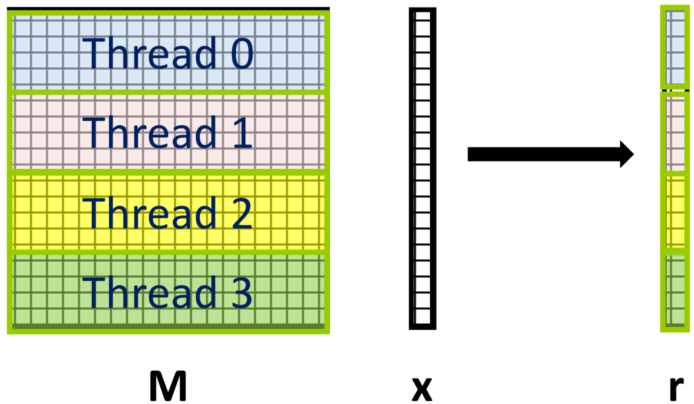
- **We know how to set up threading, but**
  - how can a large work item be divided up among threads?
    (using the API for this works in principle, but is tedious)
  - what happens with objects that already exist before the parallel region starts?
- **Example:**
  - matrix-vector multiplication r = M · x i.e. $r_i = \sum_{j=1}^{n} M_{ij} x_j$



A bunch of scalar products

Concept of work sharing

- **The idea is to split the work among threads**



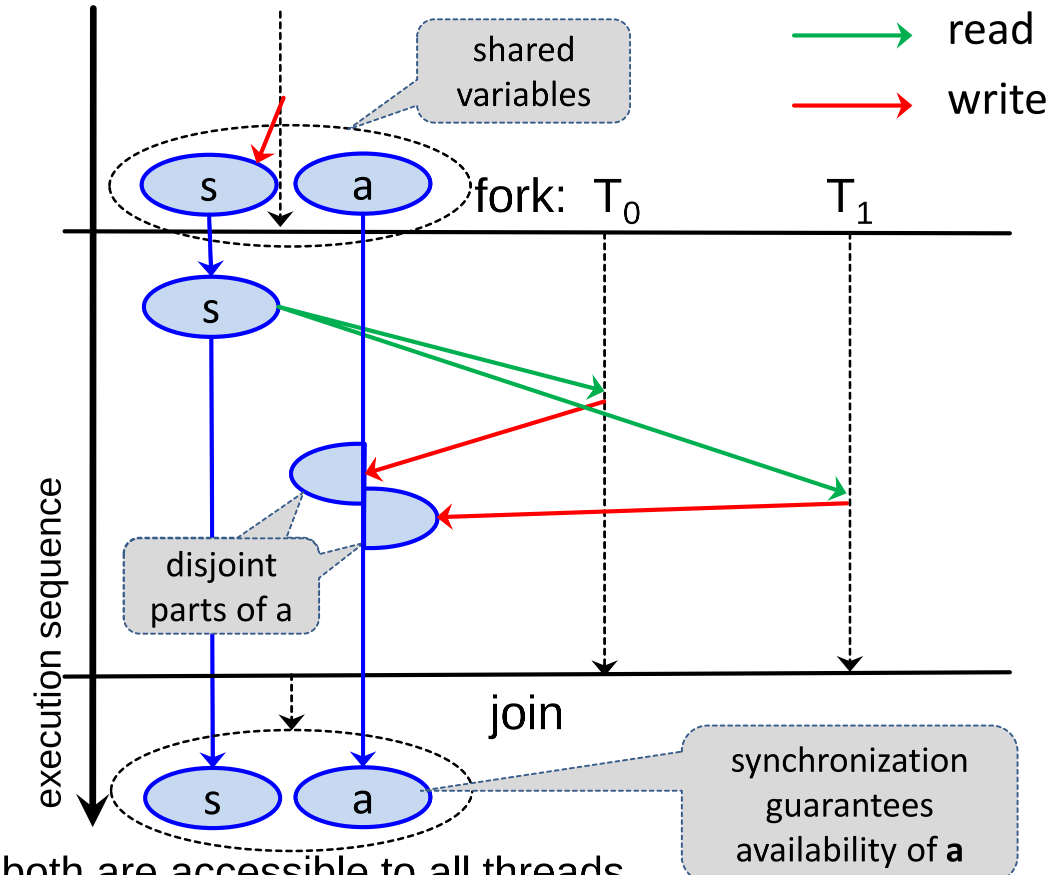
- **Note that**
  - all elements of **x** must be available to **all** threads
  - Matrix-Vector is often deployed iteratively → **r** becomes **x** in the next iteration
    → copying of data must be possible
- **Consequence:**
  - need for variables that are accessible to **all** threads
    → "data sharing" is often a prerequisite for "work sharing"
    → a natural concept for a shared memory programming model

Sharing variables across threads

```
real :: s, a(200)

  s = …
!$omp parallel shared(s,a)
  select case (me)
  case (0)
    a(1:100) = … * s
  case (1)
    a(101:200) = … * (-s)
  end select
!$omp end parallel
```

Fortran

thread ID



- **The „shared“ clause**
  - implies that scalar **s** and array **a** both are accessible to all threads

Rules for concurrent accesses to a single object

- reads/writes or writes/writes by different threads are **not permitted** („data races“)

Note: updates to array **a** are OK because **disjoint parts** of object are updated

Data dependencies that prevent parallelization

- **Flow dependency ("read after write", RAW):**

```
a = ...
b = a
c = b
```

second instruction cannot execute concurrently with first

- **Anti-dependency ("write after read", WAR):**

```
b = a
a = ...
... = a + ...
```

→

```
b = a
a2 = ...
... = a2 + ...
```

resolvable at cost of introducing a new variable ("name dependency")

- **Output dependency ("write after write", WAW):**

```
a = ...
b = a
a = ...
```

→

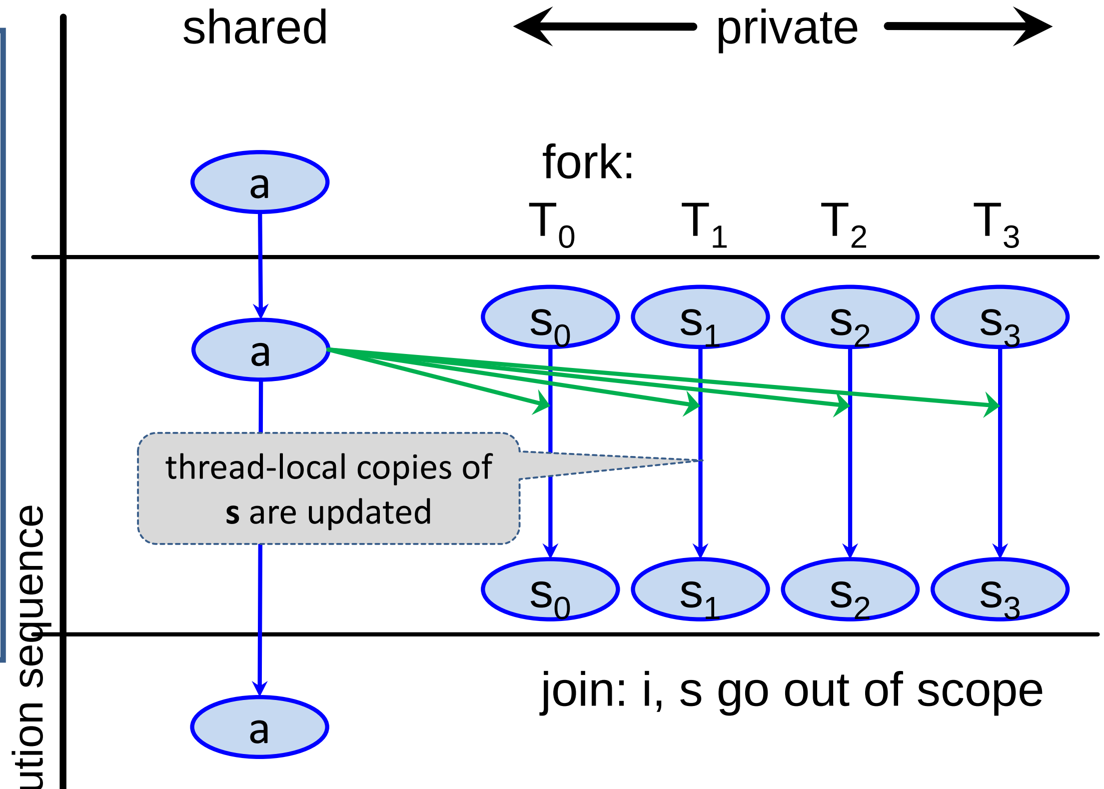
```
a = ...
b = a
a2 =  ...
```

after name dependency resolution, statements 1 and 3 can execute concurrently.
Flow dependency remains.

Privatization

C

```c
   a[k] = …;
#pragma omp parallel \
        shared(a)
  { int i; float s;
    s = 0.0;
    for (i=…;i<…;i++) {
      s += a[i];
    }
  }
```



example calculates **thread-individual** sums

useless, from a practical point of view. But bear with me - we'll fix this, eventually

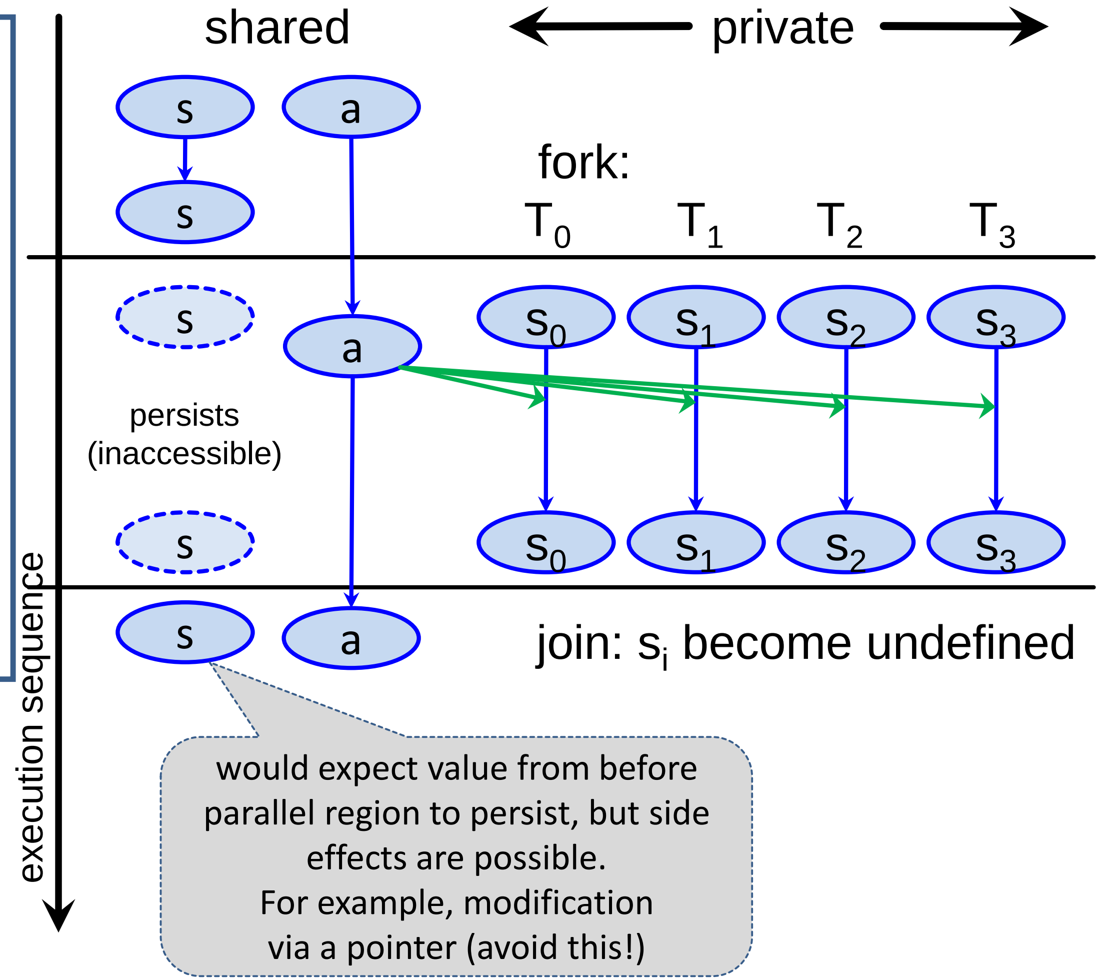
- **Block-local variables in C/C++**
  - are automatically private

Note: I would expect the same behaviour for the Fortran 2008 BLOCK construct, but this is currently not specified in the OpenMP standard

Privatization with masking

Fortran

```
real :: s
real :: a(:)
integer :: i
  s = …
!$omp parallel private(s) &
!$omp          shared(a)
  s = 0.0
  do i = …, …
    s = s + a(i)
  end do
!$omp end parallel
  … = … + s
```



- **Masking occurs**
  - for privatized variables declared outside the parallel region
- **Loop variables**
  - are always private

If **s** were shared, the program would have a race condition.

Code for work-shared Matrix-Vector multiplication: The DO / FOR directive

- **Serial**

Fortran

```
DO k = 1, n
  DO j = 1, n
    r(j) = r(j) + a(j, k) * x(k)
  END DO
END DO
```

C

```
for (k=0; k<n; k++) {
  for (j=0; j<n; j++) {
     r[j] = r[j] + a[k*n+j] * x[k];
  }
}
```

- **OpenMP parallel**

```
!$omp parallel
!$omp do
DO j = 1, n
  DO k = 1, n
    r(j) = r(j) + a(j, k) * x(k)
  END DO
END DO
!$omp end do
  … = r(…)
!$omp end parallel
```

implicit **barrier**

all threads synchronize

```
#pragma omp parallel
{
  #pragma omp for
  for (j=0; j<n; j++) {
    for (k=0; k<n; k++) {
      r[j] = r[j] + a[k*n+j] * x[k];
    }

  }
  … = r[…];
}
```

applies to j-loop

no race condition against previous definitions

Further rules for work shared loops

- **Slicing of iteration space**
  - „loop scheduling“
  - default behaviour is implementation dependent
  - usually as equal as possible chunks of largest possible size, one chunk per thread
- **In the example,**
  - slicing is done as shown some slides earlier
  - loop order was switched to avoid having many synchronizations
- **Additional clauses**
  - on both !$OMP DO and !$OMP END DO will be discussed in another talk
- **Restrictions on loop structure**
  - Trip count must be **computable** at entry to loop
  - **Disallowed:** C style loops modifying the loop variable in the loop body, or using a non-evaluable exit condition, or Fortran DO WHILE loop;
  - loop body must be a well-formed structured block with single entry and single exit point
- **Note:**
  - directive (by default) acts only on **outermost** enclosed loop

actually, we're caught between a rock and a hard place here ...

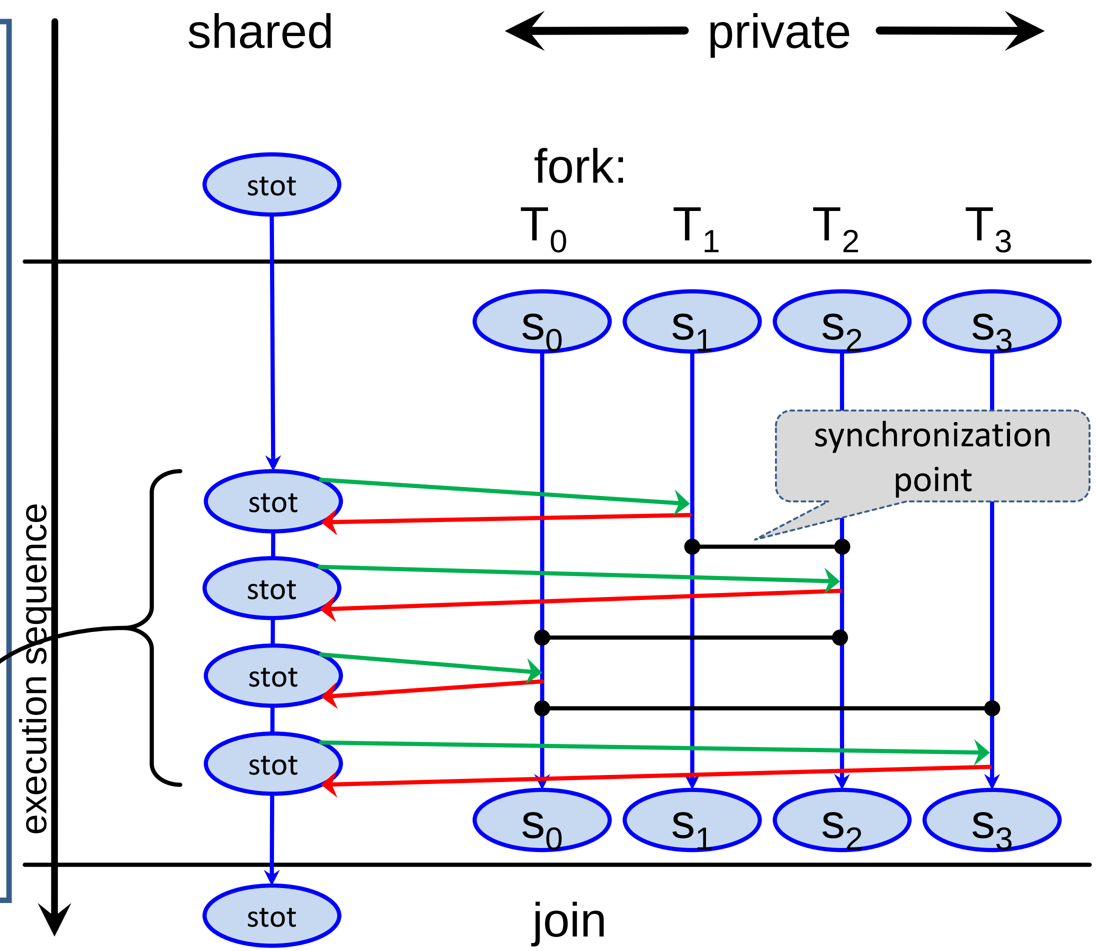
Avoiding race conditions (1): mutual exclusion via the critical directive

Fortran

```
real :: s, stot
real :: a(:)
integer :: i
  stot = 0.0
!$omp parallel private(s) &
!$omp       shared(a,stot)
  s = 0.0
!$omp do
  do i = 1, size(a)
    s = s + a(i)
  end do
!$omp end do
!$omp critical
  stot = stot + s
!$omp end critical
!$omp end parallel
```

updates are now synchronized

parallel array summation



- **Only one thread at a time can execute a critical region**
  - others must wait → code in region is **effectively serialized**

Avoiding race conditions (2): atomic updates

C

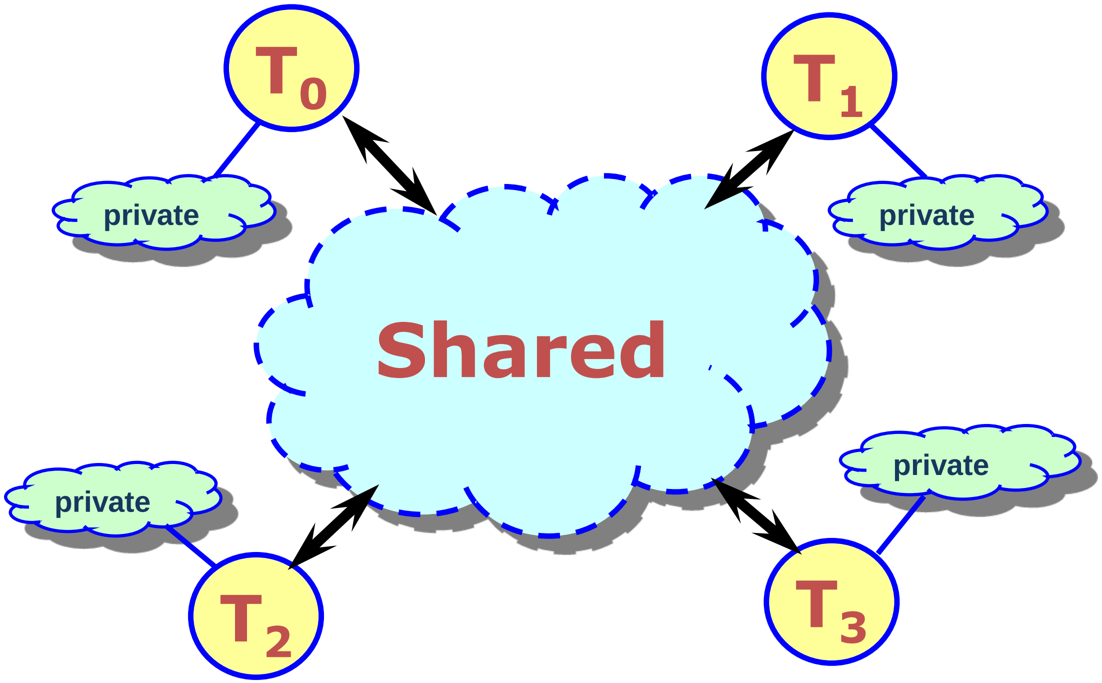
```
  float stot;
  stot = 0.0;
#pragma omp parallel \
        shared(a,stot)
  { int i; float s;
    s = 0.0;
#pragma omp for
    for (i=0;i<N;i++) {
      s += a[i];
    }
#pragma omp atomic update
    stot += s;
  }
```

parallel array summation

legacy notation
`omp atomic`
is also permitted

- **Properties of atomic operations**
  - the **atomic** directive applies only for a **single update** to a **scalar** shared variable of intrinsic type
  - this way of updating is safe when executed concurrently
  - otherwise, no synchronising effect imposed by semantics
  - if hardware atomic instructions are available, likely to be more efficient than a critical region

The two kinds of memory in OpenMP



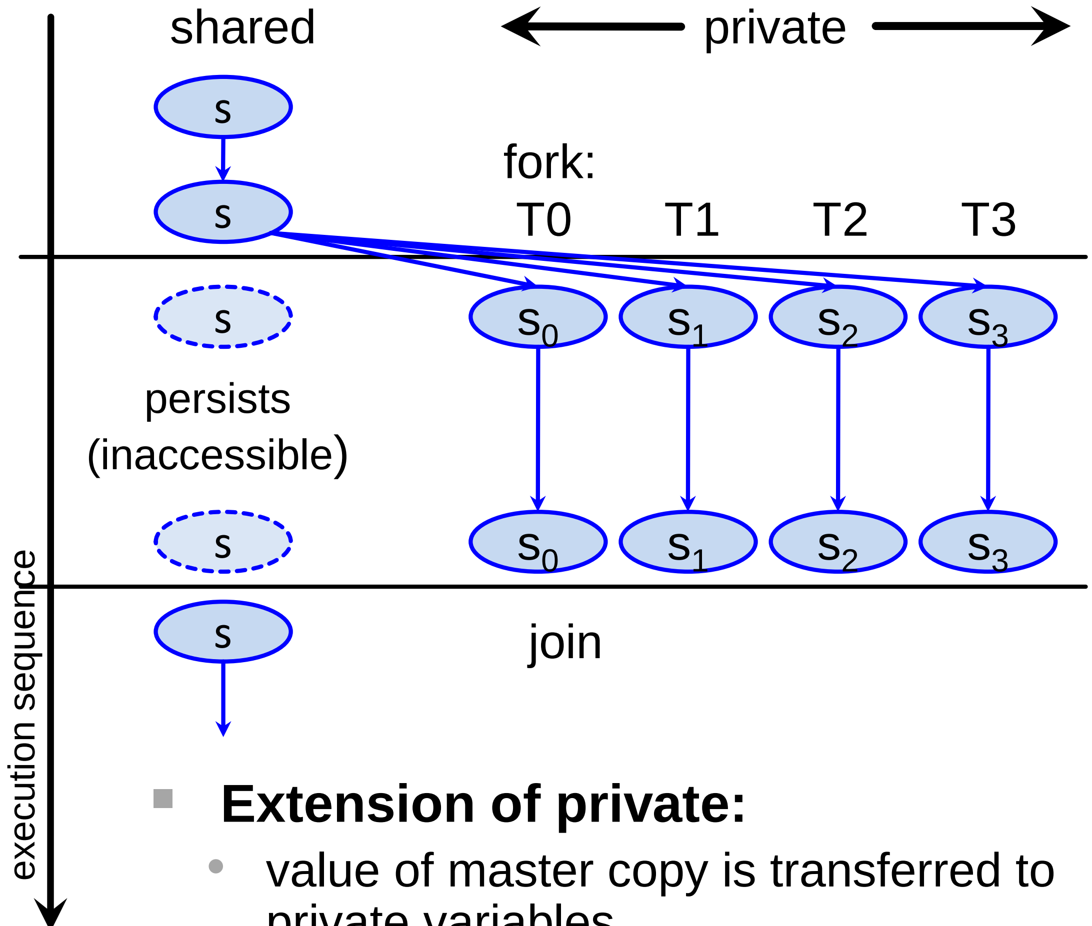
- **Data accessed by can be shared or private**
  - shared data – one instance of an entity available to all threads (in principle)
  - private data – each per-thread copy only available to thread that owns it
- **Data transfer** transparent to programmer
- **Synchronization** necessary for accessing shared data from different threads to avoid race conditions
  - implicit barrier
  - explicit directive

The firstprivate clause

Fortran

```
real :: s

  s = …
!$omp parallel &
!$omp firstprivate(s)

  … = … + s

  s = …

!$omp end parallel
  … = … + s
```

uses value from master copy



- **Extension of private:**
  - value of master copy is transferred to private variables
  - **restrictions:** not a pointer, not assumed shape, not a subobject, master copy not itself private etc.

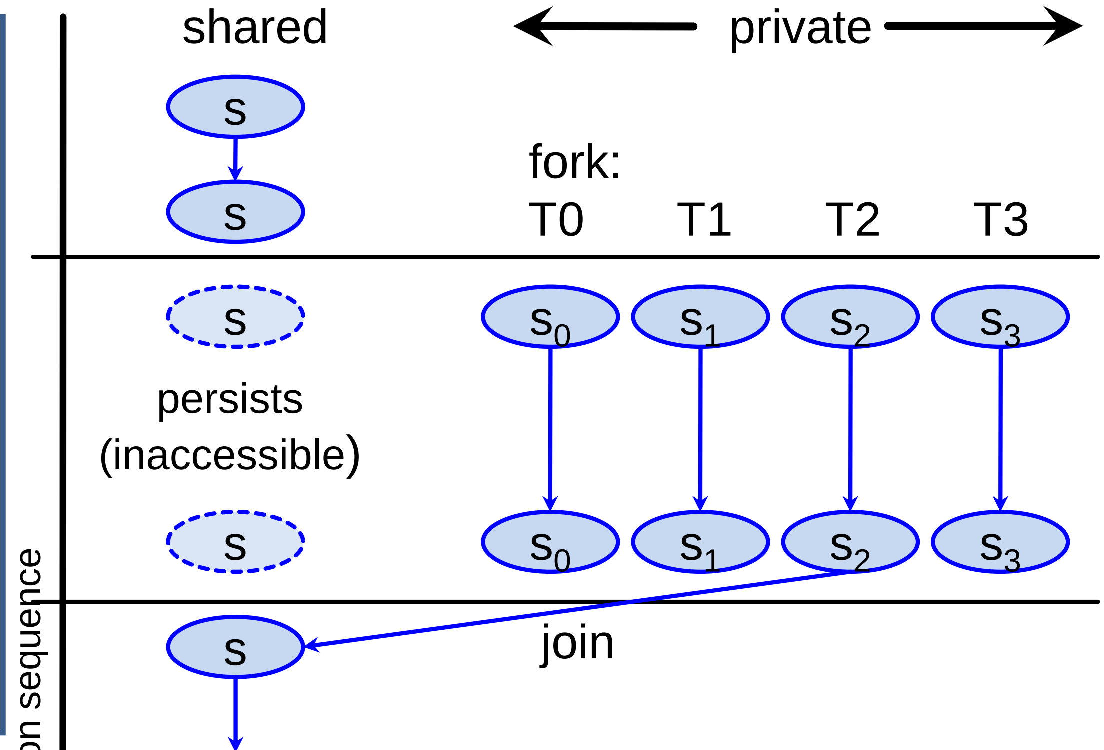
The lastprivate clause

Fortran

```
real :: s

  s = …
!$omp parallel
!$omp do lastprivate(s)
  do i = 1, n

     s = …

  end do
!$omp end do
 … = … + s
!$omp end parallel
```

on work sharing directive

s has value produced by i-loop iteration n



- **When to use?**
  - as little as possible
  - legacy code

- **Extension of private:**
  - value from thread which executes last update in the serial code is transferred back to master copy
  - restrictions similar to **firstprivate**

Data scoping defaults

- **Scoping clauses can be specified for**
  - parallel regions
  - loop work sharing constructs
- **Defaults**
  - apply if no clause is specified
  - may vary by construct, but for the above the following apply:

    pre-existing objects are by default **shared**, except for loop variables, which are **private**.

    objects declared inside the lexical or dynamic scope of the construct are **private**.

this cannot be changed, of course

- **Recommendation:**
  - specify a **default(none)** clause on each directive that permits scoping:

other values are possible

Fortran

```
!$omp parallel default(none) &
!$omp  shared(…) private(…) …
  …
```

C

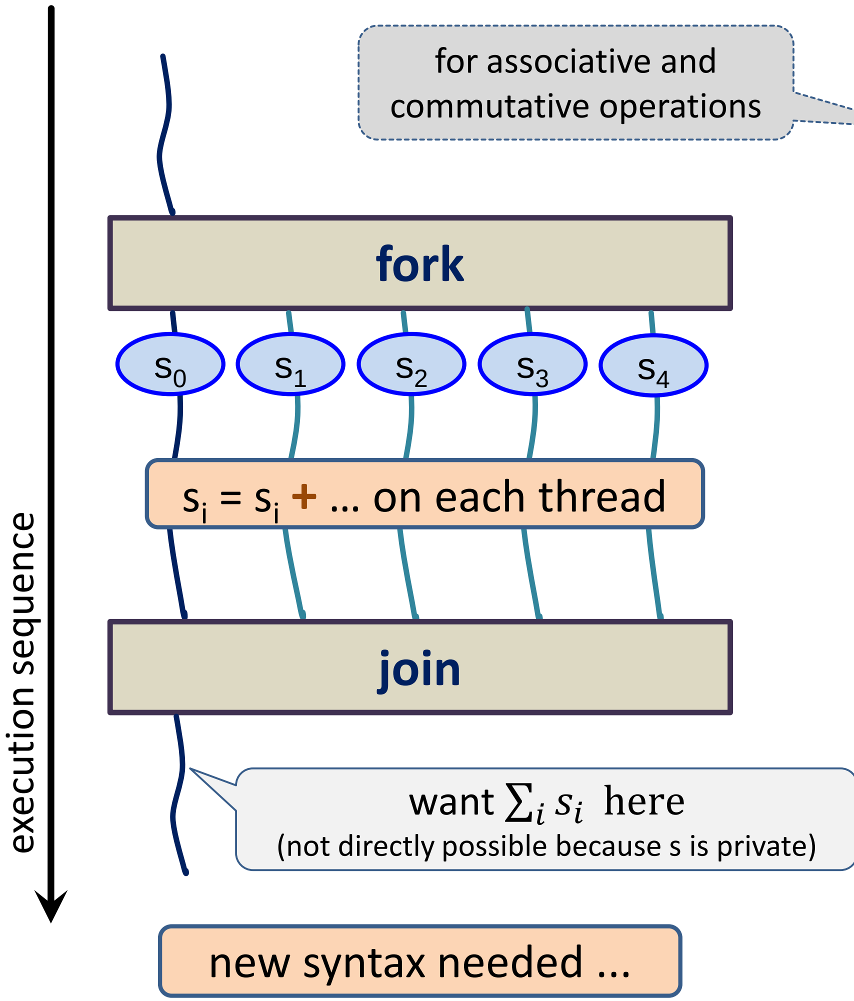
```
#pragma omp parallel default(none) \
        shared(…) private(…) …
  …
```

  - this **forces** you to explicitly consider and specify scoping for all pre-existing objects

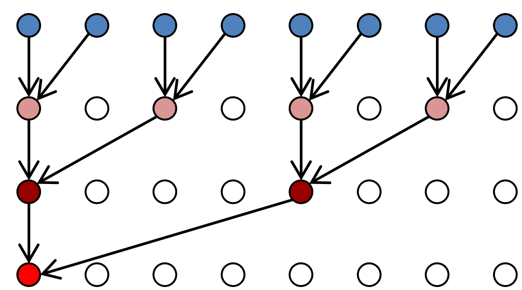
Now: Second exercise session

Reductions

Concept of Reduction



- **Seen in previous exercise:**
  - need for assembling partial results across threads
  - up to now: with critical region
- **OpenMP reductions:**
  - sometimes more efficient - implementation tunings like



    reduce complexity from $O(n_{threads})$ to $O(\log_2(n_{threads}))$
  - always easier to understand and maintain

Reduction clause

- **Example 1: Sum reduction in a parallel region**

Fortran

```
  real :: s

  s = 2.2
!$omp parallel reduction(+:s)
     …
     s = s + …

!$omp end parallel
… = … * s
```

C

```
  float s;
  s = 2.2;
#pragma omp parallel reduction(+:s)
  {
     …
     s += …;

  }
   … *= s;
```

incoming value

private copy of s (initial value 0.0)

operation consistent

s can be safely consumed due to previous implicit barrier

- value of s after end of worksharing region: $s_{\text{incoming}} + \sum_i s_i$

- **Note: multiple reductions are permitted**

```
!$omp parallel reduction(+:x,y,z)
```

```
!$omp parallel reduction(+:x,y) &
!$omp          reduction(*,z)
```

Reduction clause cont'd

- Example 2: Sum reduction in a work shared region

Fortran

```
  real :: s

  s = 2.2
!$omp parallel shared(s)
  …
!$omp do reduction(+:s)
  do i = 1, n
     …
     s = s + …
  end do
!$omp end do
  … = … * s
!$omp end parallel
```

C

```
  float s;
  s = 2.2;
#pragma omp parallel shared(s)
  {
     …
#pragma omp for reduction(+:s)
    for (i=0, i<n, i++) {
     …
     s += …;
    }
    … *= s;
  }
```

incoming value

private copy of s (initial value 0.0)

operation consistent

s can be safely consumed due to previous implicit barrier

- value of s after end of worksharing region: $s_{\text{incoming}} + \sum_i s_i$

Initial value of private reduction variables

- **Depends on operation**
- **Supported intrinsic operations:**

Fortran

Operation	Initial value
+	0
-	0
*	1
.and.	.true.
.or.	.false.
.eqv.	.true.
.neqv.	.false.
MAX	-HUGE(X)
MIN	HUGE(X)
IAND	all bits set
IEOR	all bits 0
IOR	all bits 0

C / C++

Operation	Initial value
+	0
-	0
*	1
&	0
|	0
^	0
&&	1
||	0
MAX	smallest representable value
MIN	largest representable value

Array reductions

now also supported in C/C++ (GCC 6.1)!

Fortran

```
real :: a(*)
real :: b(n)

!$omp parallel reduction(+:b) &
!$omp      reduction(*:a(1:m))
 …
```

must specify upper bound (assumed size)

C/C++

```
float *a;
float b[N];

#pragma omp parallel \
   reduction(+:b[:]) \
   reduction(*:a[0:m])
 …
```

pointee created e.g. via malloc()

same as b[0:N]

- **Example**
  - reduces complete array b and m elements of array a, elementwise
  - uses regular Fortran array section notation

    [lower bound : upper bound]

  - C example does the same as the Fortran example
  - OpenMP-defined sectioning syntax (differs from Fortran):

    [lower bound : **length**]

- **General rules:**
  - array section must be a **contiguous** object (→ no strides permitted)
  - dynamic objects must be associated / allocated, and the status must not be modified for the private copies

    no deallocate/free within reduction region

User-defined reductions

- **Using derived types**

Fortran

```
type :: fraction
  integer :: numerator, denominator
end type
```

add overloaded operators +, -, * etc.
or even user-defined operators

C

```
typedef struct {
  int numerator, denominator;
} Fraction;
```

provide functions to add, etc.

- **And now we want to write**

```
type(fraction) :: af
af = …
!$omp parallel reduction(+:af)
     …
     af = af + …
!$omp end parallel
```

```
Fraction af;
af = …;
#pragma omp parallel \
               reduction(+:af)
 {
     …
     Fraction_sum(af, …);
 }
```

- but the compiler will **refuse** to build it („+“ not known to OpenMP) unless further measures are taken ...

Declaring a user-defined reduction

```
!$omp declare reduction(+:fraction:omp_out=omp_out+omp_in) &
!$omp                         initializer(omp_priv=fraction(0,1))
```

Fortran

```
#pragma omp declare reduction(+:Fraction: \
                              Fraction_add(omp_out,omp_in)) \
                          initializer(omp_priv=Fraction{0,1})
```

C

- **Combiner**

  declare reduction(<op>:<type>:<combiner>)

  - connects to operator implementation
    Fortran: example defers to overloaded „**+**“, **C:** references „**Fraction_add**“
    special OpenMP parameters **omp_in**, **omp_out** formally describe the two operands for each operation needed

- **Initializer**

  initializer(omp_priv=...) or initializer(function(...))

  - implements initial value setting for private copies
    Fortran: uses (overloaded) structure constructor, **C** similar
    special OpenMP parameter **omp_priv** formally describes private copy

More on Work Sharing

Loops and loop scheduling

Collapsing loop nests

Parallel sections

The schedule clause

- **Default scheduling:**
  - implementation dependent
  - **typical:** largest possible chunks of as-equal-as-possible size („static scheduling“)

iteration space (threads color coded)

- **User-defined scheduling:**

Fortran

```
                       static
!$OMP do schedule( dynamic [,chunk] )
                       guided
```

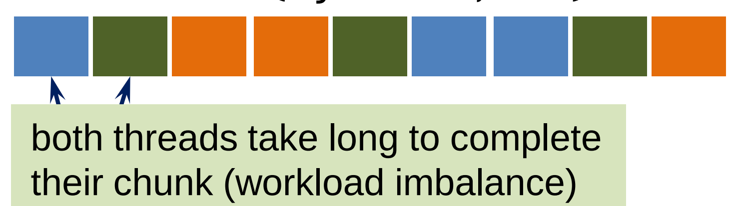
chunk: always a non-negative integer. If omitted, has a schedule dependent default value

- **1. Static scheduling**
  - `schedule(static,10)`

  - minimal overhead (precalculate work assignment)
  - default chunk value: see left

- **2. Dynamic scheduling**
  - after a thread has completed a chunk, it is assigned a new one, until no chunks are left

  `schedule(dynamic, 10)`



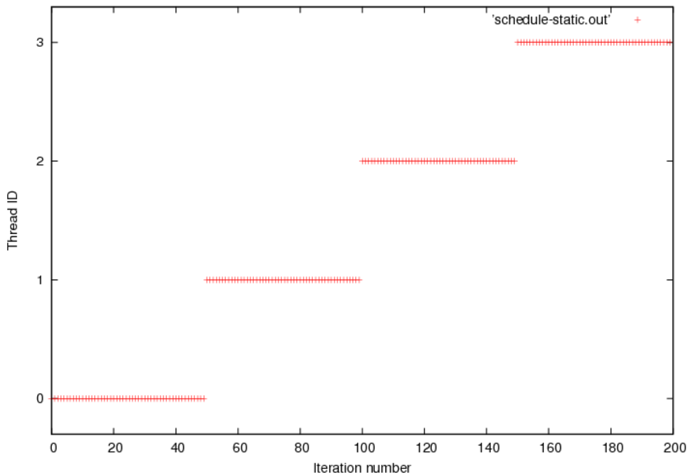
  - synchronization **overhead**
  - default chunk value is **1**

3. Guided scheduling

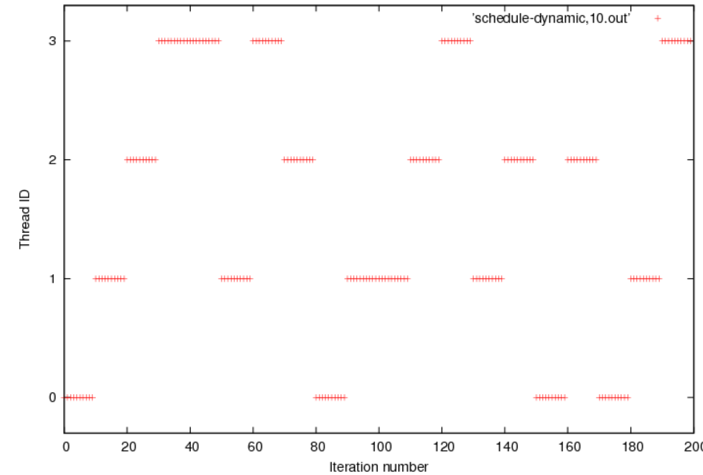
- **Size of chunks in dynamic schedule**
  - too small → large overhead
  - too large → load imbalance
- **Guided scheduling: dynamically vary chunk size.**
  - Size of each chunk is proportional to the number of unassigned iterations divided by the number of threads in the team, decreasing to chunk-size. (default: → 1)
- **Chunk size:**
  - means minimum chunk size (except perhaps final chunk)
  - default value is **1**

  - both dynamic and guided scheduling are useful for handling **poorly balanced and unpredictable** workloads.

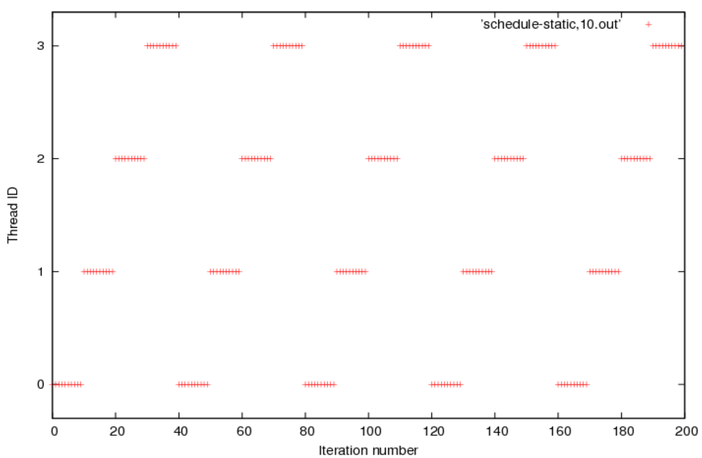
OpenMP Scheduling of simple for loops



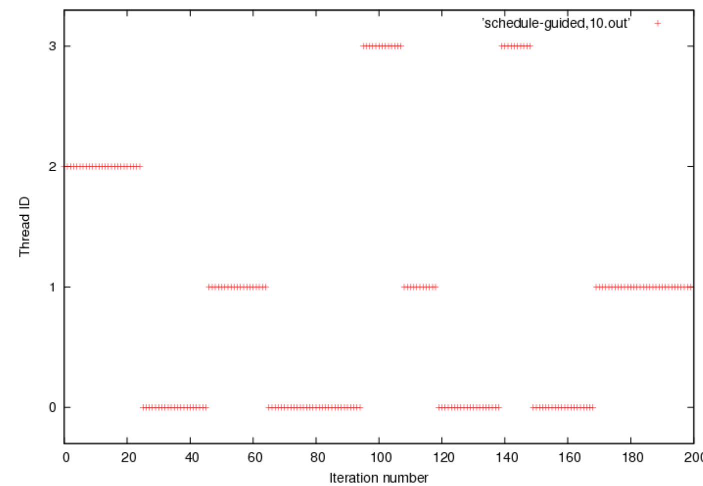
OMP_SCHEDULE=static



OMP_SCHEDULE=dynamic,10



OMP_SCHEDULE=static,10



OMP_SCHEDULE=guided,10

4. Deferred scheduling

- **Decided at run time:**

Fortran

```
                    auto
!$OMP do schedule( runtime )
```

- `auto` (automatic scheduling)
  - programmer gives implementation the freedom to use any possible mapping.
- `runtime`
  - schedule is one of the above or the previous two slides
  - determine by either setting `OMP_SCHEDULE`, and/or calling `omp_set_schedule()` (overrides env. setting)
  - find which is active by calling `omp_get_schedule()`

- **Examples:**
  - environment setting:

```
export OMP_SCHEDULE='guided'
export OMP_NUM_THREADS=4
./myprog.exe
```

  - call to API routine:

C

```
omp_set_schedule(
        omp_sched_dynamic,4);
#pragma omp parallel
{
#pragma omp for schedule(runtime)
   for (…) {
        …
   }
}
```

Final remarks on scheduling

- **Please check your compiler documentation for implementation-dependent aspects**

- **An implementation may add its own scheduling algorithms**
  - code using specific scheduling may be at a disadvantage
  - **recommendation:** Allow changing of schedule during execution

- **If runtime scheduling is chosen and OMP_SCHEDULE is not set**
  - execution starts with implementation-defined setting

Collapsing Loop nests

- **Example: Two nested loops**

```fortran
!$OMP do                    Fortran
  do k=1, kmax
    do j=1, jmax
      :
    end do
  end do
!$OMP end do
```

  - assume kmax is 2, and jmax is 3
  - then the workshared loop will scale to at most 2 threads
- **Therapy:**
  - use a collapse clause to improve scaling
  - this flattens two (or more) loop nests into a single iteration space

- **Improved example:**

```fortran
!$OMP do collapse(2)
  do k=1, kmax
    do j=1, jmax
      :
    end do
  end do
!$OMP end do
```

specify nesting level to collapse

  - slicing is performed on the virtual index I_{coll}:

I_{coll}	0	1	2	3	4	5
J	1	2	3	1	2	3
K	1	1	1	2	2	2

sequenced by serial execution order

- **Restrictions:**
  - rectangular iteration space
  - CYCLE/continue in innermost loop only

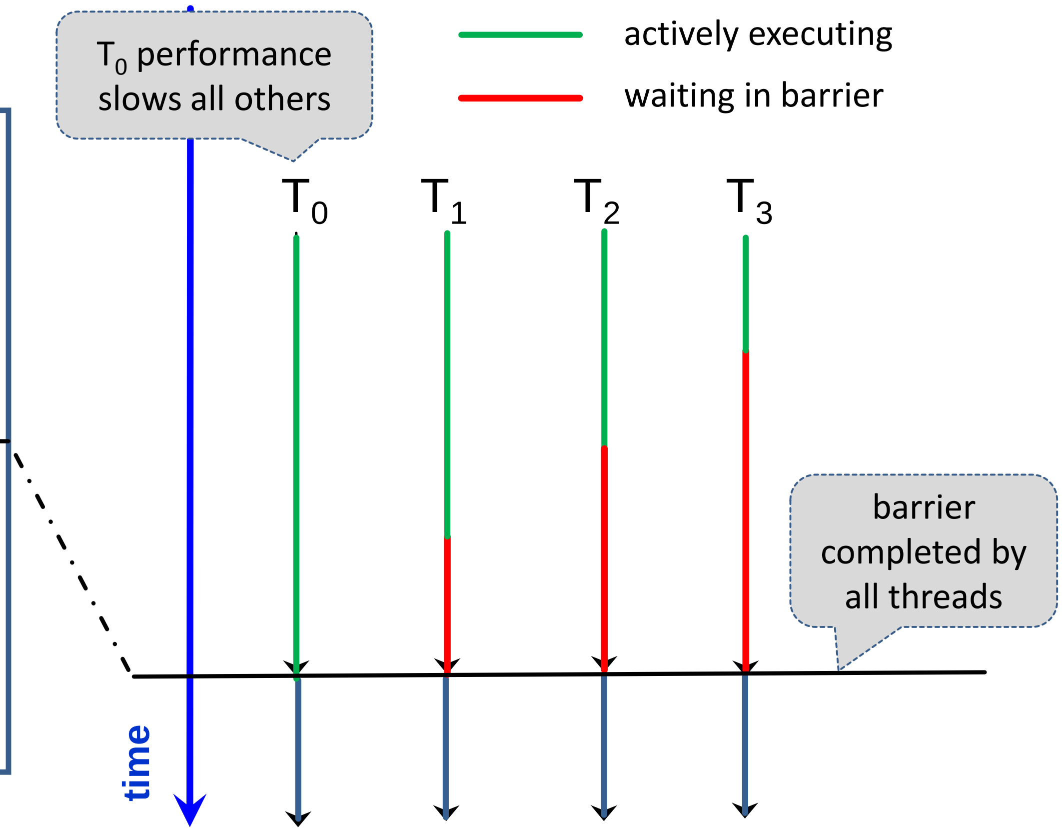
Collecting load imbalances at synchronization points

- **Example:**

```
!$omp parallel
!$omp do reduction(+:tsum)
  do k=1, kmax
    tsum = tsum + foo(a, b, c)
  end do
!$omp end do
  …
  … = tsum …

!$omp end parallel
```

implicit barrier

Fortran



- **Assumptions** on code following the synchronization point:
  - does not involve **tsum**
  - has a load imbalance that is inverse to that of preceding code block

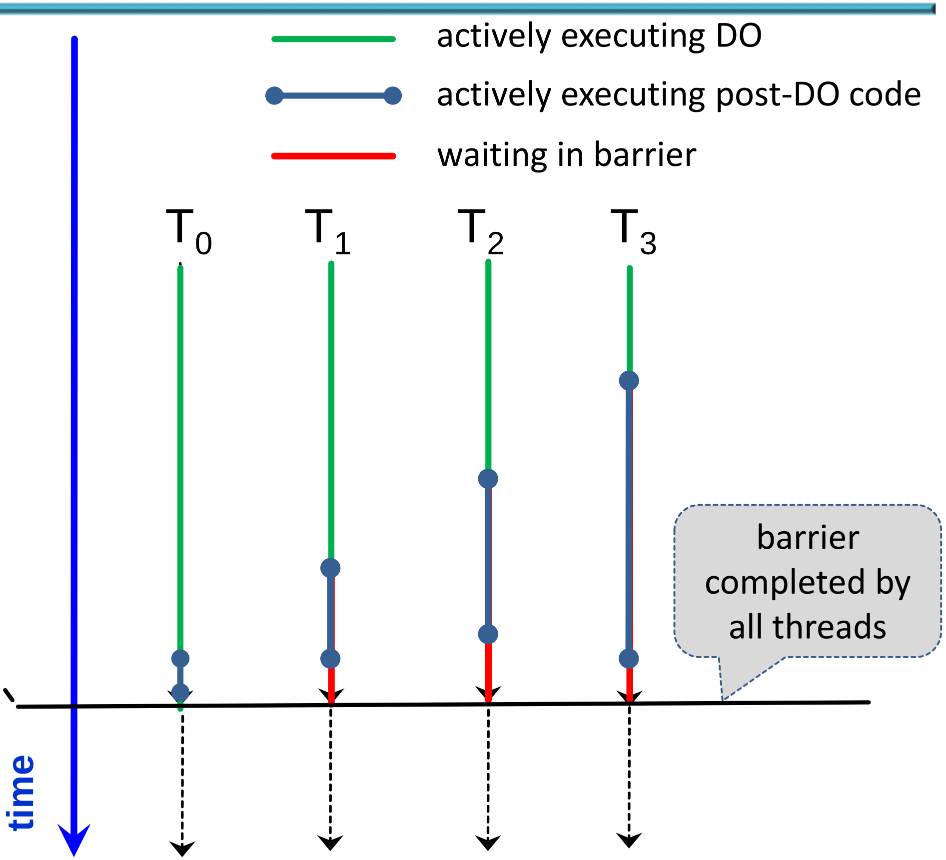
nowait clause and explicit barrier directive

```
!$omp parallel
!$omp do reduction(+:tsum)
   do k=1, kmax
      tsum = tsum + foo(a, b, c)
   end do
!$omp end do nowait

   …
!$omp barrier
   … = tsum …

!$omp end parallel
```

no barrier

code not involving tsum

Fortran



- **Reduce load imbalance**
  - by removing the barrier via the **nowait** clause
- **Assure code correctness**
  - may require explicit barrier directive before **`tsum`** (or other modified shared variable) is accessed

```
#pragma omp for reduction(+:tsum) \
                nowait
{ … }
```

C

Parallel sections

- **Non-iterative work-sharing construct**
  - distribute a static set of structured blocks

Fortran

```
!$OMP sections
!$OMP section
    :
    :
    :
!$OMP section
    :
    :
    :
…
!$OMP end sections
```

code block 1
by thread 0

code block 2
by thread 1

synchronization

C

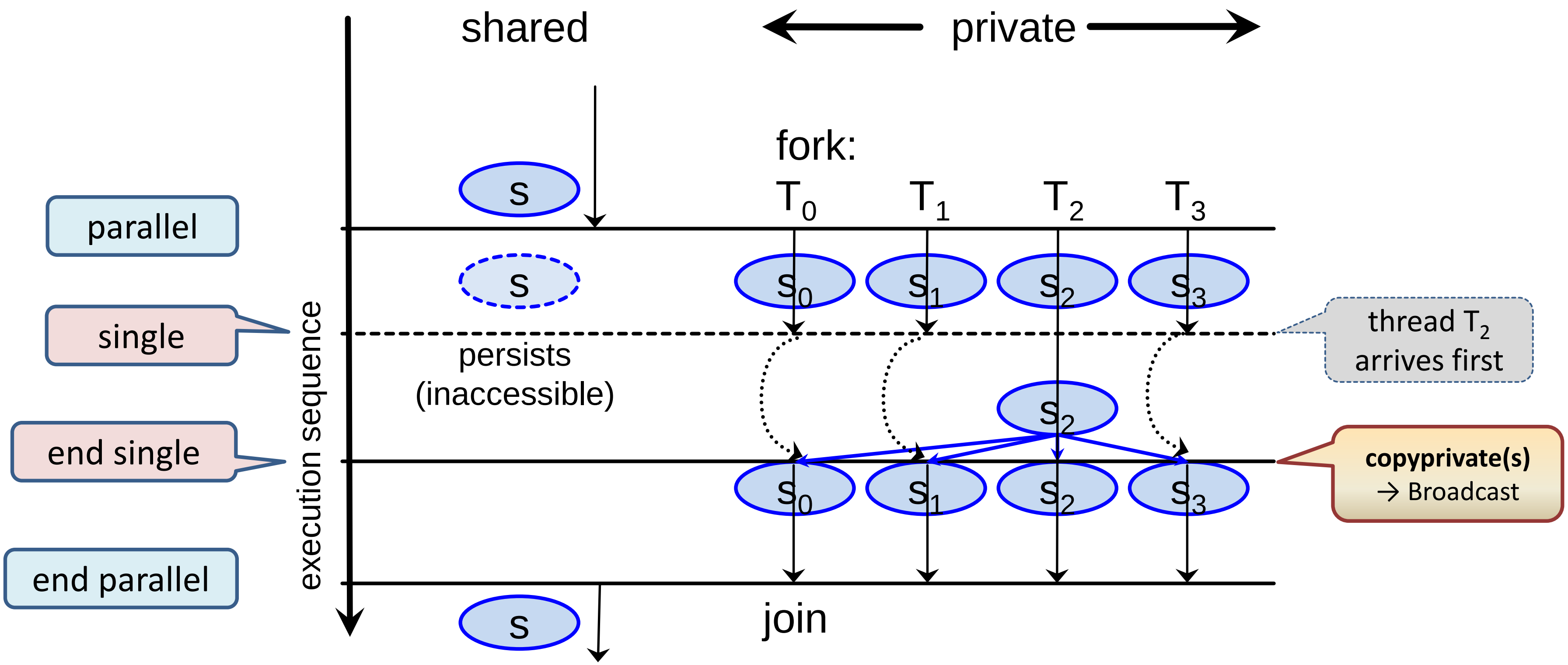
```
#pragma omp sections
#pragma omp section
 {
    :
 }
#pragma omp section
 {
    :
 }
…
// end sections
```

  - each block is executed **exactly once** by one of the threads in the team
- **Allowed clauses on sections:**
  - private, first/lastprivate, reduction, nowait

Parallel sections cont'd

- **Restrictions:**
  - **section** directive must be within lexical scope of **sections** directive, and directly enclosed (no interleaved language construct is permitted)
  - **sections** directive binds to innermost enclosing parallel region
    → only the threads executing the binding parallel region participate in the execution of the section blocks and the implicit barrier (if not eliminated with nowait)
- **Scheduling to threads**
  - implementation-dependent
  - if there are more threads than code blocks, excess threads wait at synchro-nization point
- **In modern OpenMP,**
  - **tasking** provides a much more flexible and scalable way to implement this and much more general patterns → will be treated tomorrow

single directive and copyprivate clause



- **Execution:**
  - only one thread of the team executes the statements in the block
  - others go to the end of the block
- **Synchronization**
  - of all threads at end of **single** block

single directive syntax

Fortran

```
real :: s

  s = …
!$omp parallel private(s)

!$omp single
  …
  s = …
!$omp end single &
!$omp     copyprivate(s)
 … = … + s
!$omp end parallel
```

block executed by one thread only

C

```
float s;

  s = …;
#pragma omp parallel private(s)
 {
#pragma omp single \
        copyprivate(s)
 {
  …;
  s = …;
 }  // end single
… = … + s;
} // end parallel
```

- **Note:**
  - update of shared variables inside a single block is safe against subsequent accesses, due to synchronization at the end of that block

Work sharing with single: the nowait clause

- **Implement a self-written work scheduler**
  - one possible scheme (of many ...), sketched only:

Fortran

```
   …
!$omp parallel
  do iw=1, nwork
!$omp single
     …
!$omp end single nowait
     …
!$omp barrier
  end do ! iw
!$omp end parallel
```

produce work for iteration 1

produce work for iteration iw+1 (using a non-trivial amount of time e.g. I/O)

other threads **continue** and work on iteration iw

  - not the most efficient method
    → preferably use tasking (covered tomorrow); the single construct will be relevant in this context

Global variables and threading

Global variables and their default scope

- **Examples:**

Fortran

```
module my_globals
  implicit none
  integer :: my_count
  real, allocatable :: a(:)
  …
end module
```

FORTRAN 77

```
REAL :: A(1000)
INTEGER :: MY_COUNT
COMMON / MY_GLOBS / A, MY_COUNT
```

C

```
#define NMAX 1000
float a[NMAX];
void my_func() {
  extern float a;
  …
}
```

- **Such variables by default have shared scope**
- **The same applies for variables with the SAVE (Fortran) or static (C) attribute**

Implication:

- code using such memory is often **not thread-safe**, unless mutual exclusion is used for accessing the objects

Privatizing global objects

- **When program semantics requires that each thread work on its own copy, privatization is necessary**
  - not exactly the same as private variables → separate syntax needed
- **C:**
  - `#pragma omp threadprivate(list)`
  - list is a comma-separated list of file-scope, namespace-scope, or static block-scope variables that do not have incomplete types
- **Fortran:**
  - `!$omp threadprivate(list)`
  - list is a comma-separated list of named variables and named common blocks. Common block names must appear between slashes.
- **Objects start out with master copy existing only**
  - thread-private copies (with undefined values) spring into existence when the first parallel region is started

Further properties of threadprivate storage

- **Copyin clause**
  - broadcasts object values from master copy to thread-individual copies
  - works analogous to the firstprivate clause

```
allocate(a(ndim))
a(:) = …
!$omp parallel copyin(a)
  … = a(i) + …
  a(i) = …
!$omp end parallel
```

Fortran

uses value set on master

- **Subsequent parallel regions:**
  - thread-individual copies retain their values (by thread) if

1. second parallel region not nested inside first
2. same number of threads is used
3. no dynamic threading is used

Note: none of the potential violations of the above three rules are dealt with in this course

Recommendations:

- Avoid using global variables in the context of threading
- Use object-based design instead

... useful varia

The master construct

Fortran

```
!$omp master
  block
!$omp end master
```

C

```
#pragma omp master
    { block }
```

- **Only thread zero (from the current team) executes the enclosed code block**
  - there is **no implied barrier** either on entry to, or exit from, the master construct. Other threads continue **without synchronization**
- **Notes:**
  - Not all threads must reach the construct; if the master thread does not reach it, it will not be executed at all
  - this is not a work sharing construct, it only serves for execution control

Combined constructs

- **Certain combinations of constructs can be fused**
  - the result is a single construct that behaves as if the two individual ones were tightly nested
  - may be more efficient due to reduced synchronization needs
  - is often easier to read
- **Example: joint "parallel do"** (C has "parallel for" here ...)

Fortran

```
!$omp parallel
!$omp do
  do i=1, n
     …
  end do
!$omp end do
!$omp end parallel
```

```
!$omp parallel do
  do i=1, n
     …
  end do
!$omp end parallel do
```

  - both variants have the same semantics

Conditional parallelism

- **Put an "if" clause on a parallel region**

```
!$omp parallel if (n > 8000)
   ...
!$omp end parallel
```

Fortran

process work item of size $O(n^p)$

  - specify a scalar logical argument
  - may require manual tuning for properly dealing with thread count dependency etc.

- **Specific uses:**
  1. execute serially for small problem sizes (parallel overhead may kill performance)
  2. suppress nested parallelism in a library routine:

```
#pragma omp parallel if \
        ( ! omp_in_parallel() )
{
  ...
}
```

logical / int function from OpenMP run time: are we already parallel in executing scope?

Now: Third exercise session

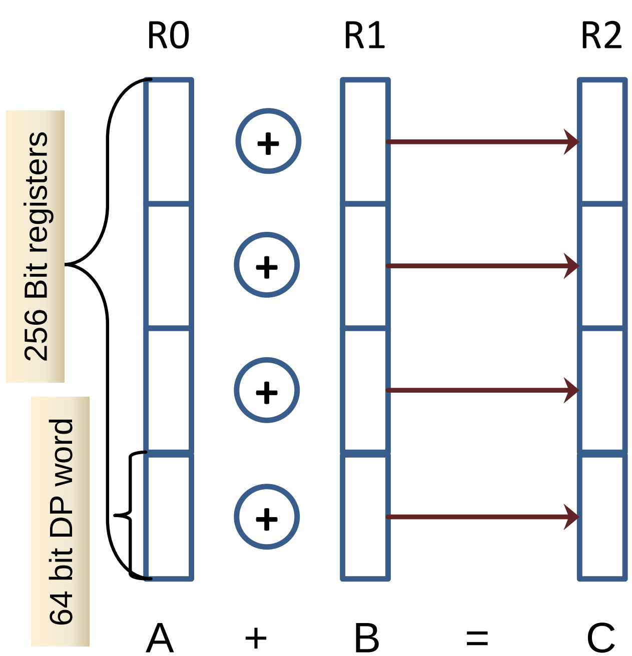
OpenMP 4.0
SIMD (vectorization) directives

Optimization of innermost loop structures

Acknowledgment due to M. Klemm (Intel)

SIMD - single instruction multiple data

- **Example:**
  - Sandy Bridge vector unit
  - 256 Bit SIMD
  - addition of 8 Byte words



4 elements with 1 **AVX instruction**

- **Instruction capability**
  - 1 vector add and 1 vector mult per cycle → theoretical Peak 8 Flops/cycle (double precision)
- **LD/ST issue capability for Sandy Bridge**
  - 4 Words LD/cycle
  - 4 Words ST/(2 cycles)
  - performance boost depends on algorithm, including its temporal locality properties
- **More recent processors may have more advanced units**
  - more SIMD lanes
  - additional vector operations

Before OpenMP 4.0 …

- **… programmers had to rely on auto-vectorization,**
  - or use **non-portable** extensions
    - programming models (e.g. Intel Cilk Plus)
    - intrinsics (e.g. `_mm_add_pd()`)
    - compiler pragmas

C

```
#pragma omp parallel for
#pragma vector always
#pragma ivdep
for (int i=0; i<N; i++) {
  a[i] = b[i] + …;
}
```

which may or may not get ignored by the compiler

OpenMP SIMD loop construct

- **Vectorize a loop nest**
  - cut into chunks that fit into a SIMD vector register
  - without parallelization of the loop body

- **Syntax**

```c
#pragma omp simd [clause[[,] clause], …]
for loops
```
C

```fortran
!$omp simd [clause[[,] clause], …]
do loops
[!$omp end simd]
```
Fortran

Simple example

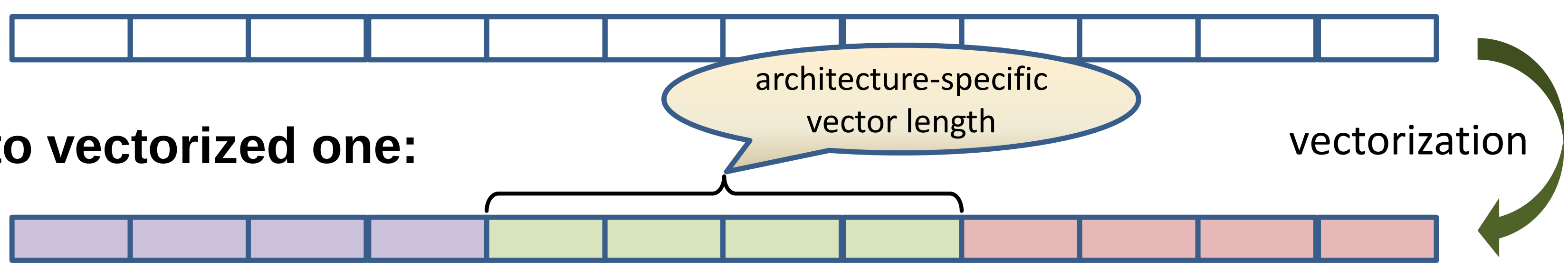
- **Scalar product**

```c
void sprod(float *a, float *b, int n) {
  float sum = 0.0f;
#pragma omp simd reduction(+:sum)
  for (int k=0; k<n; k++) {
    sum += a[k] * b[k];
  }
```

C

- **Converts serial element-wise execution**

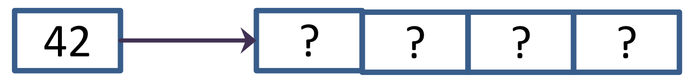
to vectorized one:



Data Sharing Clauses

- **Existing ones adapted to SIMD-style execution**
  - required for more complex loop bodies

- `private (`*`var-list`*`)`



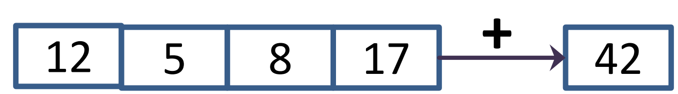
  create uninitialized vectors for variables in var-list
  (loop iteration variables are private by default)

- `lastprivate (var-list)`

  copy last iteration value to variable at the end of the construct

- `reduction (op:var-list)`

  create private copies for variables in var-list and apply the reduction operation ***op*** at the end of the construct



Loop clauses (1)

- `safelen (length)`
  - maximum distance between iterations that can run concurrently without breaking any dependencies

```
#pragma omp simd safelen(5)
  for (int k=0; k<n; k++) {
    b[k] = a[k] * b[k-j];
  }
```

- programmer assures j > 5
- compiler can use a vector length of at most 6

- `linear (list[:linear-step])`
  - produce private copy of a variable that is in linear relationship with the loop iteration variable: $x_i = x_{start} + (i - i_{start}) * \text{linear-step}$

Loop clauses (2)

- `aligned (list[:alignment])`
  - specifies that variables in the list are aligned, either by the specified integer value of alignment in units of bytes, or in implementation-specific manner

- `collapse(n)`
  - collapse iteration space of a SIMD loop nest

- **Parallelize and vectorize a loop nest**
  - distribute iteration space of loops across threads
  - subdivide loop chunks to be processed in SIMD registers

- **Syntax**

C

```
#pragma omp for simd [clause[[,] clause], …]
for loops
```

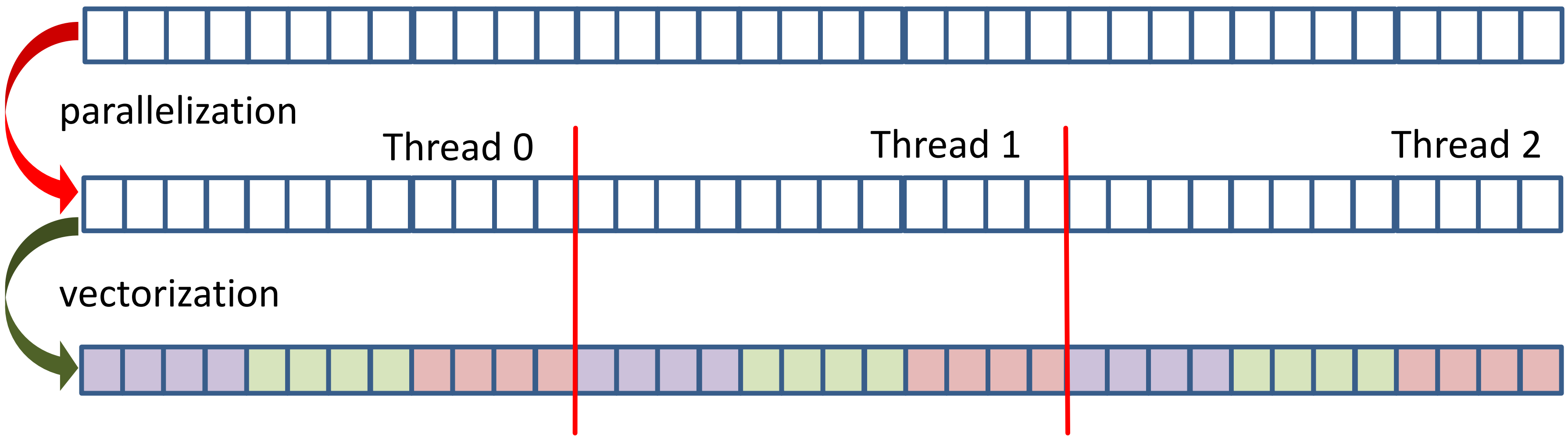
Fortran

```
!$omp do simd [clause[[,] clause], …]
do loops
[!$omp end do simd]
```

Scalar product again …

```
void sprod(float *a, float *b, int n) {
  float sum = 0.0f;
#pragma omp for simd reduction(+:sum)
  for (int k=0; k<n; k++) {
    sum += a[k] * b[k];
  }
```

assume invocation by all threads executing in a parallel region



Function vectorization

- **Function call inside SIMD region**

```
float min(float a, float b) {
  return a < b ? a : b;
}

float distsq(float x, float y) {
  return (x - y)*(x - y);
}

void example() {
#pragma omp for simd
  for (i=0; i<N; i++) {
    d[i] = min(
      distsq( a[i],b[i] ),c[i] );
  }
}
```

may fail if functions outside file scope

- **Therapy: explicitly declare for use in vectorized loops**
  - C/C++ syntax

```
#pragma omp declare simd
function def. or decl.
```

  - Fortran syntax

```
!$omp declare simd &
!$omp (proc-name-list)
```

  - clauses are also supported
  - causes generation of multi-version code by the compiler

Code generation for SIMD functions

- **vectorized versions of generated functions are shown**

```
#pragma omp declare simd
float min(float a, float b) {
  return a < b ? a : b;
}

#pragma omp declare simd
float distsq(float x, float y) {
  return (x - y)*(x - y);
}


void example() {
#pragma omp for simd
  for (i=0; i<N; i++) {
    d[i] = min(
      distsq( a[i],b[i] ),c[i] );
  }
}
```

```
vec8 min_v(vec8 a, vec8 b) {
  return a < b ? a : b;
}
```

```
vec8 distsq_v(vec8 x, vec8 y) {
  return (x - y)*(x - y);
}
```

no SIMD directives permitted inside vectorized functions!

```
vd = min_v(
     distsq_v (va, vb), vc );
```

Clauses applicable for declare simd

- `simdlen (length)`
  generate function to support supplied vector length

- `uniform (argument-list)`
  argument has a constant value between iterations of invoking loop

- `inbranch` vs. `notinbranch`
  function always / never called from inside an if statement

- `linear (list[:linear-step])`
- `aligned (list[:alignment])`
- `reduction (op:var-list)`

as before

Final remarks on SIMD

- **Case studies on vectorizable applications:**
  - show performance improvements of factor 1.5 – 4.3 compared to auto-vectorized code
  - you may not be as successful, but a 20% performance improvement for 45 min optimization work is also quite nice

- **Resolution of dependencies**
  - may sometimes involve code restructuring and splitting of loops

- **Further features available: combination of device control directives with SIMD**
  - not discussed in this talk

Now: Fourth exercise session

More on Synchronization and Correctness

Memory model
Identifying correctness problems
Named critical regions
Atomic operations
Mutual exclusion with locks

Concurrent updates on shared variables

- **Scenario:**

Fortran

```
real :: a

  a = 0
!$omp parallel shared(s) num_threads(2)
  a = a + 1
  write(*,'(''a on thread '',i0,' is '',i0)') &
              omp_get_thread_num(), a
!$omp end parallel
write(*,'(''a after construct is '',i0)') a
```

fix number of threads for parallel execution

possible results for first write

Thread 0	Thread 1
1	1
2	1
1	2

possible results for second write: 1 or 2

  - the above is **non-conforming**
  - data race causes **unpredictable** results to be produced
- **Reason:**
  - different threads can have different views on same variable: temporary view (in-register value) vs. memory value
  - these two views become inconsistent when a thread modifies the variable

Memory consistency rules

- **Flush Operation**
  - is performed on a set of (shared) variables or on the whole thread-visible data state of a program
  - **discards** temporary view:

    → modified values are forced to cache/memory (requires exclu-sive ownership)

    → next read access must be from cache/memory
  - **further** memory operations only allowed after all involved threads complete flush:

    → restrictions on memory in-struction reordering (by compiler)

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

recommend to avoid use of explicit flushes

- **Ensure consistent view of memory:**
  - Assumption: want to write a data item with one thread, read it with another one
  - Order of execution **required**:

1. thread A writes to shared variable
2. thread A flushes variable
3. thread B flushes same variable
4. thread B reads variable

- The challenge is to assure step 3 happens **after** step 2
- OpenMP synchronization semantics assure this as well as the necessary flush operations (if correctly used)

But it is possible to make mistakes ...

- **Example: update via critical region**
  - mutual exclusion is only assured for the statements inside the block
    i.e., subsequent threads executing the block are synchronized against each other
- **If other statements access the shared variable, you may be in trouble:**

```
!$omp parallel shared(x) …
  :
!$omp critical
  x = x + y
!$omp end critical
  …
  a = f(x, …)
!$omp end parallel
```

Race on read to x.
A barrier is required **before** this statement to assure that all threads have executed their atomic updates

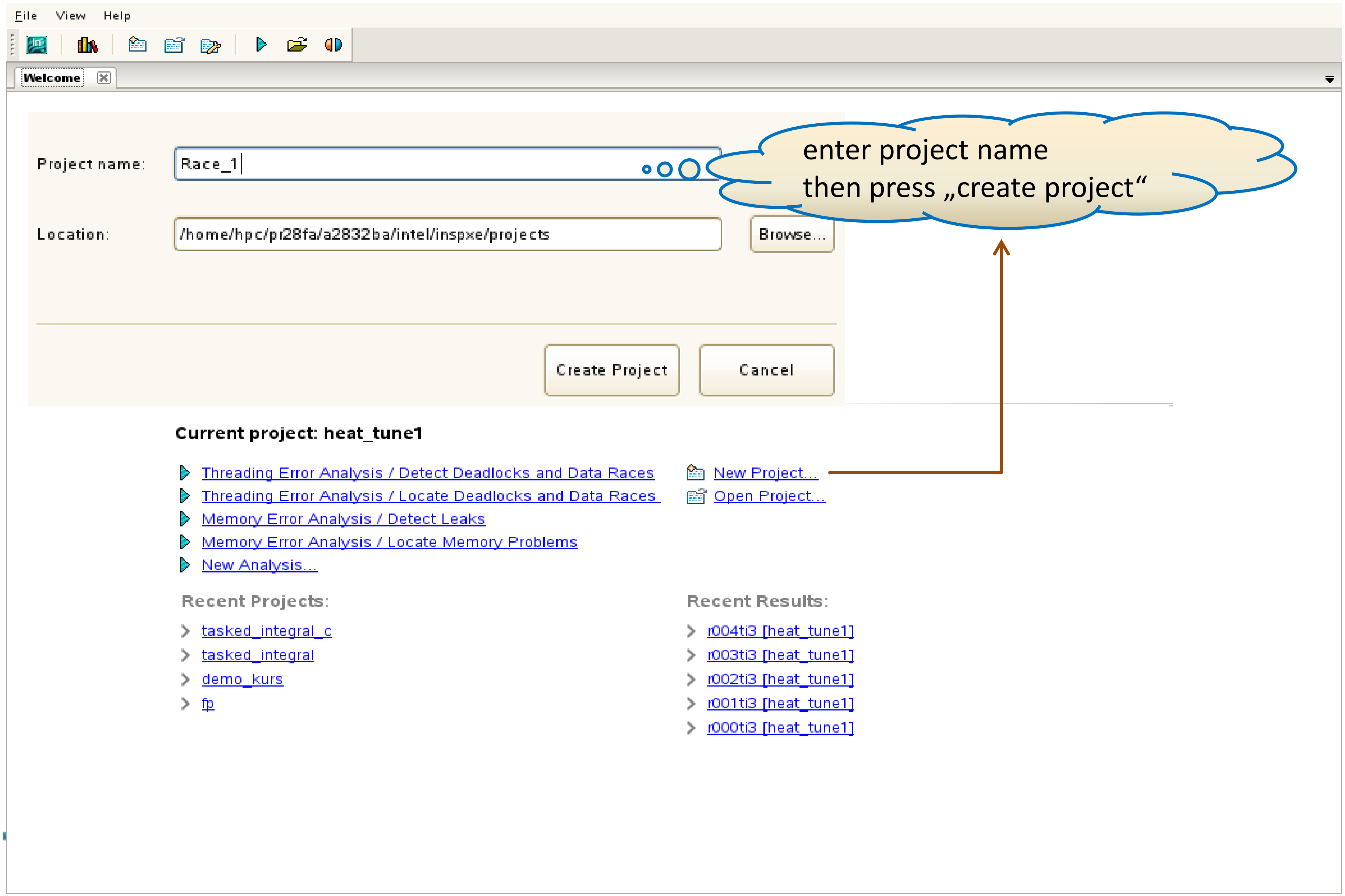
Using Intel Inspector on x86-based systems

- **OpenMP correctness analysis:**
  - no special compiler option needed (except perhaps –g)
  - GUI also for Linux-based system
- **Identify memory issues in addition to threading issues**
  - leaks, dangling pointers etc.
- **Start up GUI**
  - prerequisites: set up environment and possibly stack limit
  - then, invoke the GUI with

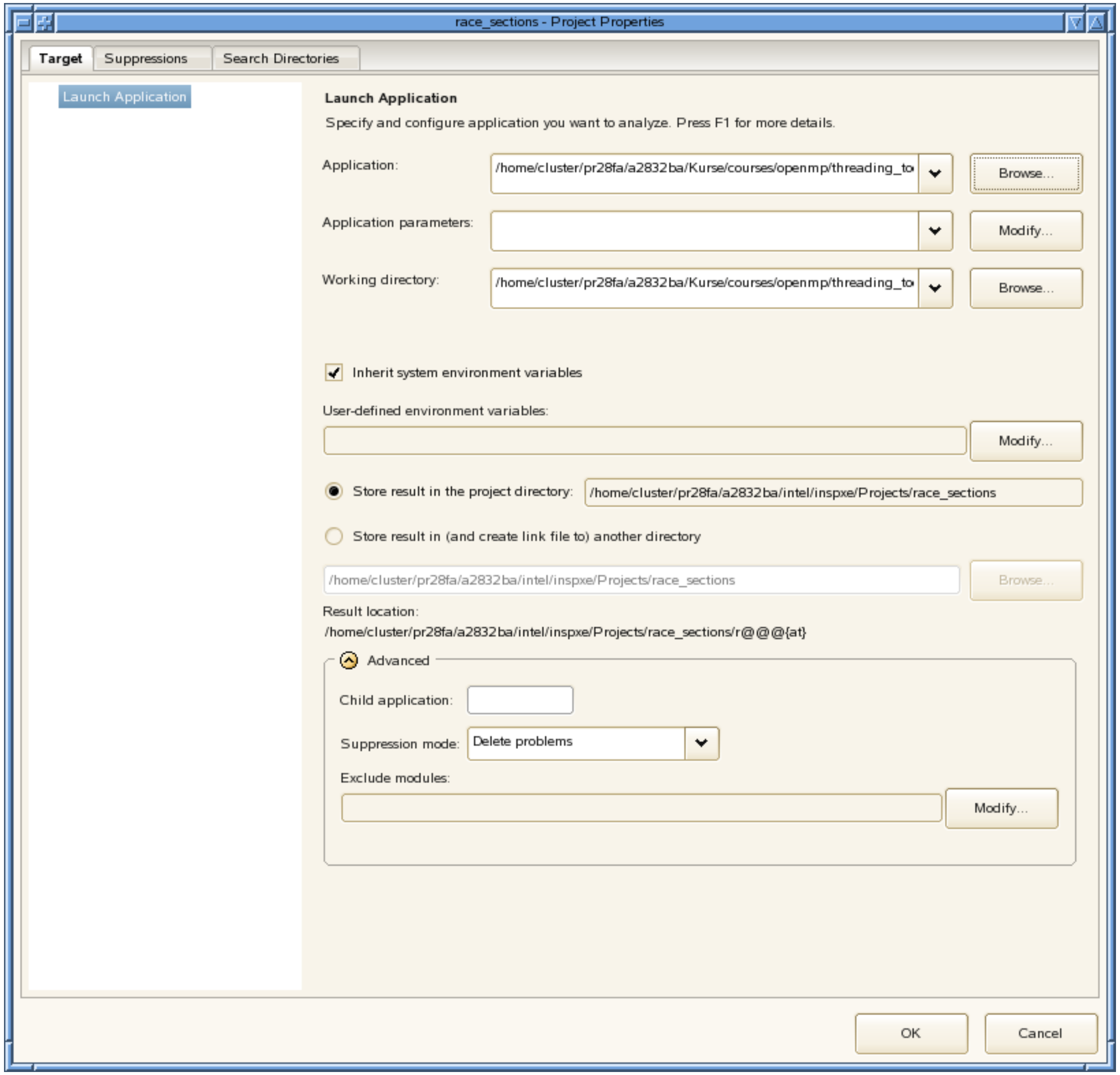
```
inspxe-gui &
```

  - command line `inspxe-cl` is also available, but will not be discussed in this talk

Starting up the GUI → start a new project

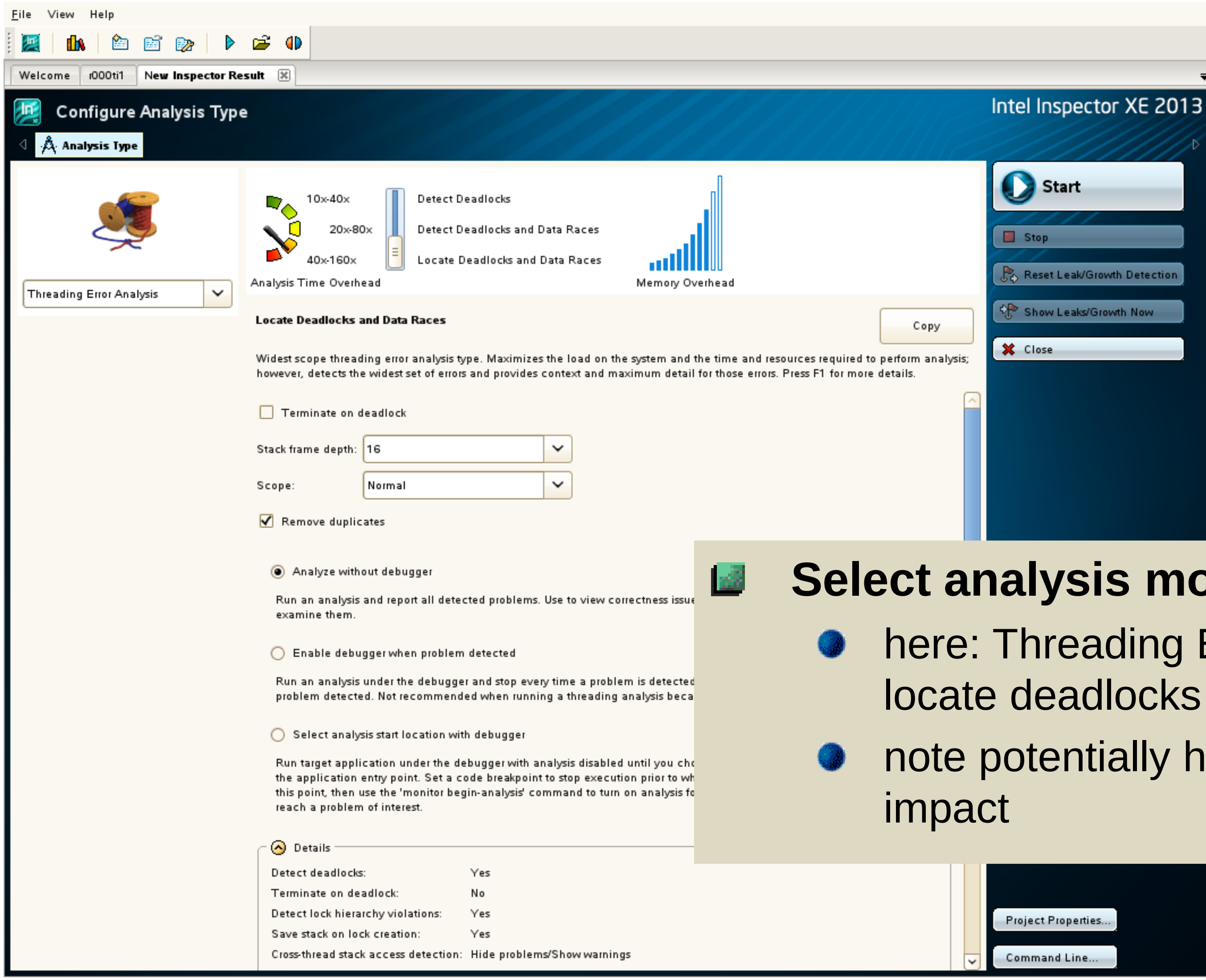


Configure the project



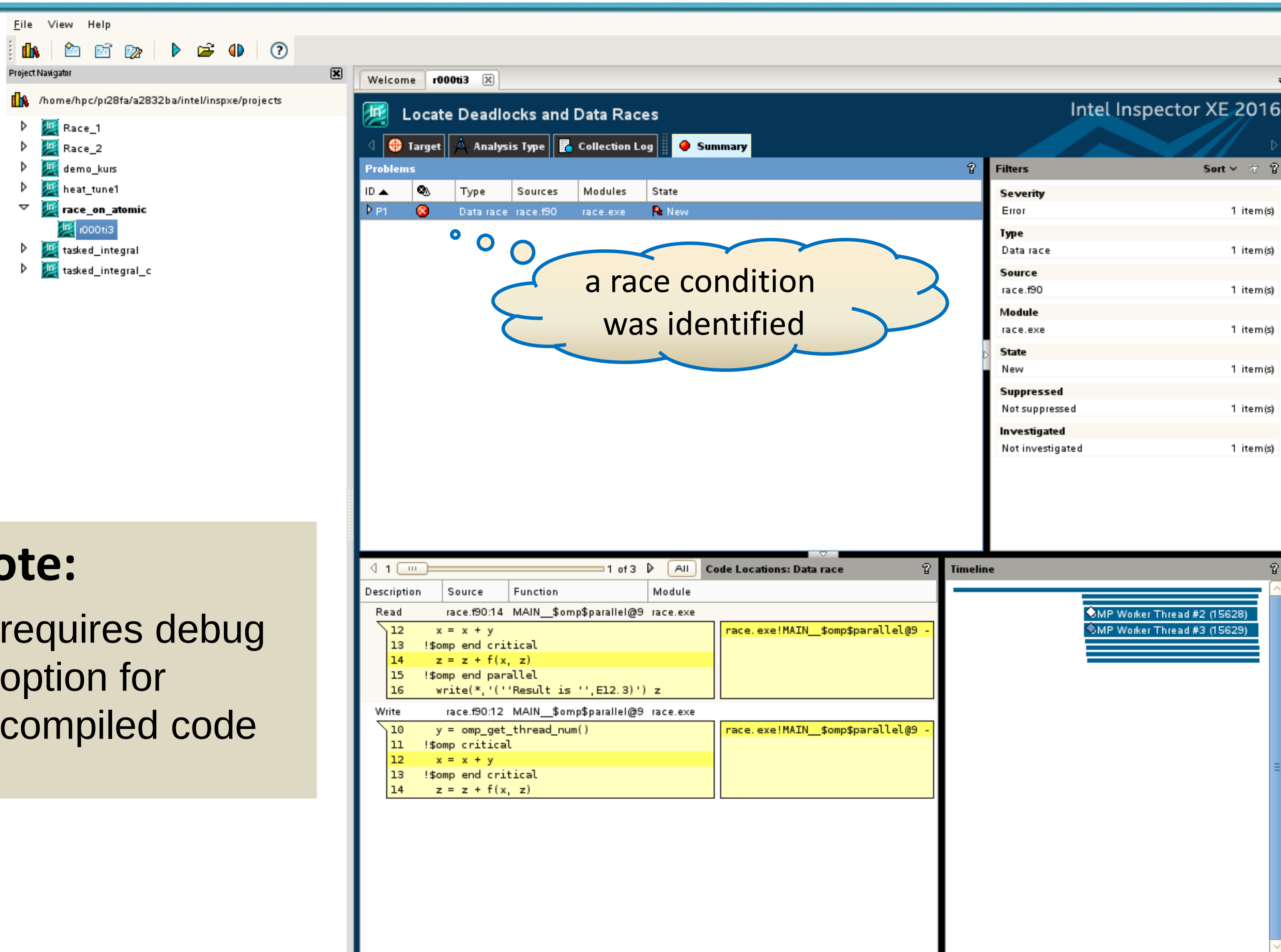
- **Needed information:**
  - executable name (must have been built with OpenMP)
  - executable path (autocompleted)
  - arguments if needed by executable
- **Further advanced settings are possible**

Run Analysis: New → Analysis Result



- **Select analysis mode, then start**
  - here: Threading Error Analysis → locate deadlocks and data races
  - note potentially high performance impact

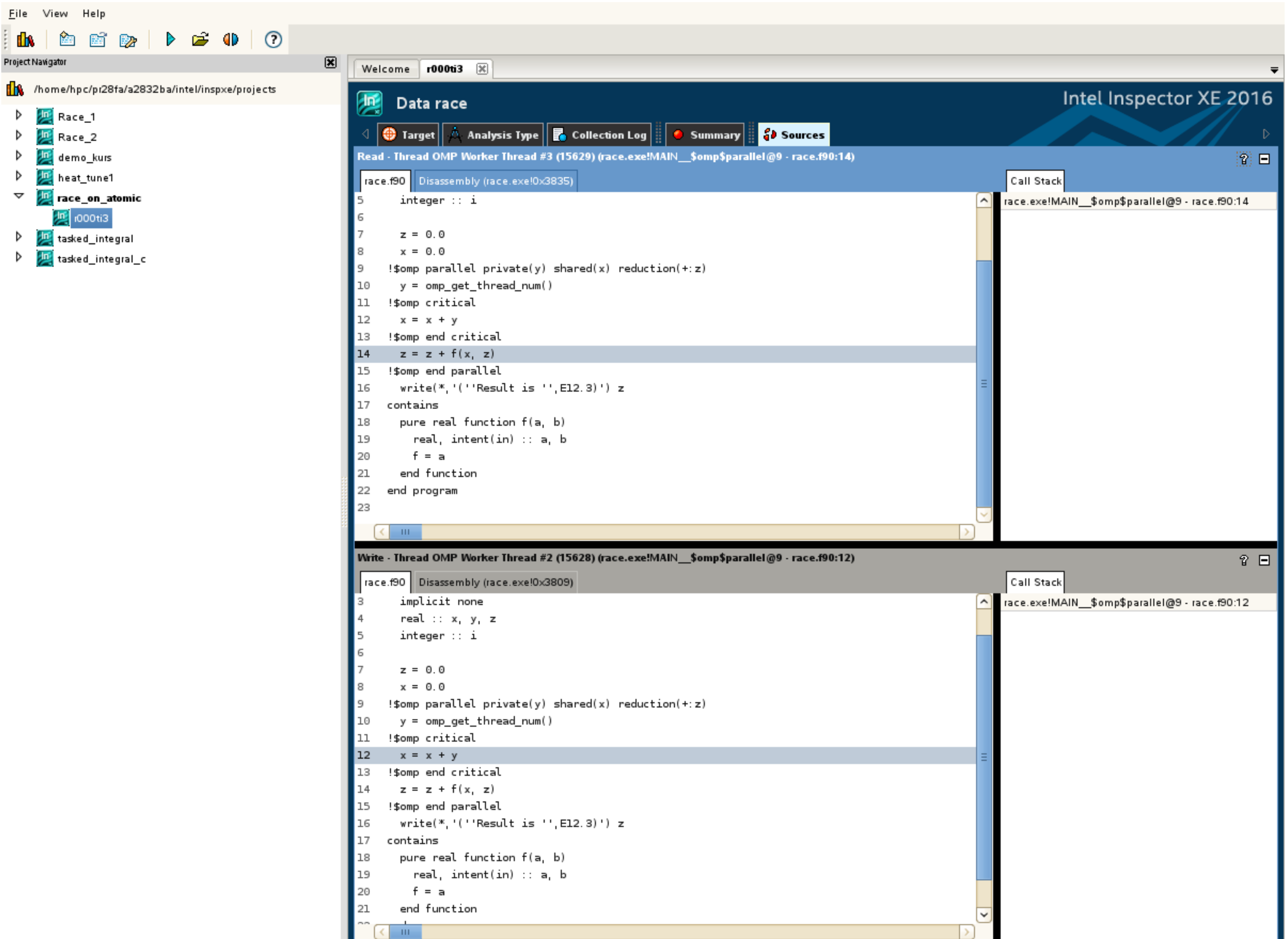
Error indication by severity



Note:

- requires debug option for compiled code

Source window: conflicting reads/writes



Critical regions: consider multiple updates

a) **same** shared variable

Fortran

thread 0	thread 1

`subroutine foo()`
`!$omp critical`
`  x = x + y`
`!$omp end critical`
	`subroutine bar()`
	`!$omp critical`
	`  x = x + z`
	`!$omp end critical`

critical region is **global** → OK

b) **different** shared variables

Fortran

```
subroutine foo()
!$omp critical
  x = x + y
!$omp end critical
```

```
subroutine bar()
!$omp critical
  w = w + z
!$omp end critical
```

mutual exclusion not required → unnecessary loss of performance

Named critical regions

- **Solution:**
  - use a **named** critical

Fortran

```
subroutine foo()
!$omp critical (foo_x)
  x = x + y
!$omp end critical (foo_x)
```

```
subroutine bar()
!$omp critical (foo_w)
  w = w + z
!$omp end critical (foo_w)
```

mutual exclusion only if same name is used for critical regions acting on different code blocks

- **Note: The atomic directive is bound to the updated variable**

→ problem does not occur when such a directive is used.

More variants of atomic operations

- **Assumption:**
  - v, w private or shared scalar variables
  - x a shared scalar variable
- **Atomic read:**

```
#pragma omp atomic read
  v = x;
```

- **Atomic write:**

```
#pragma omp atomic write
  x = v;
```

- **Atomic capture**

```
!$omp atomic capture
  v = x
  x = x <op> w
!$omp end atomic
```

  - different ordering of statements also allowed
- **Not atomic:**
  - evaluation of expressions or updates on v
- **Atomic update:**
  - `!$omp atomic update`
  - same as „traditional“ atomic directive

Atomic operations require care

- **Atomic directives**
  - permit the programmer to explicitly program with race conditions
- **Rationale for use:**
  - performance
  - tailored synchronizations → will usually require explicit flush operations (not discussed)

Programmer's responsibility

  - to assure that no inconsistencies result → must evaluate results from all possible interleavings of execution by different threads
  - tools might not be able to observe problems

- **Synchronization effect**
  - apart from the value change on the variable itself being visible, no synchronization is done
  - **sequentially consistent** atomic operations:

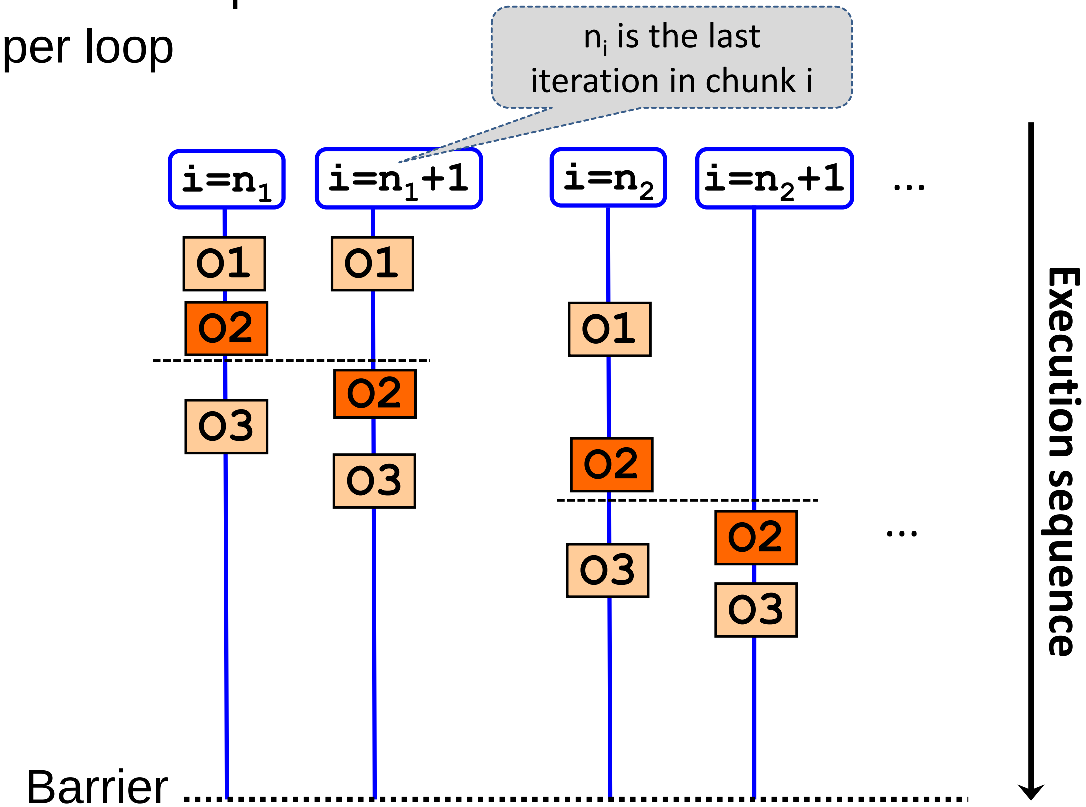
```
#pragma omp atomic \
        seq_cst update
  x = x + v;
```

perform a flush on all thread-visible variables (but no synchronization otherwise). Semantics are the same as for such operations in the C++11 standard

The ordered clause and directive

- **Statements must be within body of a loop**
  - threads do work **with statements in O2 ordered as in sequential execution**
  - requires `ordered` clause on enclosing loop worksharing directive
  - only effective if code is executed in parallel
  - only **one** ordered region per loop
- **Execution scheme:**

```
!$OMP do ordered
do I=1,N
   O1
!$OMP ordered
   O2
!$OMP end ordered
   O3
end do
!$OMP end do
```



Two applications of ordered

- **Loop contains recursion**
  - dependency requires serialization
  - only small part of loop (otherwise performance issue)

```
#pragma omp for ordered
for (i=1;i<n;i+) {
  … // large block
#pragma omp ordered
  { a(i) = a(i-1)+…; }
} // end loop
```

Fortran

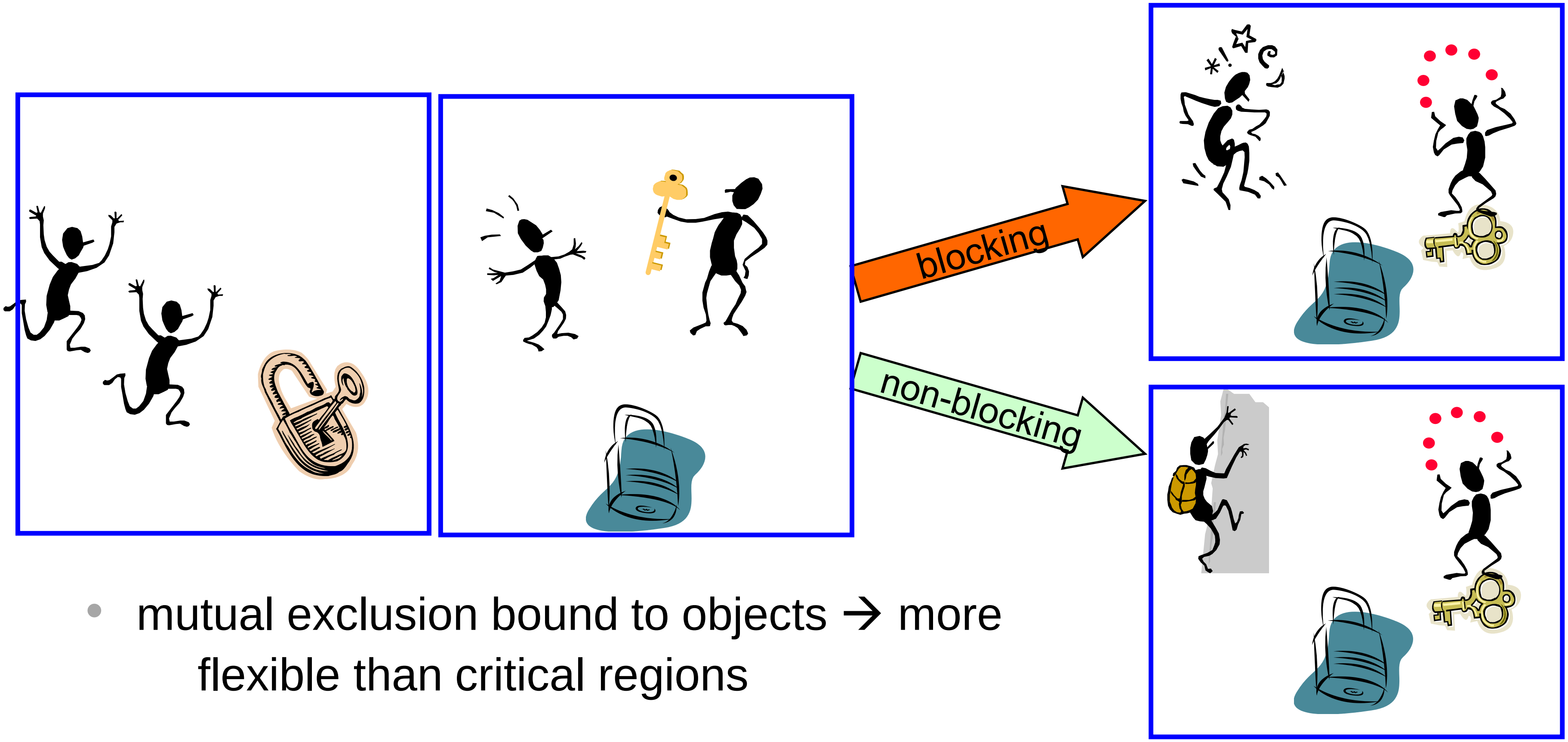
- **Loop contains I/O**
  - it is desired that content of output (file) be consistent with serial execution

```
!$OMP do ordered
do I=1,N
 … ! calculate a(:,I)
!$OMP ordered
  write(unit, …) a(:,I)
!$OMP end ordered
end do
!$OMP end do
```

C

Mutual exclusion with locks

A shared lock variable can be used to implement specifically designed synchronization mechanisms



- mutual exclusion bound to objects → more flexible than critical regions

OpenMP lock variables

- **Two variants of locks exist:**
  - simple locks
  - nestable locks (will not be dealt with in detail in this course)
- **Declaration of a lock variable**

Fortran

```
use omp_lib
…
integer(omp_lock_kind) :: a_lock
integer(omp_nest_lock_kind) :: a_nestable_lock
```

typically an integer capable of representing an adress

C

```
#include <omp.h>
…
omp_lock_t  a_lock;
omp_nest_lock_t a_nestable_lock;
```

Preparing locks for use

- **The initial state of a lock variable is "uninitialized"**
  - i.e. it is not actually associated with a lock variable
- **Need to invoke an initialization function on it before it is used**
  - subroutines / void functions provided in OpenMP run time

Name	**Purpose**
`omp_init_lock(omp_lock_t *lock)`	initializes an uninitialized lock; the lock variable has the state "unlocked" on return
`omp_destroy_lock(omp_lock_t *lock)`	destroys a lock that has the state "unlocked".
`omp_init_nest_lock (omp_nest_lock_t *lock)`	initializes an uninitialized nestable lock; the lock variable has the state "unlocked" on return, and its nesting count is zero.
`omp_destroy_nest_lock (omp_nest_lock_t *lock)`	destroys a nested lock that has the state "unlocked".

- Fortran: replace *lock argument by integer of appropriate kind

Lock ownership

- **An initialized OpenMP lock can be in one of the states unlocked, or locked**
- **The (unique) thread that has successfully acquired the lock is said to own the lock**
- **Only the thread that owns the lock can release it, returning it to the unlocked stage.**

Name	**Purpose**
`omp_set_lock(omp_lock_t *lock)`	If the lock is already locked by another thread, block until the state of the lock changes. If the lock is in the state unlocked, acquire it, setting it to the locked state, and continue execution.
`omp_unset_lock(omp_lock_t *lock)`	Release the lock that is owned by the executing thread.

- **Notes:**
  - state combinations not described in the table are not permitted (e.g., a thread trying to unset a lock it does not own)
  - the lock variable must be shared in the calling scope

Simplest possible example

- **Usage pattern analogous to named critical region**
  - programmer is responsible for relationship between lock and objects protected by it

Fortran

```fortran
use omp_lib
integer(omp_lock_kind) :: lock
call omp_init_lock(lock)
…
!$omp parallel
call omp_set_lock(lock)
…
call omp_unset_lock(lock)
…
!$omp end parallel
call omp_destroy_lock(lock)
```

C

```c
#include <omp.h>
omp_lock_t lock;
omp_init_lock(&lock);
#pragma omp parallel
  {
    omp_set_lock(&lock);
    …
    omp_unset_lock(&lock);
    …
  }
omp_destroy_lock(&lock);
```

starts in unlocked state

only one thread at a time gets to play with the red balls

release resources

Non-blocking attempt at ownership

- **Function call signature**

Fortran
```
logical function omp_test_lock(lock)
```

C
```
int omp_test_lock(omp_lock_t *lock)
```

  - if the lock is already locked by another thread, return "false"
  - if the lock has the state unlocked, acquire it (setting the state to locked) and return the value "true".

- **Permits implementing additional concurrency**

Fortran
```
!$omp parallel
do while (.not. omp_test_lock(lock))
  …
end do
  …
call omp_unset_lock(lock)
!$omp end parallel
```

C
```
#pragma omp parallel
{
  while (! omp_test_lock(&lock)) {
    …
  }
  …
  omp_unset_lock(&lock);
}
```

do stuff unrelated to the red balls

play with the red balls

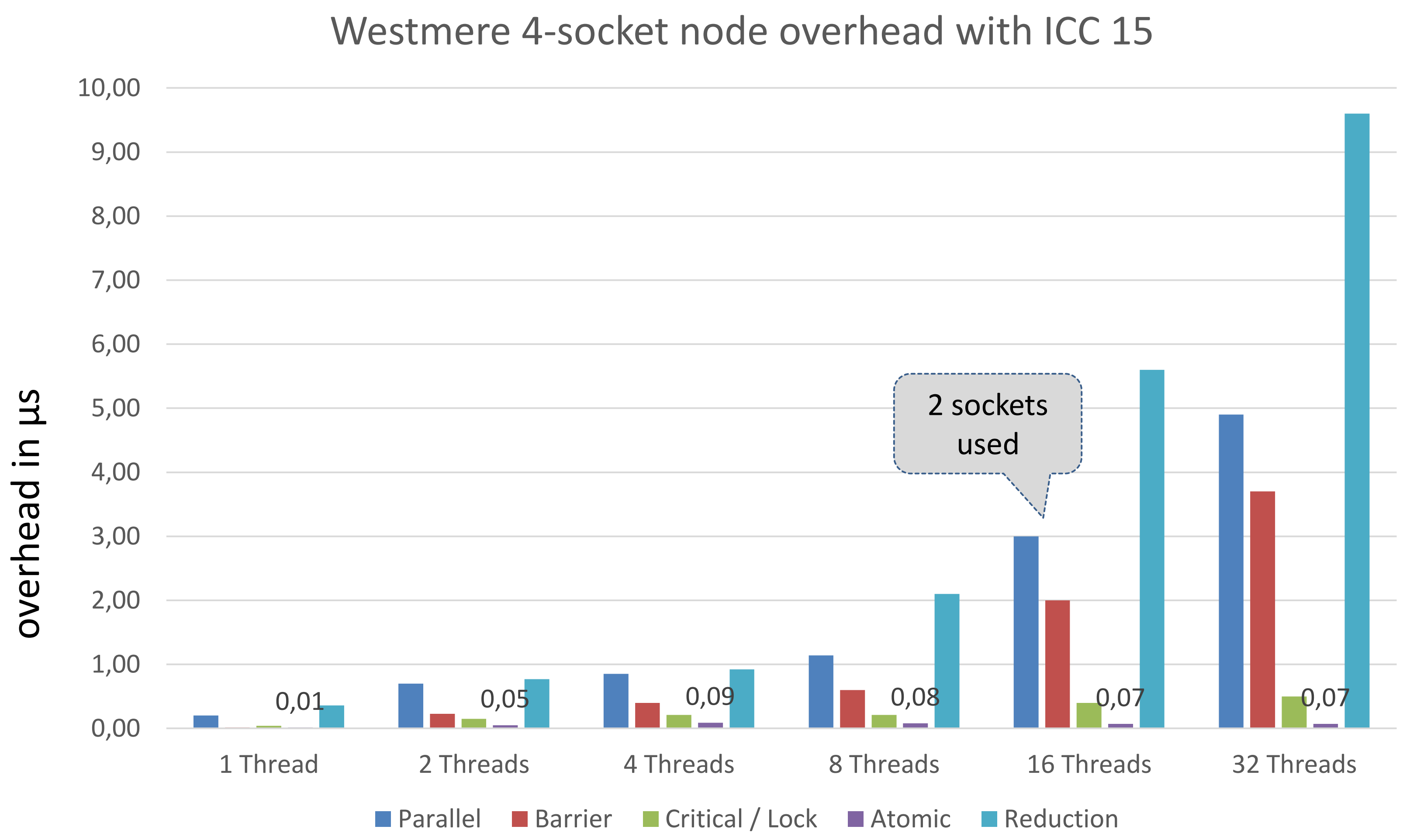
Final notes on locking

- **Potential performance issues**
  - locks are a relatively expensive synchronization mechanism
  - lock contention (algorithm dependent)
- **Programming issues**
  - easy to produce deadlock (non-composable against other constructs)
- **Nestable locks**
  - extended semantics for repeated locking (additional nesting count)
- **Locks with hints (OpenMP 4.5)**
  - programmer can specify expected usage pattern, but the actual effect is implementation dependent
  - this is an advanced topic, and success may require special hardware features (transactional processing)

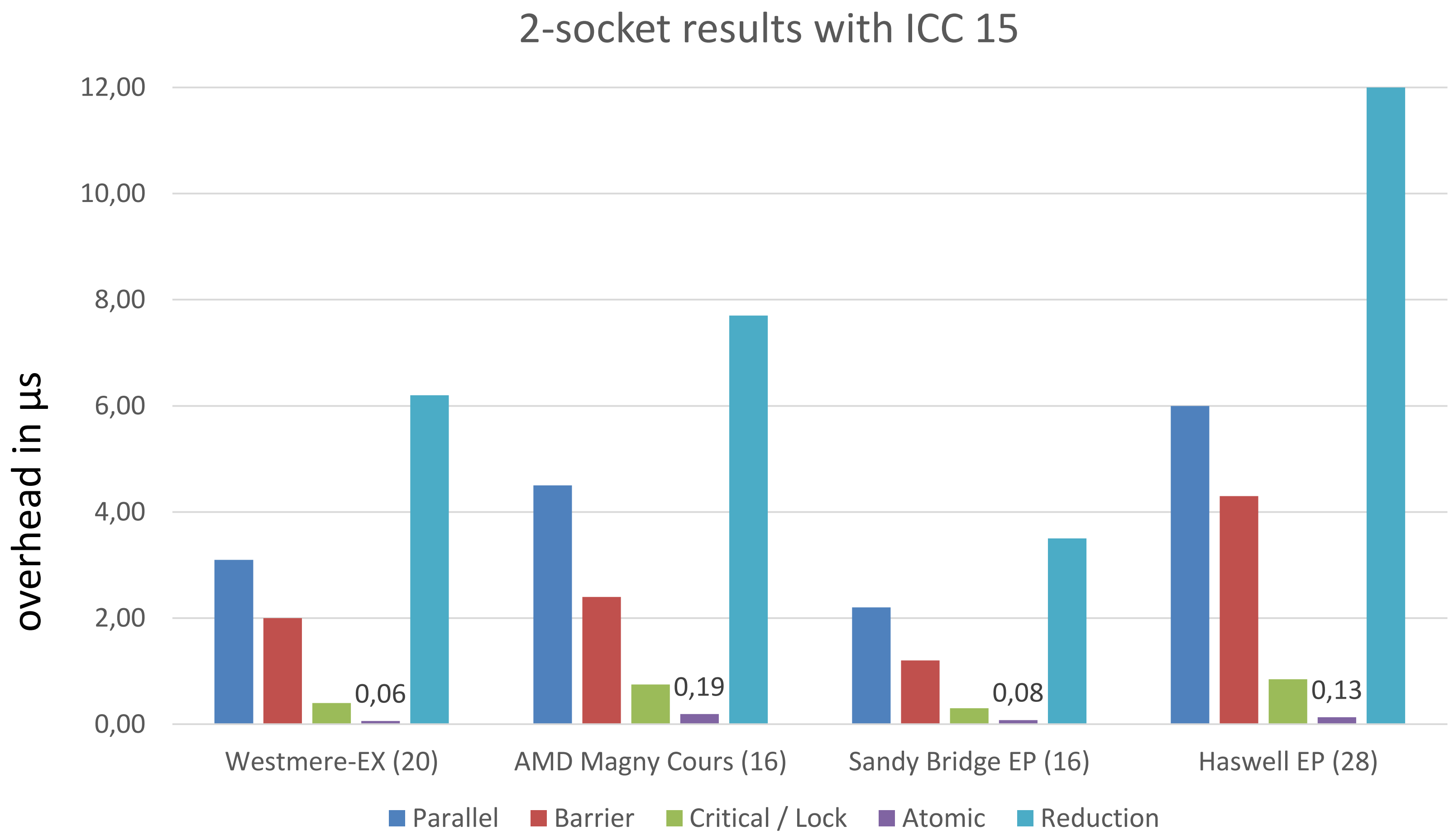
Synchronization overhead

- **Syncbench from the EPCC OpenMP microbenchmarks is used**
  - evaluates the overheads for all synchronizing constructs systematically
  - overhead is what remains even if no workload is processed
- **Showing results as a function of thread count**
  - alternatively, depending on node architecture and used compiler
- **Note order of magnitude**
  - a microsecond typically corresponds to a couple of thousand CPU cycles

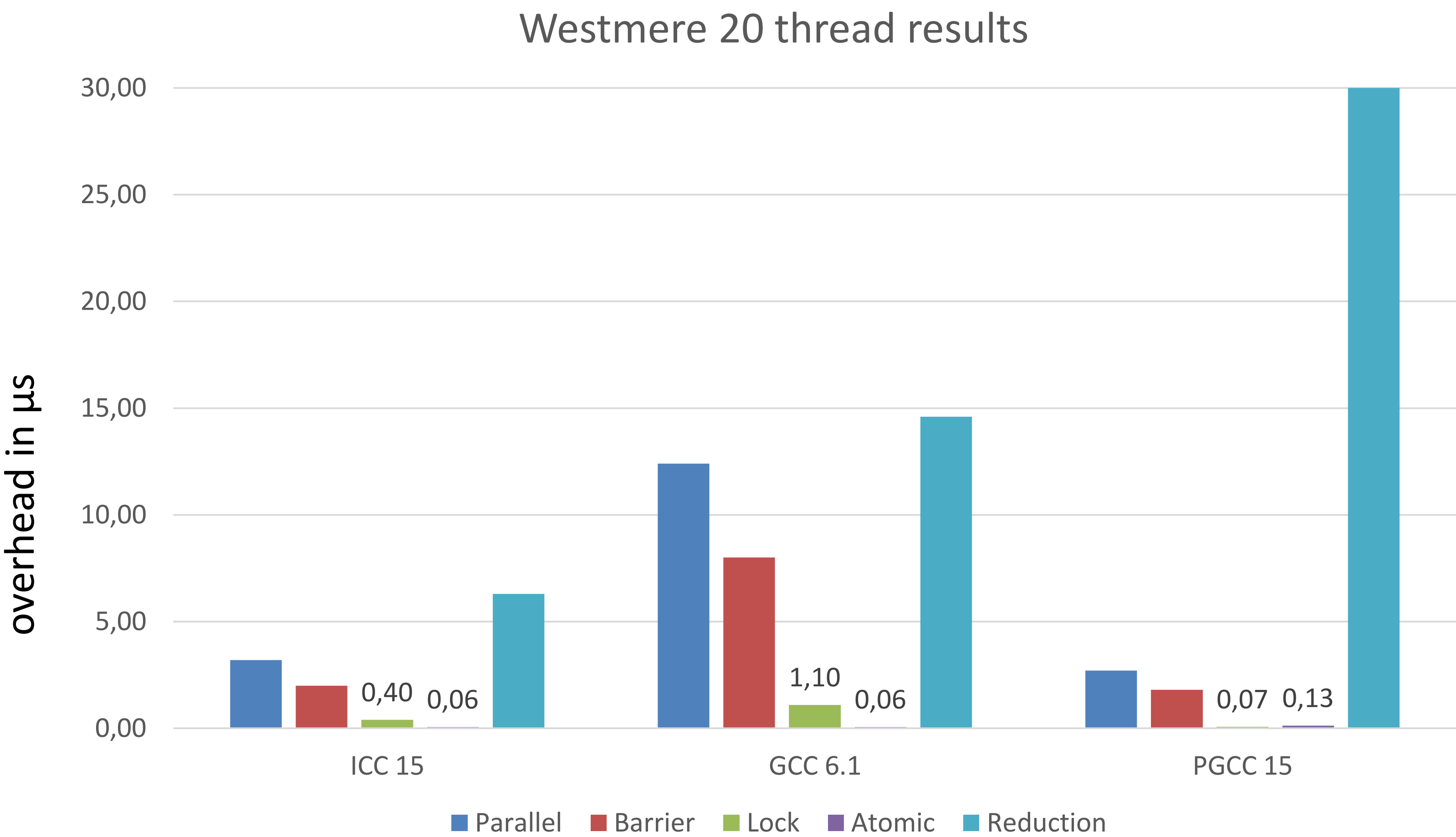
Thread count dependence



Architecture dependence



Compiler dependence



How to deal with synchronization overhead

- **Therapy 1:**
  - use the right compiler
  - **note:** x86 does not (yet) support hardware synchronization
- **Therapy 2:**
  - execute serially for small problem sizes
  - conclude parallel execution if not needed any more
- **Therapy 3 (may be most effective):**
  - reduce the synchronization requirements of your algorithm
  - **Examples:** `nowait` clause, or extend parallel regions to reduce number of forks/joins

Now: Fifth exercise session

Tasking

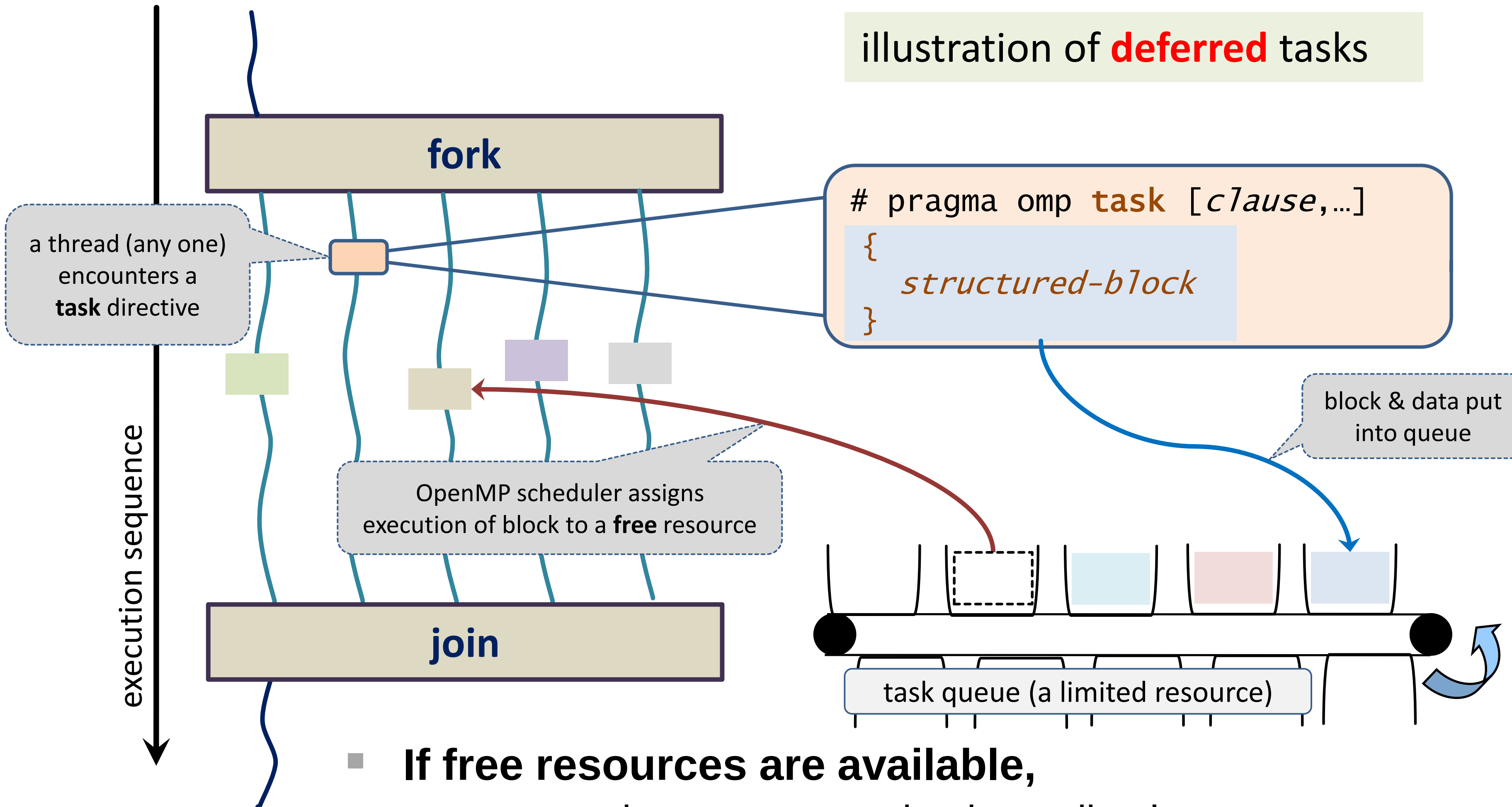
Work sharing for irregular problems, recursive problems and information structures

Acknowledgement due to L. Meadows/T. Mattson (Intel) for their SC08 slides

What is a task?

- **Aim: make OpenMP worksharing more flexible**
- **Semantics:**
  - When a thread encounters a **task construct**, a task is generated from the code of the associated structured block.
  - **Data environment of the task** is created (according to the data-sharing attributes, defaults, …)
  - The encountering thread may immediately execute the task, or defer its execution.
    In the latter case, **any thread in the team** may be assigned the task.
- **Introduced with OpenMP 3.0**
  - additional features and improvements added in later versions of the standard

Concept of tasking



- **If free resources are available,**
  - expect task to start execution immediately
- **Task binds to innermost enclosing parallel region**

Simplest example: code sections

Fortran

```
program code_sections
  use mod_functions
  implicit none
  real :: a, b
  integer :: n = …
!$omp parallel
!$omp master

!$omp task
   a = function_1(n)
!$omp end task

!$omp task
   b = function_2(n)
!$omp end task

!$omp end master
!$omp end parallel
  write(*,*) a + b
end program
```

concurrently executed if sufficiently many threads available

no synchronization (different than `single`)

C

```
int main() {
  float a, b;
  int n = …;
#pragma omp parallel
#pragma omp master
  {

#pragma omp task
   { a = function_1(n); }

#pragma omp task
   { b = function_2(n); }

  }

  printf("%f\n",a + b);
}
```

only thread 0 creates tasks

a and b have shared scope

Data scoping in task regions

C

```
int main() {
  float a, b;
  int n, i;
  a = …; n = …;
#pragma omp parallel private(b)
  b = …;
#pragma omp master
#pragma omp task
  {
    for (i=0;i<n;i++) {
      b = b + …;
      … = a + foo(i);
    }
  }
}
```

i is **private** (loop index)

b is **firstprivate**

a is **shared** (because it is shared in all lexically enclosing constructs)

default scopings

- **Recommendation:**
  - use a `default(none)` clause on all task directives
  - explicitly specify the scoping for each data object

Processing a linked list (1)

- **Type declaration**

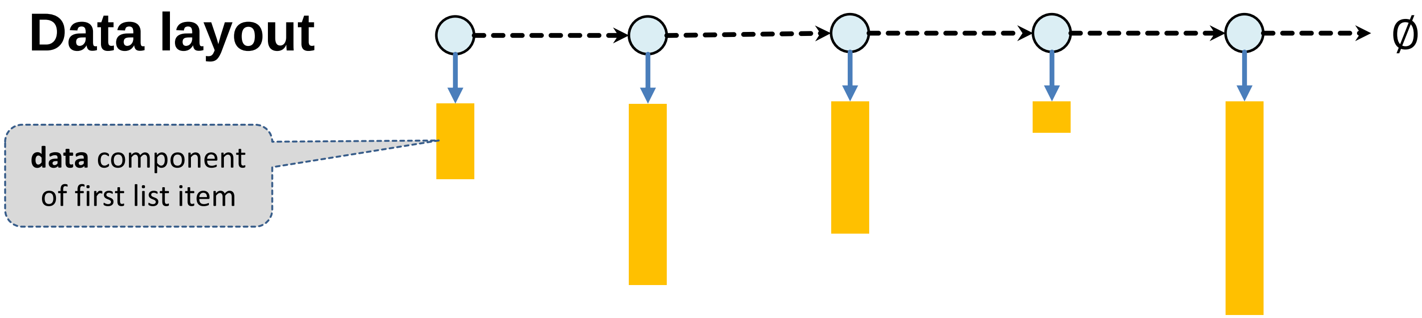
Fortran

```
type :: list
  type(list), pointer :: next => null
  real, allocatable :: data(:)
end type
```

C

```
typedef struct {
  list *next;
  real *data; int n;
} List;
```

- **Data layout**



  - each list item may carry a different payload
  - parallel processing on a per-list-item basis → load imbalance is likely to occur
  - the list as a whole is intended to be **shared** (i.e. no copies of payload should be created during processing)

Processing a linked list (2)

```fortran
subroutine process_list(head)
  type(list), target :: head
  type(list), pointer :: p
!$omp parallel
!$omp single shared(p)
  p => head
  do while (associated(p))
!$omp task firstprivate(p)
    call do_work(p%data)
!$omp end task
    p => p%next;
  end do
!$omp end single nowait
!$omp end parallel
end subroutine
```

Fortran

only one thread creates tasks

task region (includes procedure execution)

synchronization here → all tasks done

```c
void process_list(list *head) {
  list *p = head;
#pragma omp parallel
{
#pragma omp single \
            nowait shared(p)
  {
    while(p) {
#pragma omp task firstprivate(p)
      { do_work(p->data, p->n); }
      p = p->next;
    }
  } // end single
} // end parallel
```

C

- **Need to have local pointer p firstprivate:**
  - avoid race condition on shared original (vs. subsequent update)
  - assure that association status is copied to thread executing the task region

The „if“ clause on a task directive

- **When „if“ argument is false,**
  - the task region is executed immediately by encountering thread (an „undeferred task“)
  - but otherwise semantics are the same (data environment, synchronization) as for a „deferred“ task

```c
#pragma omp task firstprivate(p) if (sizeof(p->data) > threshold)
      { do_work(p->data); }
```

C

```fortran
!$omp task firstprivate(p) if (size(p%data) > threshold)
      call do_work(p%data)
!$omp end task
```

Fortran

- **User-directed optimization („task pruning“)**
  - avoid overhead for deferring small task
  - avoid creating too many tasks
  - cache locality / memory affinity are likely to change

Recursive tasking

- **Divide and conquer**

```c
float daq(float *data, int n) {
  float xl, yl;
  int n1 = …, n2 = …;
  float *data2 = …;
  if (n1 < threshold)
      { … }
#pragma omp task shared(xl)
  { xl = daq(data, n1); }
#pragma omp task shared(yl)
  { yl = daq(data2, n2); }
#pragma omp taskwait
  return xl - yl;
}
```

private at this point

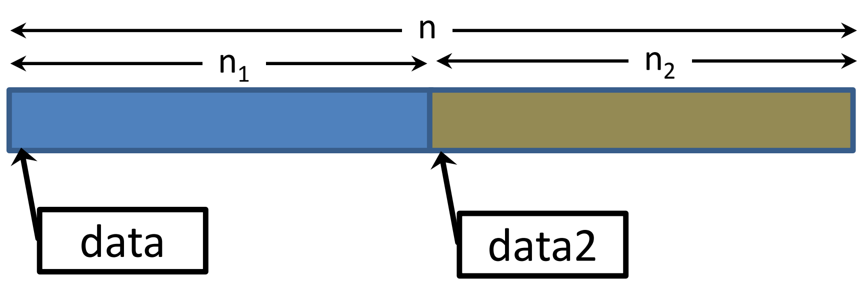
terminate recursion

C

  - initial function invocation in a parallel region, usually from a single thread

- **Previous example:**
  - only sibling tasks are created
- **This example:**
  - each task creates two child tasks

- **Shared scope for xl, yl:**
  - start out as private variables
  - only newly created tasks share scope with these variables
  - shared scope is needed to communicate data outside the task regions



Tasking-specific synchronization

- **The taskwait directive**
  - **suspends execution** until immediate child tasks of current task **complete** (the directive does not apply for descendants of child tasks)
- **Syntax:**

```
!$omp taskwait
```

Fortran

```
#pragma omp taskwait
```

C

- **Needed in example from previous slide**
  - avoid race condition of assignments vs. evaluation
  - avoid local variables vanishing into thin air while tasks are still executing

Task switching

- **Possible issues with task scheduling:**
  - large number of tasks are created → implementation-defined limit on unassigned tasks may be reached
  - all currently active tasks reach a synchronization statement → threat of deadlock?
- **Task switching**
  - permits a thread to suspend a task and start or resume another task **at a task scheduling point**
  - for tied tasks, the thread is obliged to resume execution of the suspended task later

Task scheduling points
immediately after generation of a task
at the end of a task region
in implicit or explicit barrier regions
in a taskwait region
NEW in a taskyield region
NEW at the end of a taskgroup region

e.g., a thread that creates lots of tasks may stop doing so and start working on one of them

tasks are tied by default ...

Programmer-defined task scheduling points

- **Syntax and Semantics**

```
!$omp taskyield
```

Fortran

```
#pragma omp taskyield
```

C

  - permits (but does not force) task suspension for the current task at the point where the directive is placed

- **Example**
  - avoid deadlock in a mutual exclusion region
    (taken from the OpenMP examples)

```
subroutine foo ( lock, n )
  use omp_lib
  integer(kind=omp_lock_kind) :: lock
  integer :: n
  integer :: i

  do i = 1, n
!$omp task
    call something_useful()
    do while &
       ( .not. omp_test_lock(lock) )
!$omp taskyield
    end do
    call something_critical()
    call omp_unset_lock(lock)
!$omp end task
  end do

end subroutine
```

Fortran

Task group synchronization

- **Example:** Fortran
  - a procedure that uses tasking internally without synchronization

```
subroutine p(r,s,…)
  real, intent(inout) :: r, s
  if (…) then
    …
    r = r + …
  else
    do while (…)
!$omp task reduction(+:r) shared(s)
      r = r + …
      call q(s,…)
!$omp end task
    end do
  end if
end subroutine
```

terminate recursion

procedure q might itself do tasking

- **Top-level invocation:**

```
real :: ra, sa
ra = 0.0
!$omp parallel shared(ra, sa)
!$omp taskgroup
!$omp master
   sa = …
   call p(ra, sa, …)
!$omp end master
    …
!$omp end taskgroup
    …  = ra * sa + …
!$omp end parallel
```

assure all created tasks have completed before **ra** is referenced

- **Synchronization**
  - includes all tasks created inside the region (including descendants)

Thread switching

- **Default behaviour:**
  - a task assigned to a thread must be (eventually) completed by that thread → task is **tied** to the thread
- **Change this via the untied clause**

```
# pragma omp task untied
  structured-block
```

C

  - execution of task block may change to **another** thread of the team at any task scheduling point
- **Deployment of untied tasks**
  - **Starvation scenario:**
    Task switching has caused the task-generating thread to run a long calculation, with the result that all generated tasks were consumed and most threads idle.
    If the task that generates the work is untied, a different thread can take over the task-generating workload.

Untied tasks may be very unsafe to use

Thread-related semantics used in the untied task region are likely to trip you up, for example ...

- relying on results delivered by `omp_get_thread_num()`
  → may become inconsistent after thread switch
- referencing and defining values stored in threadprivate global variables
  → may access a different copy after thread switch
- using locks or critical regions
  → may, after thread switch, attempt to unlock from a thread which has not taken the lock, etc. Crash may be imminent ...

Even for tied tasks, one needs to beware ...

- **Use of threadprivate data**
  - value of threadprivate variables cannot be assumed to be unchanged across a task scheduling point. Can be modified by another task executed by the same thread.
- **Tasks and locks:**
  - if a lock is held **across** a task scheduling point, interleaved code trying to acquire it (with the same thread) may cause **deadlock**
- **Tasks and critical regions:**
  - similar issue if suspension of a task happens inside a critical region and the same thread tries to access the same critical region in another scheduled task

- **Tools?**
  - correctness tools will currently only find some of the issues that can arise

Final and mergeable tasks

- **Final tasks**
  - use a **final** clause with a condition on a task directive
  - the resulting task is always **undeferred**
  - reduces the overhead of placing tasks in the "task pool"
  - all tasks created inside task region are also final (different from an **if** clause)
  - inside a task block, `omp_in_final()` can be used to check whether the task is final
- **Merged tasks**
  - using a **mergeable** clause may create a merged task if it is undeferred or final
  - a merged task has the same data environment as its creating task region
- **Final and/or mergeable**
  - can be used for optimization purposes
  - e.g. to optimize wind-down phase of a recursive algorithm

Now: Sixth exercise session

Performance:

Architectural aspects

We need ideas on ...

- **What can be expected from the processor architecture?**
  - want at least an estimate for performance limits → avoid „stumbling in the dark“
  - much more detailed node performance engineering and modeling: course by G. Hager and G. Wellein – see

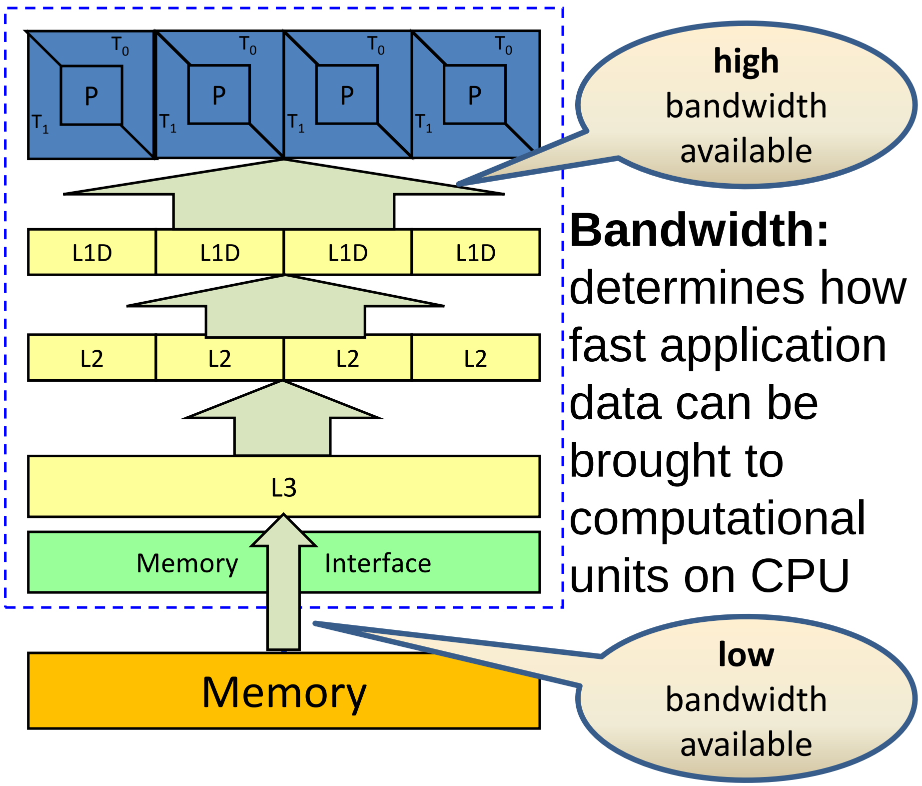
http://moodle.rrze.uni-erlangen.de/moodle/course/view.php?id=300&username=guest&password=guest&lang=en

and references cited within

- **How to exploit the architecture as best as possible**
  - use optimal data access patterns
  - minimize synchronization overhead
  - Account for interactions of OpenMP features with „serial“ optimization techniques (might be compiler optimization or lack thereof!)

Processor Architecture

- **Performance Characteristics**
  - determined by memory hierarchy



Bandwidth: determines how fast application data can be brought to computational units on CPU

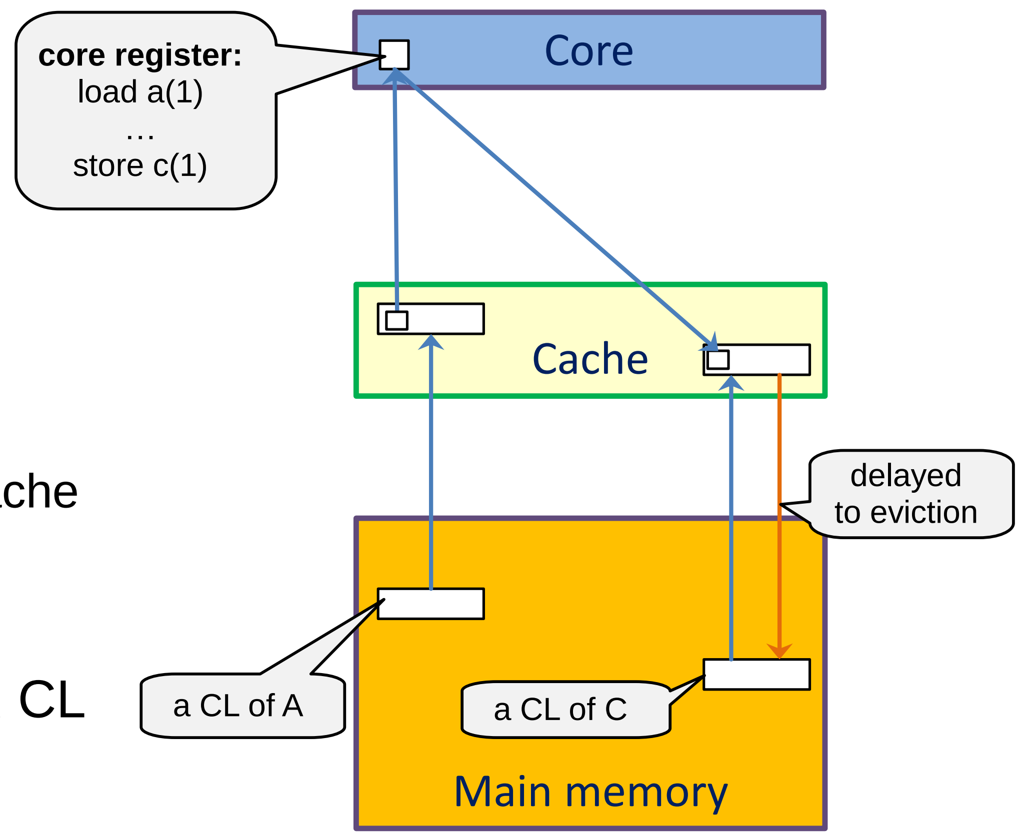
- **Impact on Application performance: depends on where data are located**
  - **temporal locality:** reuse of data stored in cache allows higher performance
  - **no temporal locality:** reloading data from memory (or high level cache) reduces performance
- **For multi-core CPUs,**
  - available bandwidth may need to be shared between multiple cores

→ shared caches and memory

Concept of cache

- **A small but fast memory area**
  - used for storing a (small) memory working set for efficient access
- **Reasons:**
  - physical and economic limitations
- **Loads (stores) to (from) core registers**
  - may trigger cache miss → transfer of memory block („cache line“, CL) from memory
- **Cache fills up …**
  - usually least recently used CL is evicted

- **Example:** c(:) = a(:) + …

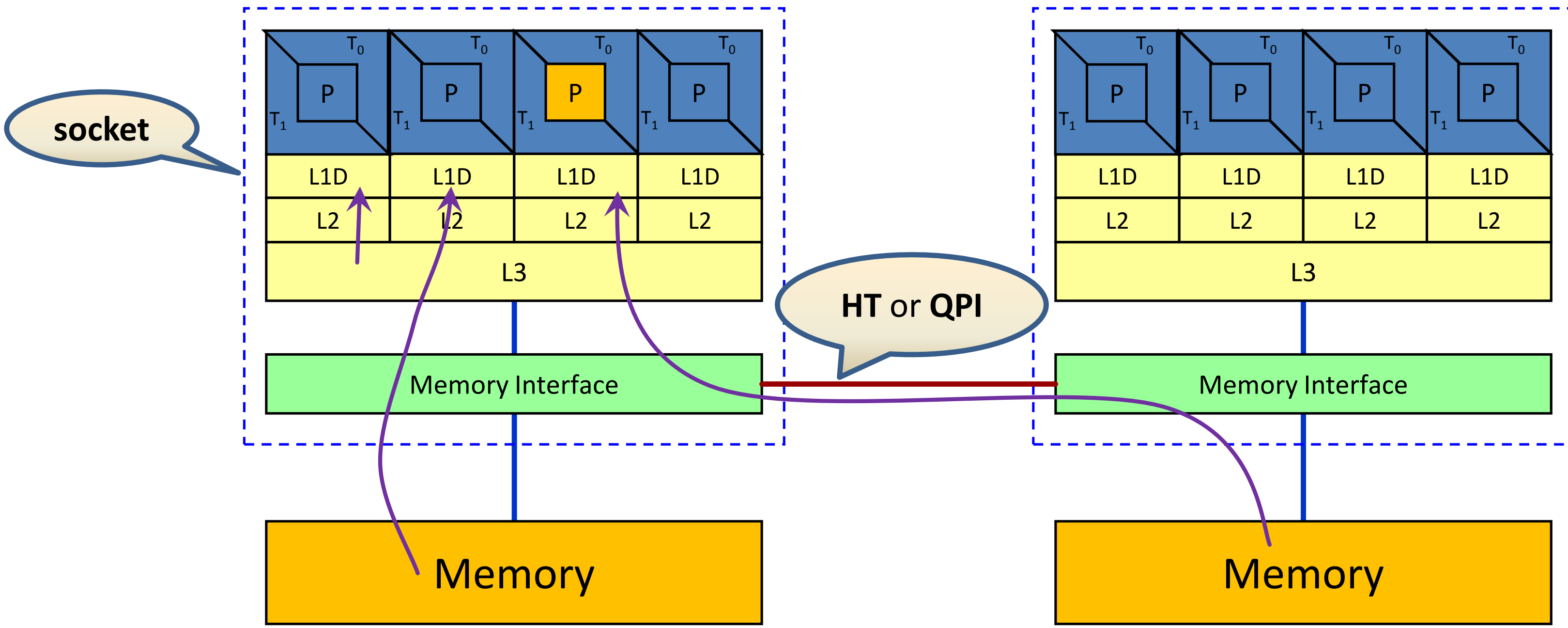


Control of Affinity
NUMA effects
False Sharing

Current Node architecture ...

- **multi-core** **multi-threaded** processors with a deep cache hierarchy
- typically, two **sockets** per node

Illustration shows 4 cores per socket. Current sockets have 8 – 14 cores



ccNUMA architecture: „cache-coherent **non-uniform** memory access"

Prolegomenon: nested parallelism

- **An implementation might support this:**

```
#include <stdio.h>
int main() {
#pragma omp parallel
  { …
#pragma omp parallel
    {
      …
    }
  }
  return 0;
}
```

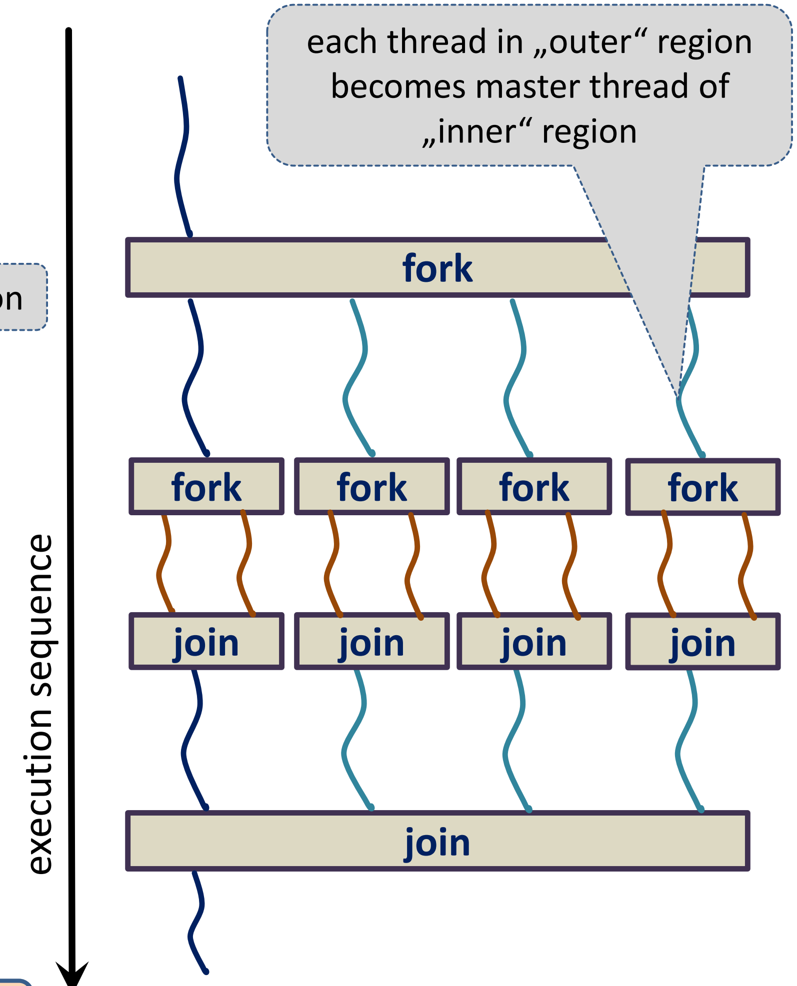
„outer“ region

„inner“ region

C

- nesting of parallel regions

mentioned here for illustrative purposes



Resource assignment

- **Suitable environment settings**

```
export OMP_NUM_THREADS=4,2
export OMP_NESTED=true
export OMP_DYNAMIC=false
…
./my_nested_openmp_program.exe
```

one integer for each nesting level

else, „inner“ regions might/will execute with 1 thread only.

forbid implementation to interfere with number of threads assigned

- **Operating system:**
  - responsible for assigning hardware resources to threads
  - in general not trivial – note that (active) thread count can change during execution
- **Possible issues (performance impact):**
  - threads might move around between cores
  - multiple threads might share a core (or other resources)

→ a mechanism for controlling thread affinity / binding is desirable

Thread affinity – Processor binding

- **Two aspects:**
  1. What entity should a thread be bound to? → concept of **place**
  2. How should the binding be performed (if at all ...)?

- **Optimal binding strategy** depends on machine and application
- **Putting threads far apart („spread“, „scatter“)** might
  - improve aggregate memory bandwidth
  - improve combined cache size
  - decrease performance of synchronization constructs
- **Putting threads close together (i.e. on two adjacent cores) might**
  - improve performance of synchronization constructs
  - decrease available memory bandwidth and cache size per thread

→ available since **OpenMP 4.0**
before that: implementation-specific mechanisms

- **Places are defined via either**
  - an abstract name (**threads**, **cores**, or **sockets**), optionally followed by a bracketed positive integer (number of places):

```
export OMP_PLACES=“cores(8)“
```

8 places with 1 physical core each

  - or an explicit list of places, specified as list of integer intervals (in the following example, all three specs are equivalent)

```
export OMP_PLACES=“{0,1,2,3},{4,5,6,7}“

export OMP_PLACES=“{0:4},{4:4}“

export OMP_PLACES=“{0:4}:2:4“
```

2 places with 4 hw threads each

same, using <offset:length> notation

same, using <firstplace:#_of_places:stride_of_offset> notation

meaning of the index is **implementation defined**, but you can expect the smallest unit of execution (a hardware thread on x86) to be used.

OpenMP binding

- **Determine whether threads should be pinned**
  - environment variable OMP_PROC_BIND
  - with values **true** or **false**, or
  - a comma-separated list of entries:

`master`	bind created threads to same place as master thread
`close`	bind created threads to a place close to the one assigned to the master
`spread`	use a sparse distribution pattern to bind created threads to places

- **Example:**

```
export OMP_PROC_BIND=spread,close
```

  - binding is determined for at most two levels of parallel nesting

Example for OpenMP binding

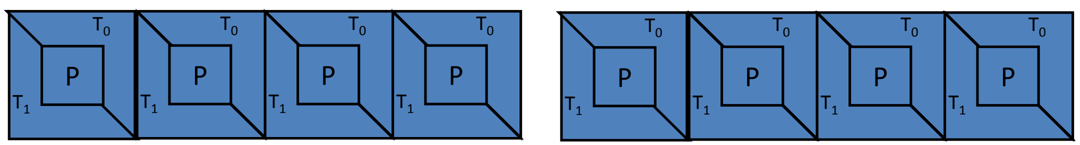
- **Nested parallelism example from earlier**

```
export OMP_NUM_THREADS=4,2
…
export OMP_PLACES="cores(8)"
export OMP_PROC_BIND=spread,close
./my_nested_openmp_program.exe
```

- Threads are named S_i, and S'_i, S''_i, ..., for outer and inner region, respectively:

Socket 0 Socket 1

Node



outer region	S_0		S_1		S_2		S_3	
inner region	S'_0	S'_1	S''_0	S''_1	S'''_0	S'''_1	S^{iv}_0	S^{iv}_1

- Overcommitment causes places to be reused (i.e. multiple threads per place)

Identifying binding strategy within the program

- **The function**

```fortran
integer(…) function omp_get_proc_bind()
```
Fortran

```c
omp_proc_bind_t omp_get_proc_bind(void)
```
C

returns one of the following constants:

omp_proc_bind_false	0
omp_proc_bind_true	1
omp_proc_bind_master	2
omp_proc_bind_close	3
omp_proc_bind_spread	4

- **The value may depend on the nesting level from which the function is called**

Identifying placement

- **A number of functions exist to handle various inquiries:**

Name	Result type	Purpose
`omp_get_num_places()`	int	number of places available
`omp_get_place_num_procs (int place_num)`	int	number of processors available in `place_num` (0 .. number of places - 1)
`omp_get_place_proc_ids (int place_num, int *ids)`	void	`ids` contains numerical identifiers of processors in place `place_num`
`omp_get_place_num()`	int	place number of place to which calling thread is bound
`omp_get_partition_num_places()`	int	number of places in place partition of innermost implicit task
`omp_get_partition_place_nums (int *place_nums)`	void	list of place numbers for innermost implicit task

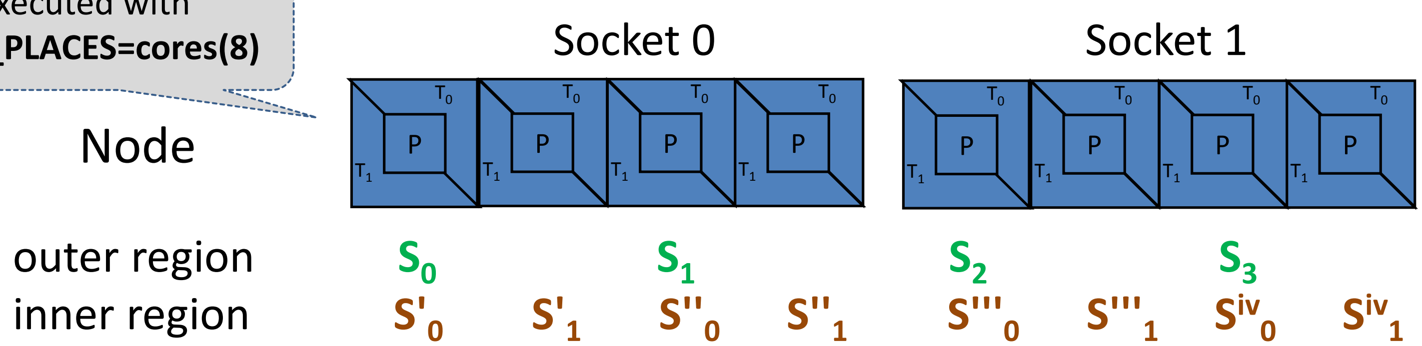
Program-internal binding

- A proc_bind clause can be specified
- Example:

```
#pragma omp parallel num_threads(4) proc_bind(spread)
  { …
#pragma omp parallel num_threads(2) proc_bind(close)
    { …
    }
  }
```

C

executed with
OMP_PLACES=cores(8)



Identifying node topology

- **Topology =**
  - Where in the machine does core #n reside?
  - awkward numbering anyway?
  - which cores share which cache levels
  - which hardware threads ("logical cores") share a physical core?
- **Use LIKWID tool to identify**
  - developed by J. Treibig
  - see http://code.google.com/p/likwid for source code and documentation

- **Available commands**
  - **likwid-topology:** Print thread and cache topology
  - **likwid-pin:** Pin threaded application without touching code
  - **likwid-perfctr:** Measure perfor-mance counters
  - **likwid-mpirun:** mpirun wrapper script for easy LIKWID integration
  - **likwid-bench:** Low-level bandwidth benchmark generator tool
  - … some more

Intel / Sandy Bridge topology

- **Output of likwid-topology –g (ASCII art section):**

```
Socket 0:
+-------------------------------------------------------------------------------------+
| +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ |
| | 0  16 | | 1  17 | | 2  18 | | 3  19 | | 4  20 | | 5  21 | | 6  22 | | 7  23 | |
| +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ |
| +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ |
| |  32kB | |  32kB | |  32kB | |  32kB | |  32kB | |  32kB | |  32kB | |  32kB | |
| +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ |
| +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ |
| | 256kB | | 256kB | | 256kB | | 256kB | | 256kB | | 256kB | | 256kB | | 256kB | |
| +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ |
| +-----------------------------------------------------------------------------+ |
| |                                     20MB                                    | |
| +-----------------------------------------------------------------------------+ |
+-------------------------------------------------------------------------------------+
Socket 1:
+-----------------------------------------------------------------------------------------+
| +---------+ +---------+ +---------+ +---------+ +---------+ +---------+ +---------+ +---------+ |
| |  8  24  | |  9  25  | | 10  26  | | 11  27  | | 12  28  | | 13  29  | | 14  30  | | 15  31  | |
| +---------+ +---------+ +---------+ +---------+ +---------+ +---------+ +---------+ +---------+ |
| +---------+ +---------+ +---------+ +---------+ +---------+ +---------+ +---------+ +---------+ |
| |  32kB   | |  32kB   | |  32kB   | |  32kB   | |  32kB   | |  32kB   | |  32kB   | |  32kB   | |
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| |  256kB  | |  256kB  | |  256kB  | |  256kB  | |  256kB  | |  256kB  | |  256kB  | |  256kB  | |
| +---------+ +---------+ +---------+ +---------+ +---------+ +---------+ +---------+ +---------+ |
| +---------------------------------------------------------------------------------------------+ |
| |                                           20MB                                              | |
| +---------------------------------------------------------------------------------------------+ |
+-----------------------------------------------------------------------------------------+
```

hyperthreaded cores

L1D

L2

shared L3

each socket forms a NUMA domain

AMD / Magny Cours topology

- **Output of likwid-topology –g (ASCII art section):**

```
Socket 0:
+-------------------------------------------------------------------------------------+
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| |   0    | |   1    | |   2    | |   3    | |   4    | |   5    | |   6    | |   7    | |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| |  64kB  | |  64kB  | |  64kB  | |  64kB  | |  64kB  | |  64kB  | |  64kB  | |  64kB  | |
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| | 512kB  | | 512kB  | | 512kB  | | 512kB  | | 512kB  | | 512kB  | | 512kB  | | 512kB  | |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| +--------------------------------------+ +--------------------------------------+ |
| |                 5MB                  | |                 5MB                  | |
| +--------------------------------------+ +--------------------------------------+ |
+-------------------------------------------------------------------------------------+
Socket 1:
+-------------------------------------------------------------------------------------+
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| |   8    | |   9    | |   10   | |   11   | |   12   | |   13   | |   14   | |   15   | |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| |  64kB  | |  64kB  | |  64kB  | |  64kB  | |  64kB  | |  64kB  | |  64kB  | |  64kB  | |
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| +--------------------------------------+ +--------------------------------------+ |
| |                 5MB                  | |                 5MB                  | |
| +--------------------------------------+ +--------------------------------------+ |
+-------------------------------------------------------------------------------------+
```

single threaded cores

L1D

L2

shared L3

each socket forms **two** NUMA domains

likwid-pin – Overview

- **Pins processes/threads to specific cores without touching code**
  - Directly supports pthreads, gcc OpenMP, Intel OpenMP
  - Based on combination of wrapper tool together with overloaded pthread library → binary must be **dynamically linked**!
- **Can also be used as a superior replacement for Linux command taskset**
- **Supports logical core numbering within a node and within an existing CPU set**
  - Useful for running inside CPU sets defined by someone else, e.g., the MPI start mechanism or a batch system
- **Usage examples:**
  - Physical numbering (as given by likwid-topology):

```
likwid-pin -c 0,2,4-6 ./myApp parameters
```

  - Logical numbering by topological entities:

```
likwid-pin -c S0:0-3 ./myApp parameters
```

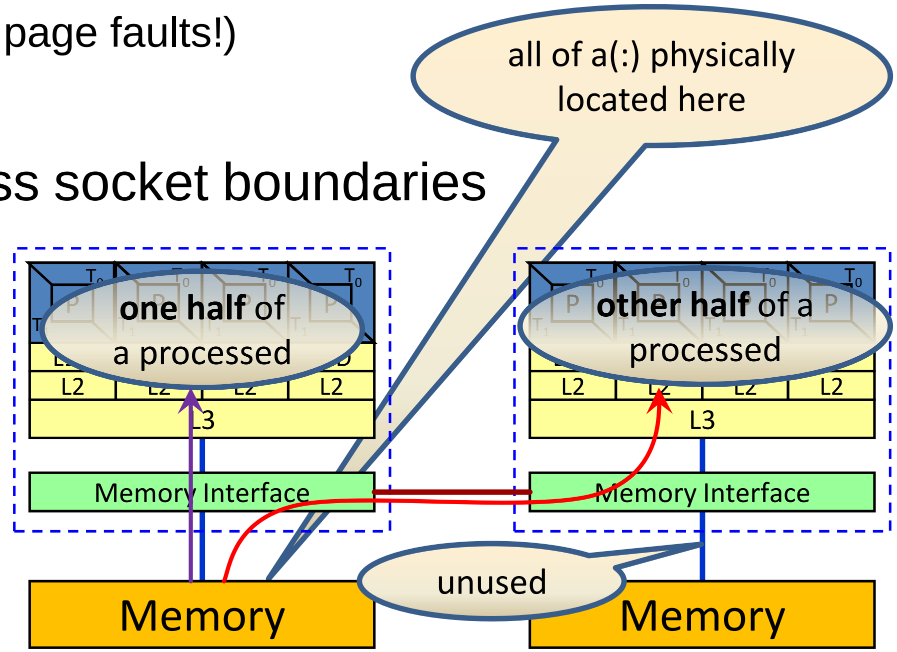
Memory affinity

- **Allocation of memory (with C malloc() / Fortran ALLOCATE)**
  - only provides a virtual memory address
- **Physical memory**
  - is assigned when a memory location is initialized („first touch“)
  - units of pages (note overhead due to page faults!)
- **Consequence for OpenMP**
  - possible memory accesses across socket boundaries

Fortran

```
a(:) = 0.0
!$omp parallel do
DO i=1, size(a)
  … = … a(i) …
END DO
!$omp end parallel do
```

first touch here



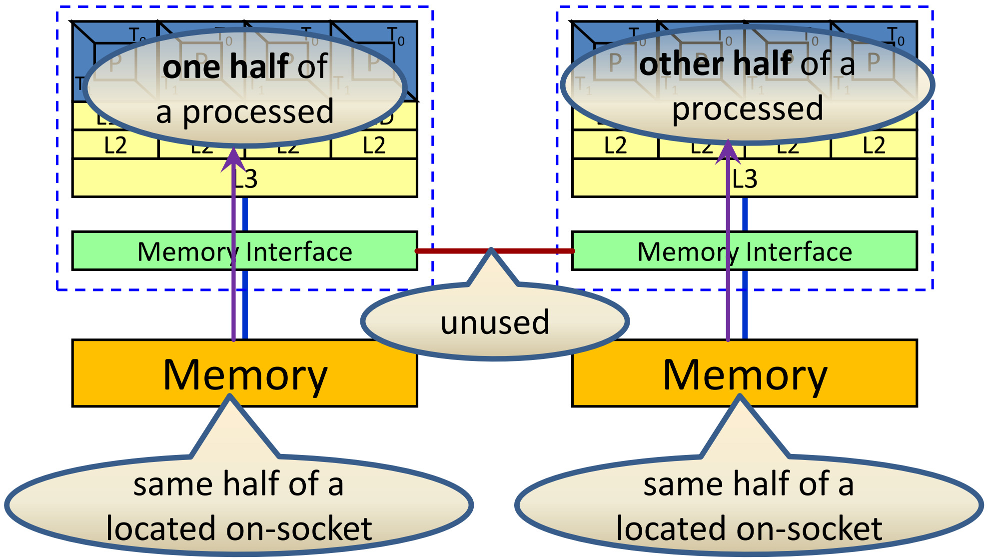
- only **half** the available memory BW might be exploited on a 2-socket system

Balancing memory affinity

- **Desirable and scalable memory access pattern:**
  - requires initialization with an OpenMP parallelized loop
- **Distributed first touch**
  - ideally, uses same loop schedule as later processing

Fortran

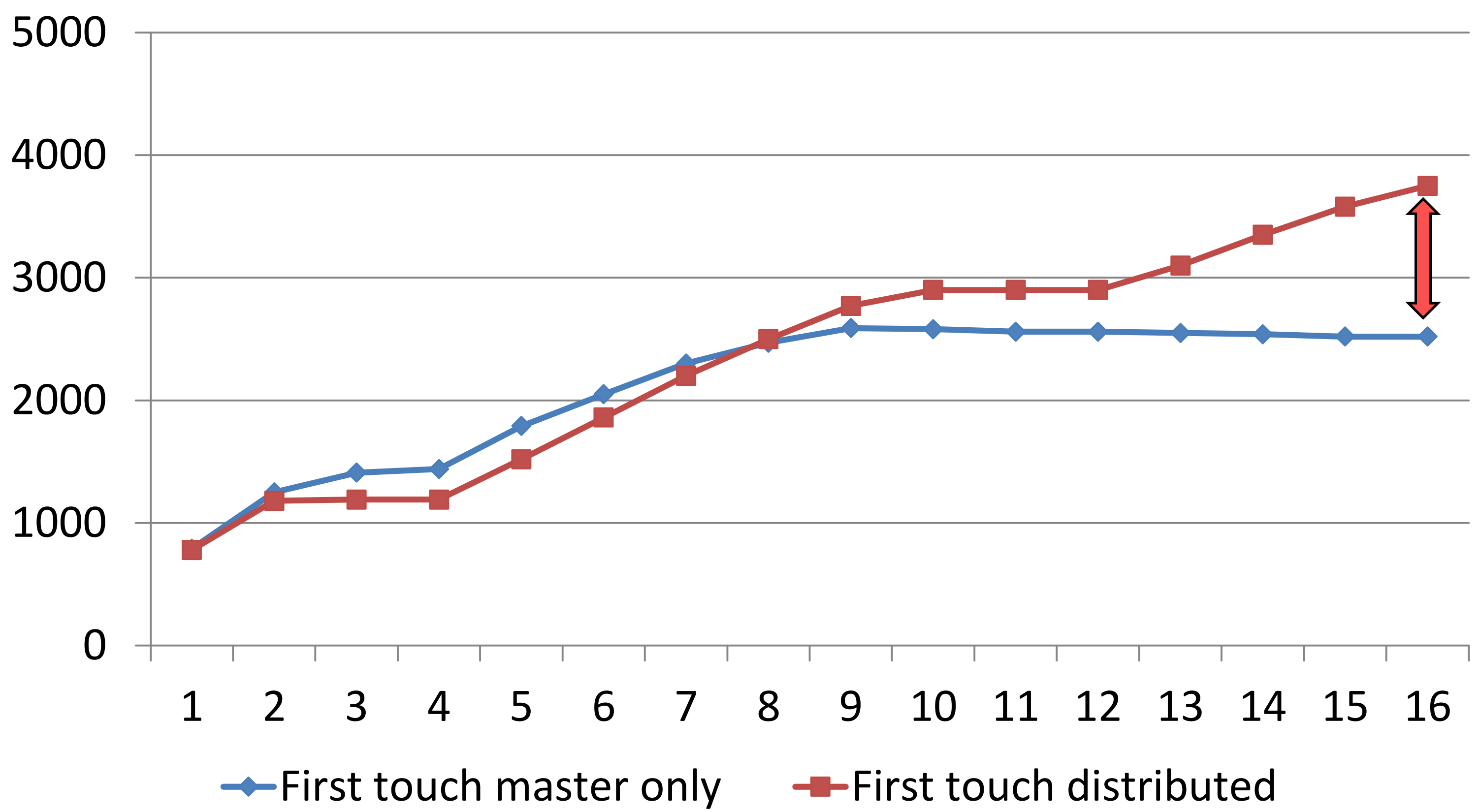
```
!$omp parallel do
DO i=1, size(a)
  a(i) = …
END DO
!$omp end parallel do
…
!$omp parallel do
DO i=1, size(a)
  … = … a(i) …
END DO
!$omp end parallel do
```



  - now, the **full** available memory BW can be exploited on a **multi**-socket system

MVM performance for N=8000

- **Measured on two AMD Magny Cours sockets**
  - thread pinning uses „close“ strategy



Tasking and NUMA effects

- **Remember:**
  - tasking decouples data items and associated functions from the threading model

```
#pragma omp task
   execute_my_function(a, b, c);
```

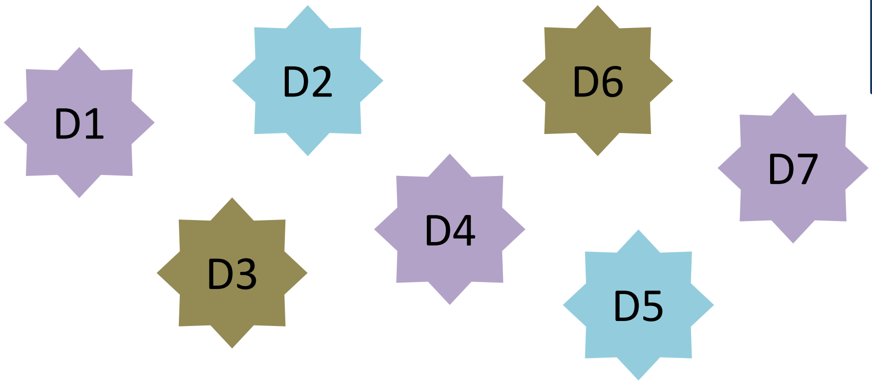
- **Consequence:**
  - repeated execution of tasking on data items might use different threads → memory affinity will get lost!

```
#pragma omp task shared(a, b, c)
   establish_my_data(a, b, c);
#pragma omp taskwait
#pragma omp task shared(a, b, c)
   execute_my_function(a, b, c);
```

this function might execute on a **different** thread than this one

Partial therapy: register locality

- **At initialization**
  - store which thread performed it – threads are color coded below

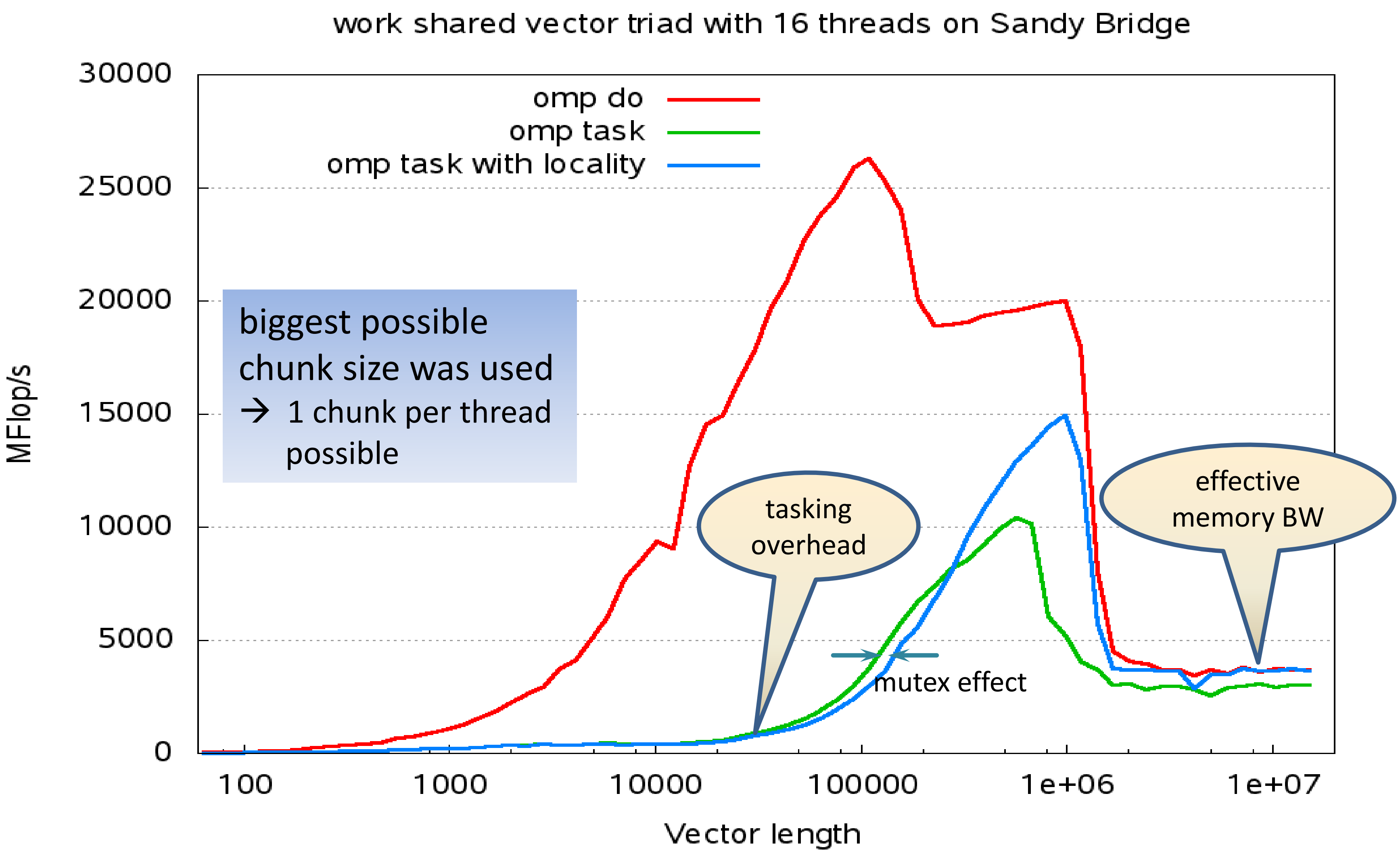



```
integer :: work_item(idm, nthr)
```

thread	0	1	2
item #	1	2	3
item #	4	5	6
item #	7	-	-

- **Working on data items**
  - first work on items that are local to the executing thread
  - next work on items that are located elsewhere (nearby first)
    - task stealing due to unpredictable thread assignment
  - additional bookkeeping (mutual exclusion) is needed to assure complete and unique execution

Simple example: NUMA-aware tasked triads



Performance problems with small shared variables

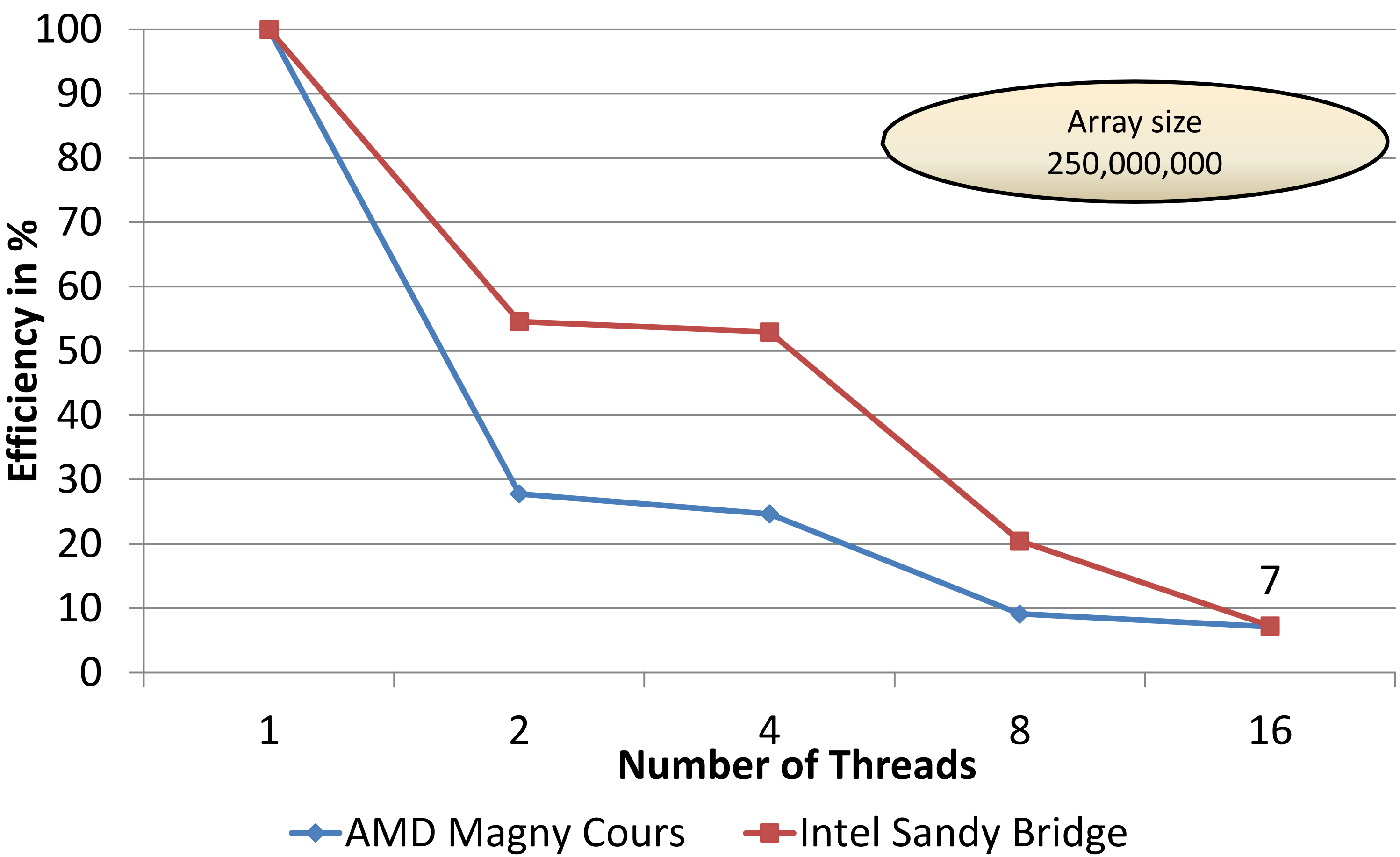
- **Example program: count even and odd array values**

```
integer is(2), ict(2,ntdm), ia(n)
  …                                   initialization omitted
!$omp parallel private(myid) shared(ict, ia)
  myid = omp_get_thread_num()+1
!$omp do private(index)
  do i=1,n
    index = mod(ia(i),2)+1
    ict(index,myid) = ict(index,myid) + 1
  end do                              formally correct,
!$omp end do                          no race condition
!$omp critical
  is = is + ict(1:2,myid)
!$omp end critical
!$omp end parallel
```

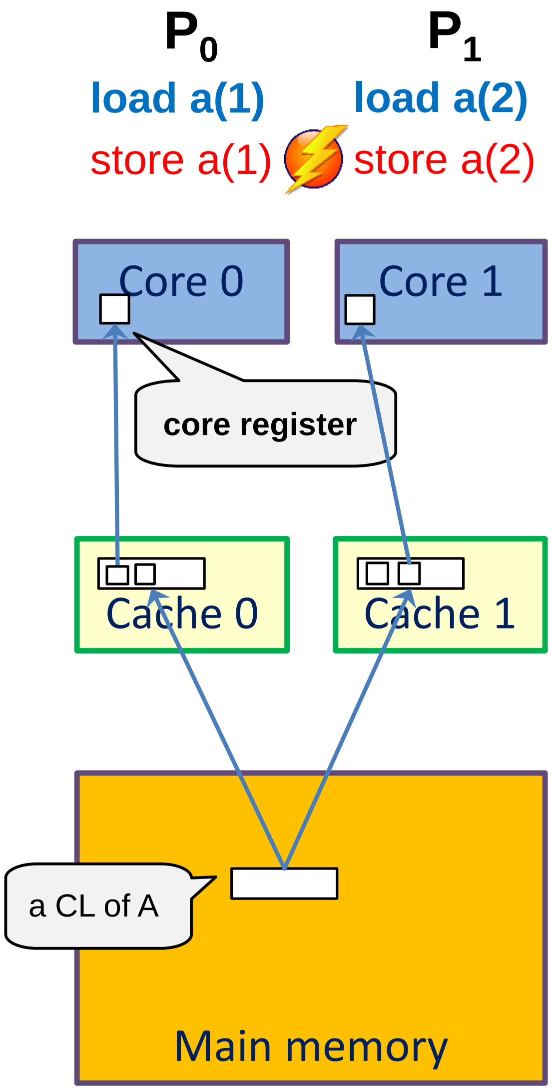
Fortran

Example program parallel efficiency

- **Baseline 1 thread execution time: AMD 0.75 s, Intel SandyBridge 0.37 s**

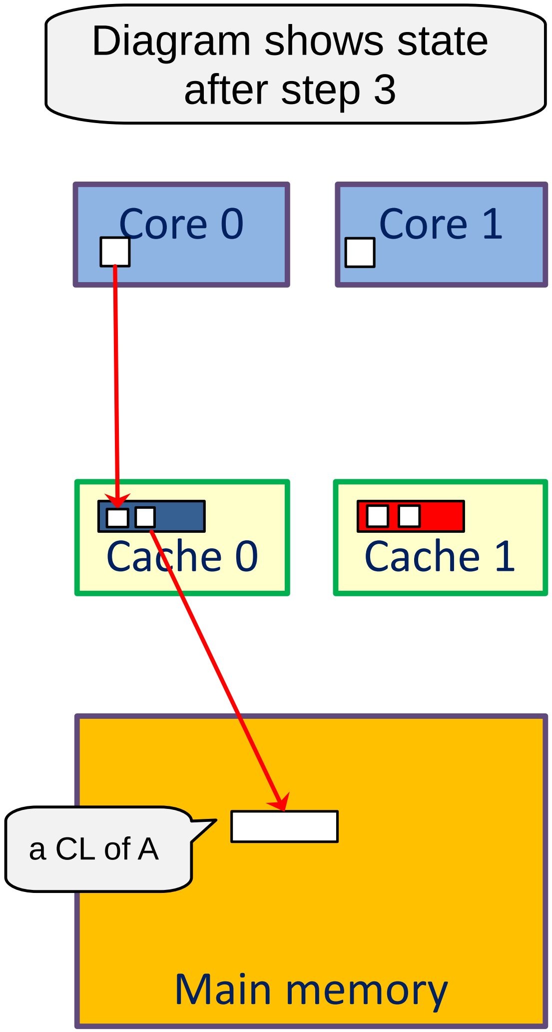


Updating neighbouring data from different cores



- **Store operation**
  - write back always done on **complete** cache lines
  - "merging of partial cache lines" is **not** possible
- **Cache coherence protocol**
  - keeps track of cache line status
  - assures data consistency by enforcing hardware synchronization between writes

Typical sequence of write operations



- **Hardware execution sequence for write on Core 0:**
  1. Request exclusive access to CL (Core 0 issues it first)
  2. **Invalidate** CL in Cache 1
  3. Modify CL in Cache 0 (exclusively owned)
  4. mark CL **shared**
- **Hardware execution sequence on Core 1:**
  5. Request CL from memory for reading (granted after CL is marked shared)
  6. Request exclusive access to CL
  7. **Invalidate** CL in Cache 0
  8. Modify CL in Cache 1 (exclusively owned)
  9. mark CL **shared**

Consequences

- **Repeated access to data in same cache line:**
  - causes thrashing of cache lines
  - for each access, more than twice the memory latency may be accumulated, resulting in significant performance reduction

- **This effect is called "false sharing"**

- **Privatization – here through use of a reduction variable**

```
integer is(2), ia(n)
  …
!$omp parallel shared(ict, ia)
!$omp do private(index) reduction(+:is)
  do i=1,n
    index = mod(ia(i),2)+1
    is(index) = is(index) + 1
  end do
!$omp end do
!$omp end parallel
```

initialization omitted

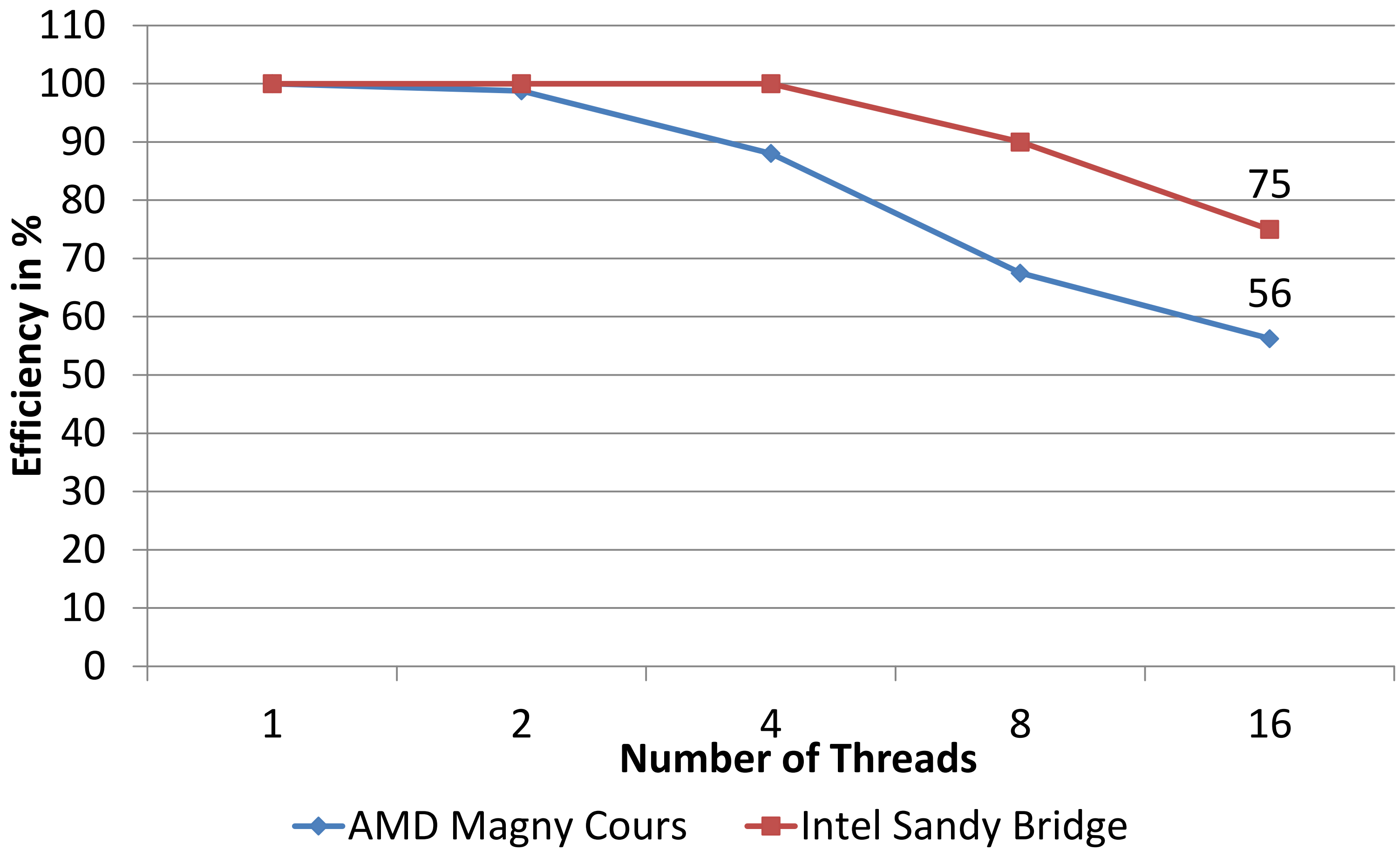
private variables are assured of using well-separated parts of the physical memory (thread-individual stack or heap)

Fortran

- **Alternative for retaining shared variables: Add padding**
  - tradeoff: may lose spatial locality

Parallel efficiency for improved example

- **Baseline 1 thread execution time: AMD 0.81 s, Intel SandyBridge 0.36 s**



Now: last exercise session

Outlook: Towards quantifying performance

Characteristics

- known operation count, load/store count
- some variants of interest:

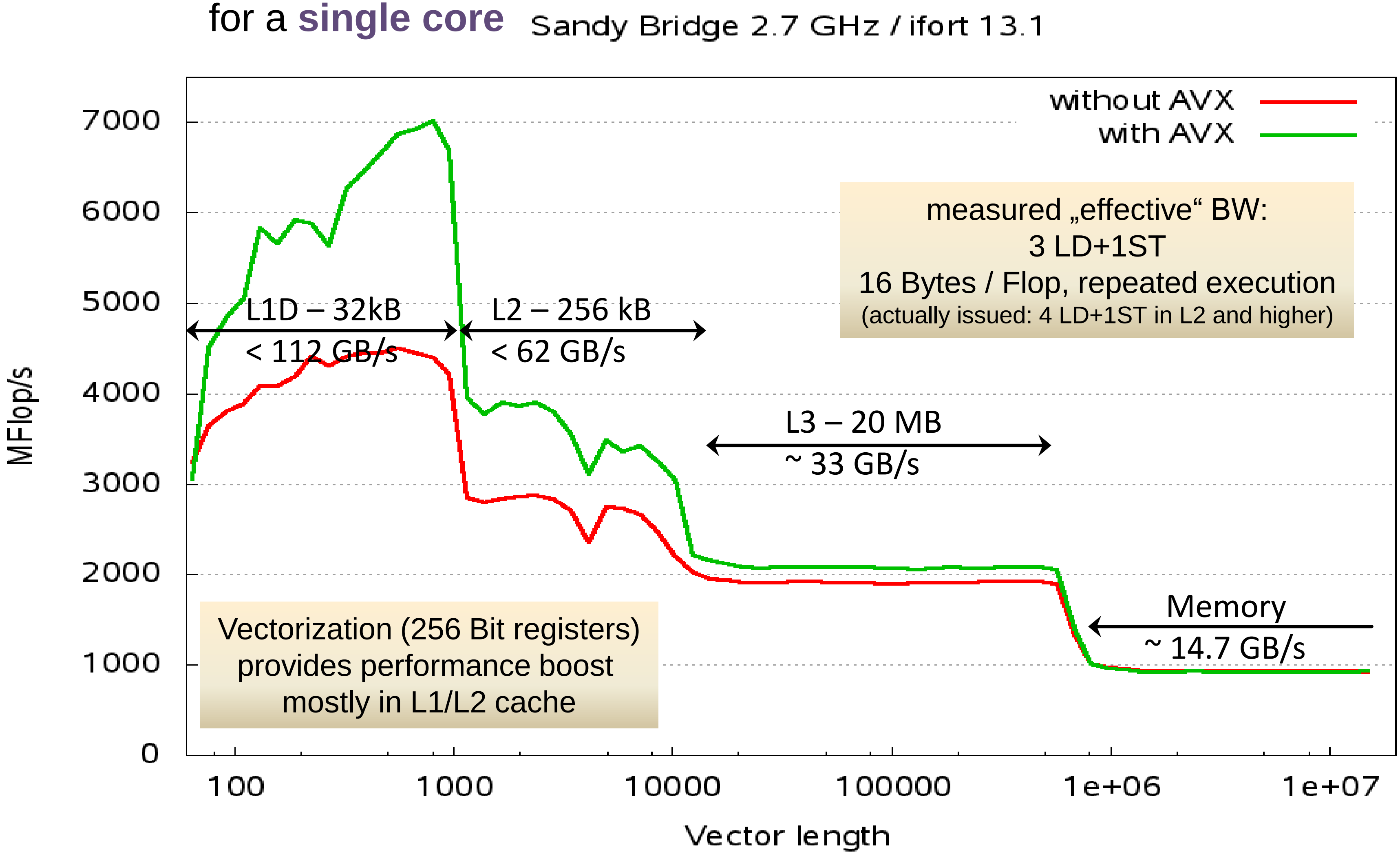
Kernel	Name	Flops	Loads	Stores
$s = s + a_i * b_i$	Scalar Product	2	2	0
$n^2 = n^2 + a_i * a_i$	Norm	2	1	0
$a_i = b_i * s + c_i$	Linked Triad (Stream)	2	2	1
$a_i = b_i * c_i + d_i$	**Vector Triad**	2	3	1

- run repeated iterations for varying vector lengths (working set sizes)

Vector Triad D(:) = A(:) + B(:) * C(:)

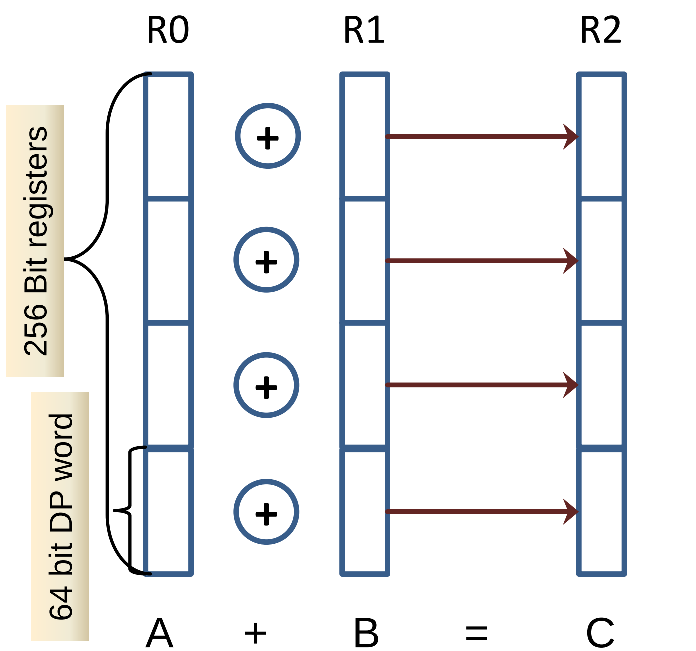
- **Synthetic benchmark:** bandwidths of „raw“ architecture

  for a **single core**



Theoretical performance limit

- **Sandy Bridge vector unit:**
  - 256 Bit SIMD (single instruction multiple data)
  - Example: addition of 8 Byte words



4 elements with 1 AVX instruction

- **Instruction capability**
  - 1 vector add and 1 vector mult per cycle → theoretical Peak 8 Flops/cycle
- **LD/ST issue capability**
  - 4 Words LD/cycle
  - 4 Words ST/(2 cycles)

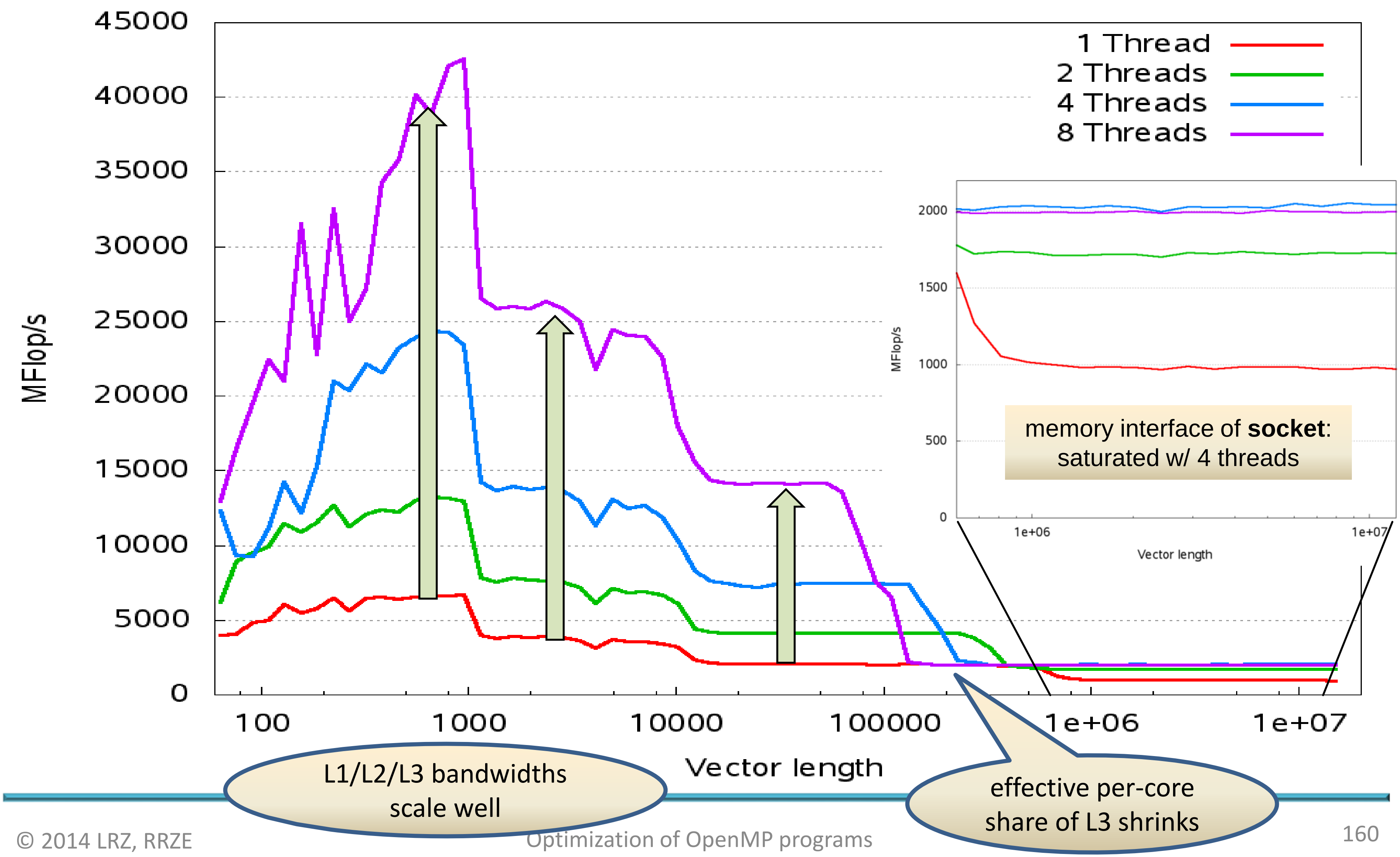
Only L1 might maintain needed bandwidth

- **Vector triad:**
  - required loads limit performance to 8 Flops / 3 cycles

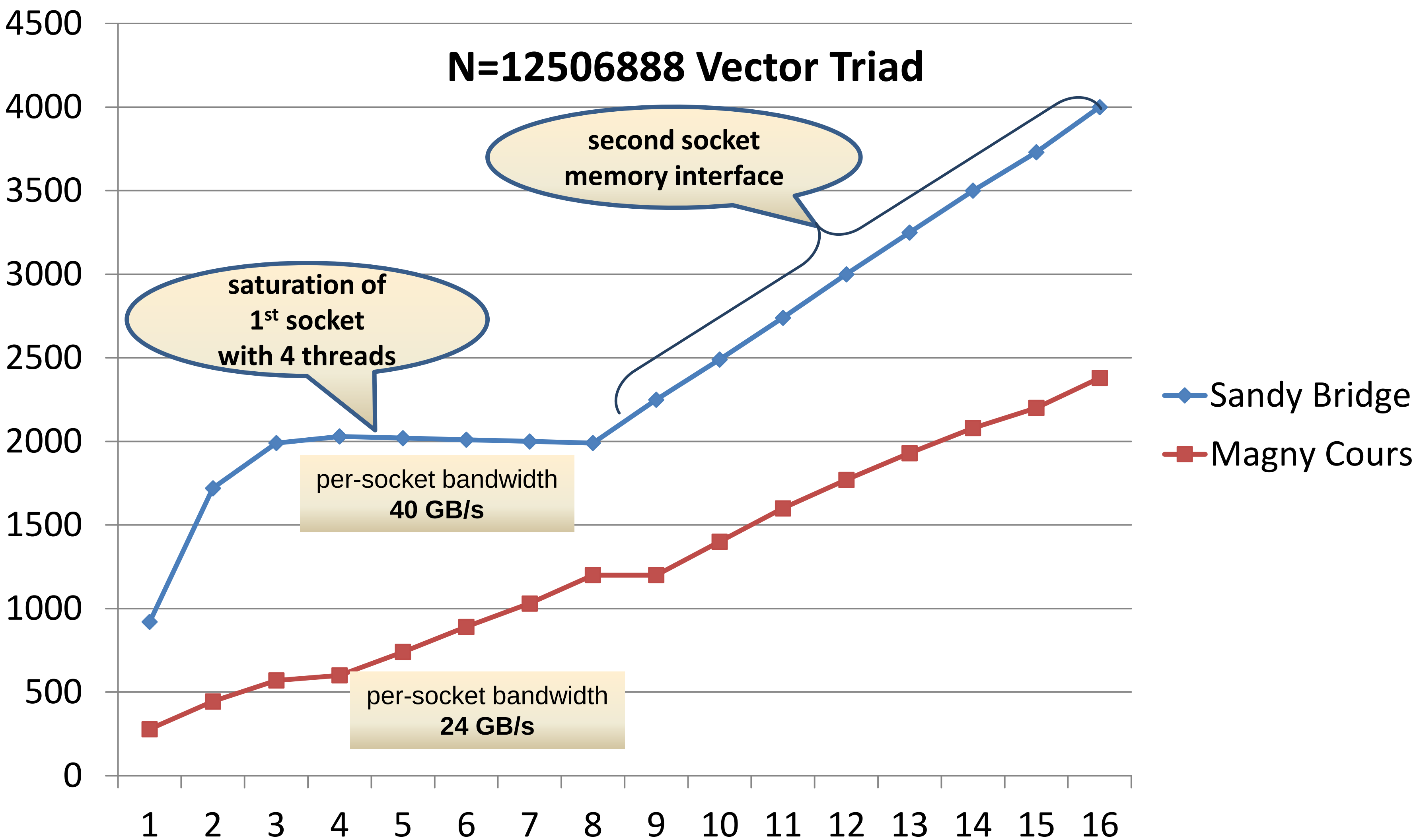
    i.e. **7.2 GFlop/s** at 2.7 GHz
- **Consult processor-specific architecture manual**

Vector Triad D(:) = A(:) + B(:) * C(:)

- **Throughput mode:** run with independent threads **up to number of cores** on a socket

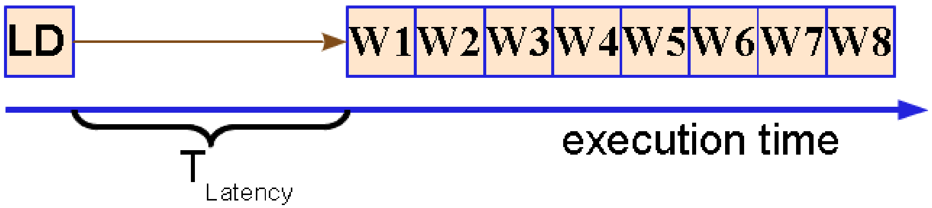


Looking at Memory Performance

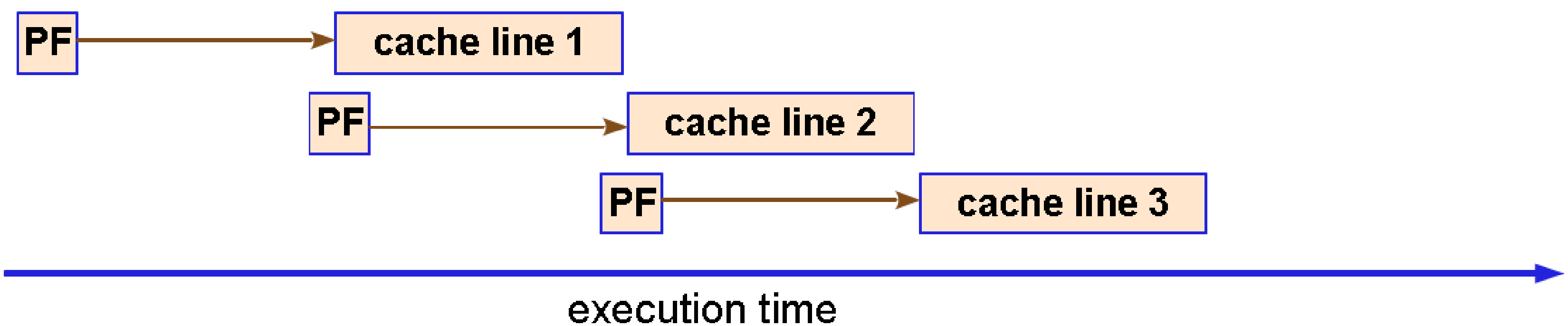


More on cache-based memory systems

- **Loads and Stores**
  - usually apply to cache lines



  - size: 64, 128 or more Bytes
- **Pre-fetch**
  - avoid latencies when streaming data



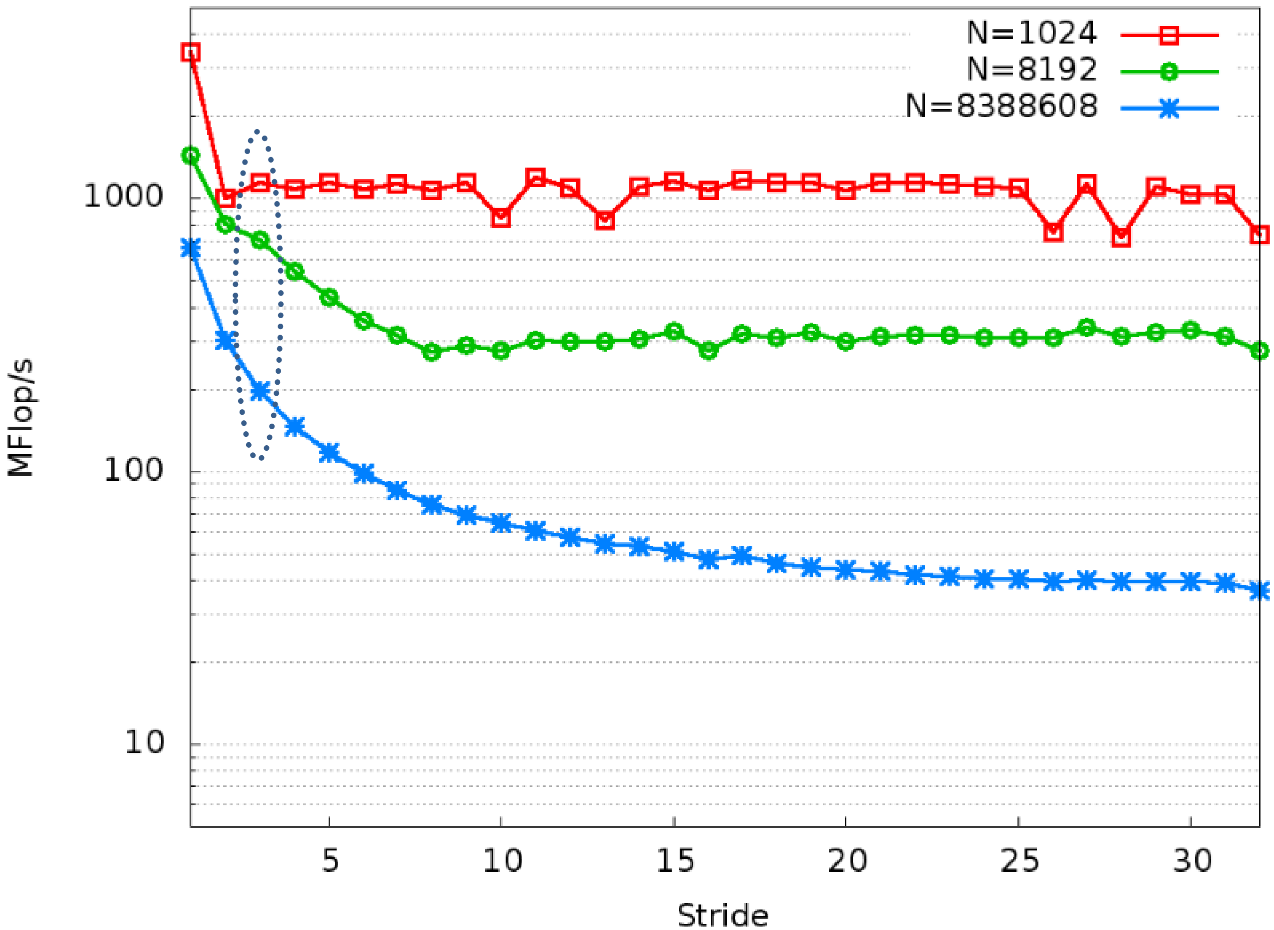
  - pre-fetches usually done in hardware
  - decision according to memory access pattern
- **Pre-Requisite:**
  - spatial locality
  - violation of spatial locality:

    if only part of a cache line is used → effective reduction in bandwidth

Performance of strided triad on Sandy Bridge - loss of spatial locality

```
D(::stride) = A(::stride) + B(::stride)*C(::stride)
```

Example: stride 3



Notes:

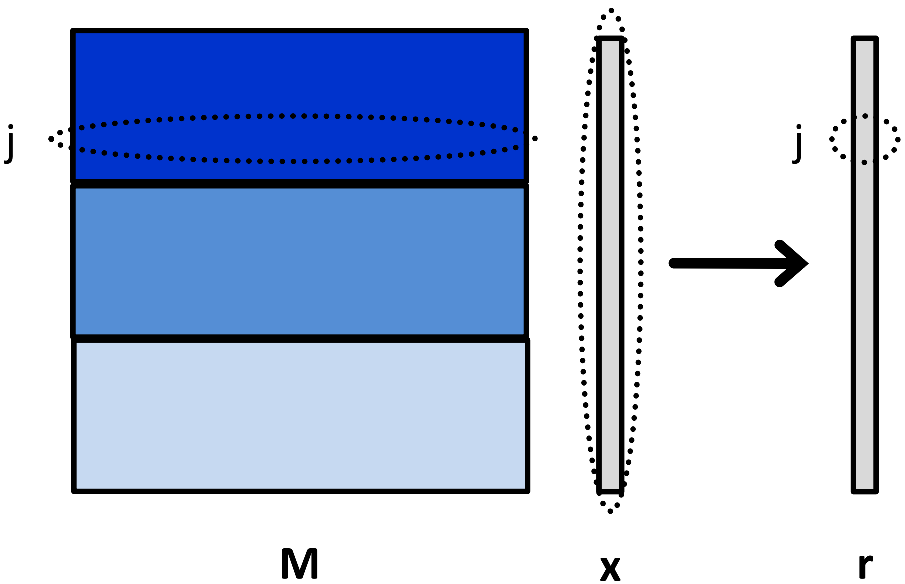
- stride known at compile time
- serial compiler optimizations may compensate perfor-mance losses in real-life code

ca. 40 MFlop/s

(remains constant for strides > ~25)

Returning to the matrix-vector product

- **r = M · x i.e.** $r_i = \sum_{j=1}^{n} M_{ij} x_j$



- **First parallelization attempt:**

```
!$omp parallel
!$omp do
DO j = 1, n
  DO k = 1, n
    r(j) = r(j) + a(j, k) * x(k)
  END DO
END DO
!$omp end do
  … = r(…)
!$omp end parallel
```

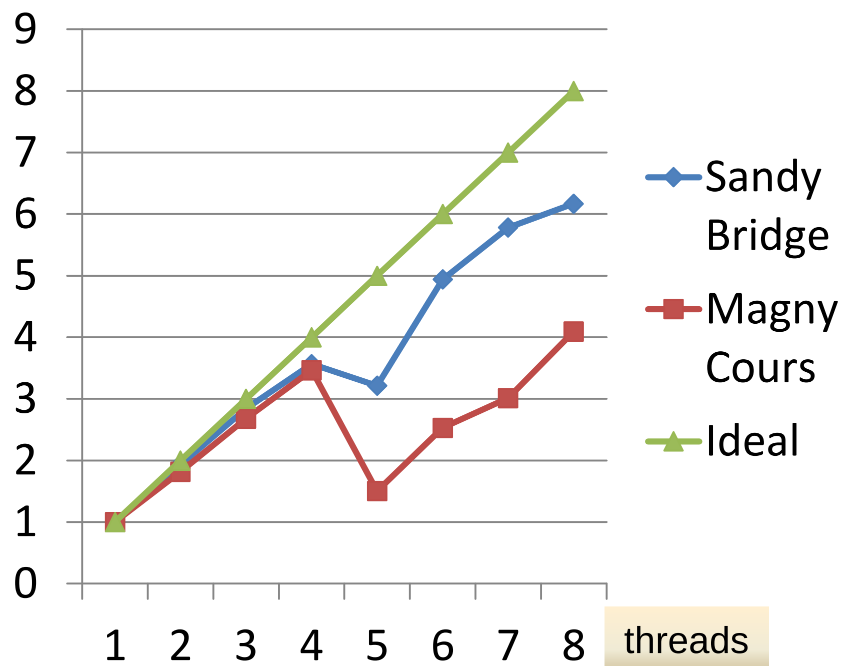
index ordering causes non-contiguous accesses

- **Parallel patterns used:**
  - data decomposition (load balanced)
  - loop parallelism (no dependencies)
- **Directive placement:**
  - coarse grained parallelism to avoid synchronization overhead

Measured performance (size 8000)

- **Speed-Up:** $S(n_t) = \dfrac{T(1)}{T(n_t)}$

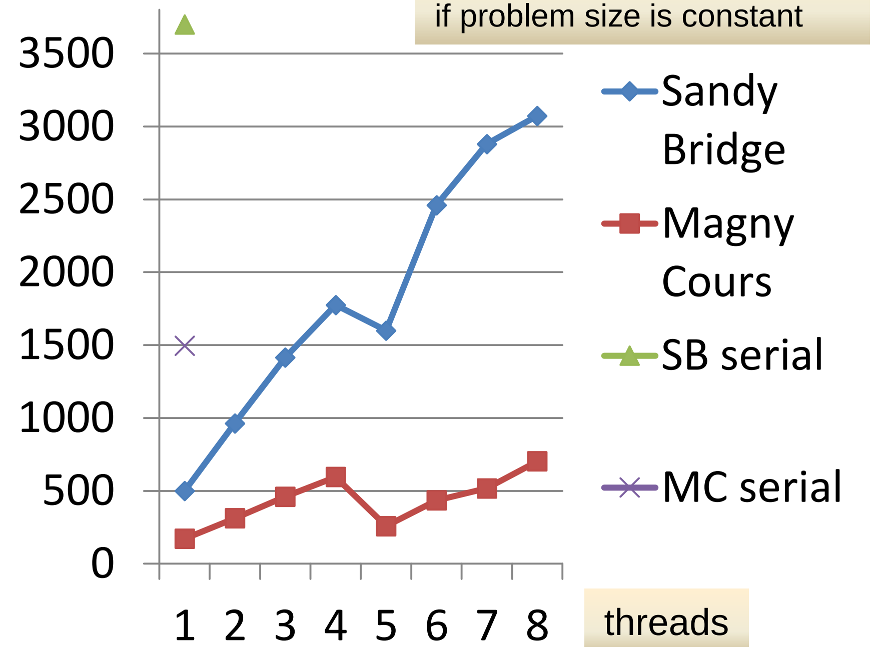
  as a function of number of threads on 8-core processors



  - Scaling **bad** beyond 4 threads

- **Absolute performance:**
  - MFlop/s = $2 \cdot n^2$ / time

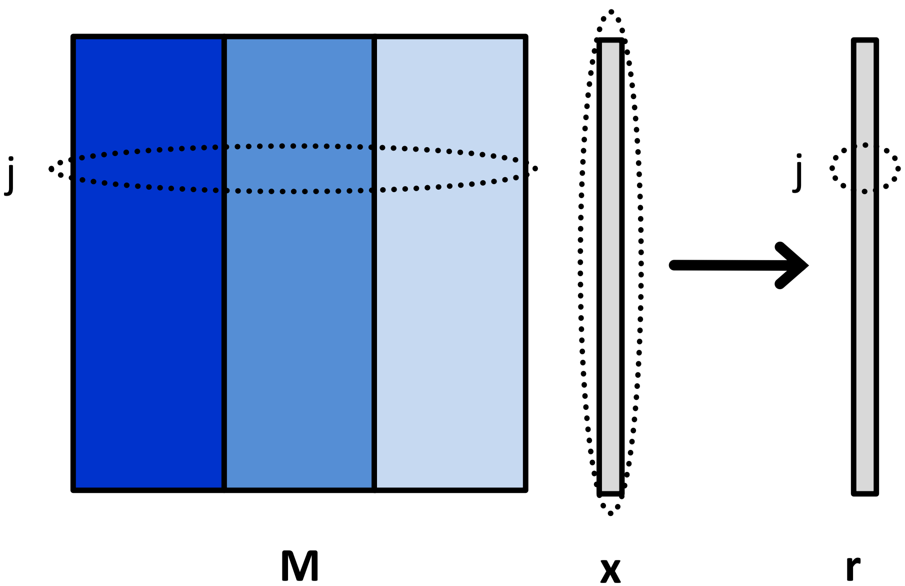
a measure for execution time if problem size is constant



  - used **dgemv** for serial run
- **Speed-Up useless if baseline performance is bad**

Improved Matrix-Vector Multiply

- **Switch loop order**
  - map **column** blocks to threads:



  - color code indicates thread assignment

- **Variant 2 of code:**
  - **contiguous** access to M
  - array reduction on result vector

```
!$omp parallel do reduction(+:r)
DO k = 1, n
  DO j = 1, n
    r(j) = r(j) + M(j, k) * x(k)
  END DO
END DO
!$omp end parallel do
```

vector add

scalar mult

1 store (?)

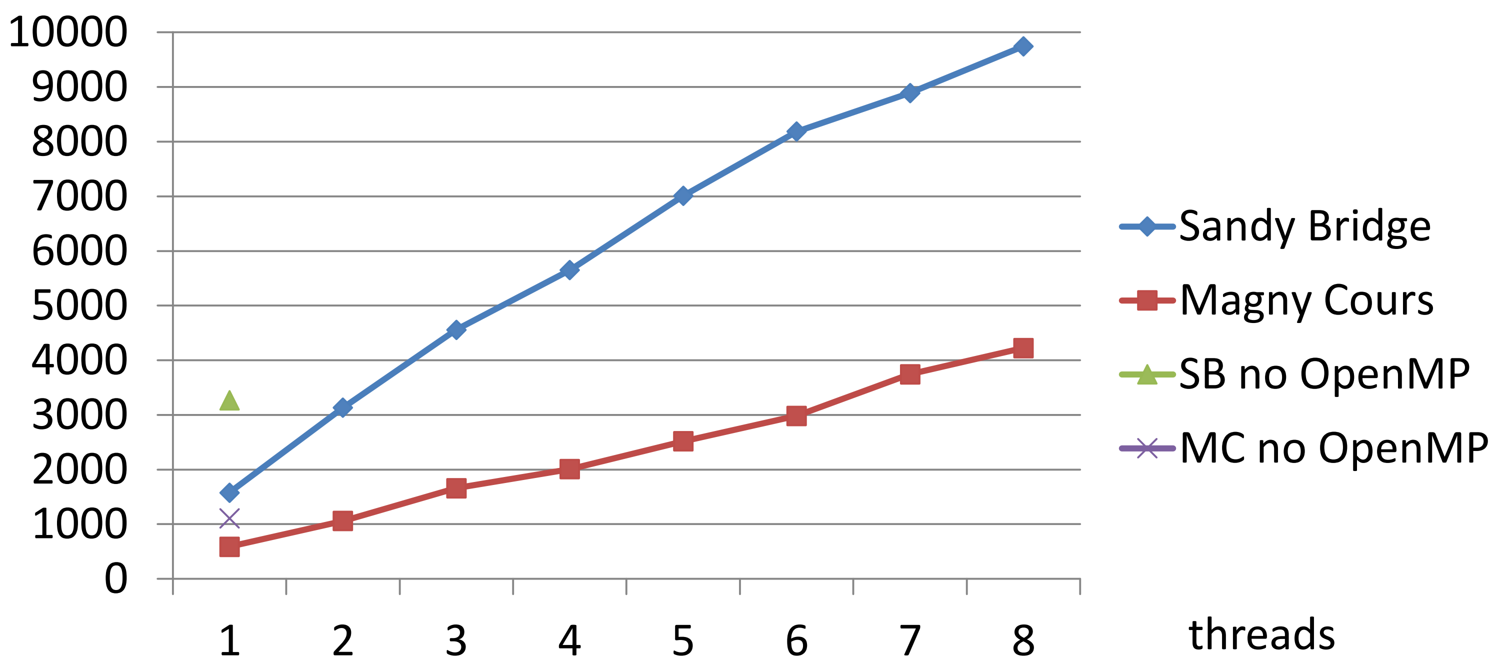
2 loads (?)

- **Performance estimate for single thread:**
  - double that of triad → 1.86 GFlop/s

Cannot be the whole truth –
remember serial performance: 3.7 GFlop/s!

Re-measured performance (size 8000)

- **For variant 2 of the MVM:** Performance in MFlop/s



- **Comments:**
  - „no OpenMP“ → variant 2 compiled **without** OpenMP
  - Conclusion: compiler stops making certain serial optimizations if OpenMP switch is toggled

Variant 3: Reduce memory traffic

Outer loop unrolling

```
!$omp parallel do reduction(+:r)
DO k = 1, n-3, 4
  DO j = 1, n
    r(j) = r(j) + M(j, k) * x(k)&
                + M(j, k+1) * x(k+1) &
                + M(j, k+2) * x(k+2) &
                + M(j, k+3) * x(k+3)
  END DO
END DO
!$omp end parallel do
```

- conditioning omitted
- asymptotically increases intensity to 2 Flops per word (1 load on matrix per original loop iteration)

> Unrolling is **limited** by number of available registers and prefetch streams (architecture-dependent!)

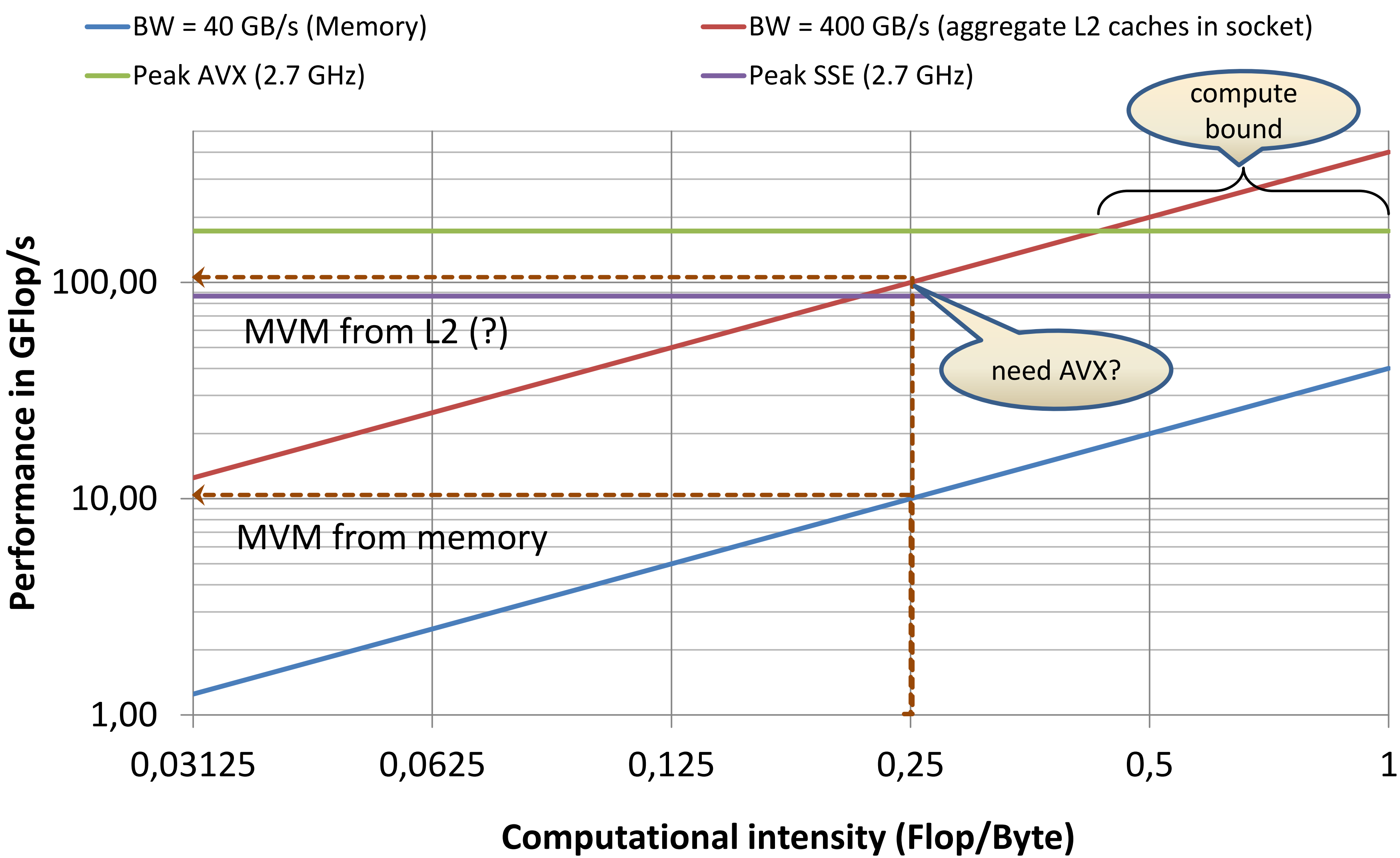
Expected performance

- for M from memory (i.e. outside any cache)
- contiguous streaming of data
- assuming 40 GB/s bandwidth for a socket

$$\text{Perf} = \underbrace{\frac{2\ \text{Flop}}{8\ \text{Bytes}}}_{\text{computational intensity}} * \underbrace{\frac{40\ \text{GB}}{\text{s}}}_{\text{available bandwidth (slowest path)}} = 10\ \text{GFlop/s}$$

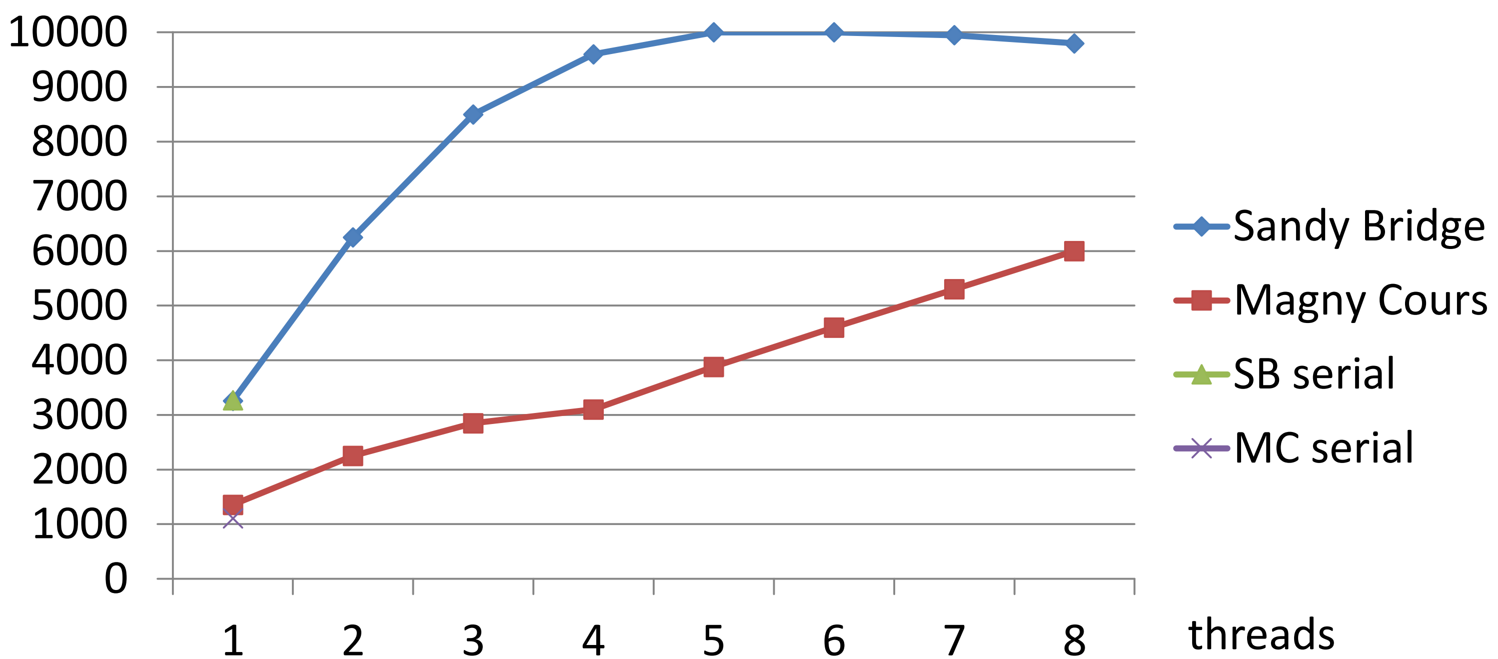
- estimation method is known as „Roofline Model“

Graphical representation of Roofline



Variant 3 MVM performance (N=8000)

- **In MFlop/s.** Unroll factors: Sandy Bridge 4, Magny Cours 8



- **Comment:**
  - roofline model only predicts „saturated“ performance
  - single-thread performance is limited by non-overlapping memory/core operations (see ref. (2))

Why use variant 3 …

- **… if variant 2 gives us the full performance anyway?**
  - even if this only is attained with 8 threads

- **Possible reasons:**
  - „switch off" cores 6-8 to save energy (relevant for you if this is budgeted – may happen not too far in the future!)
  - use cores 6-8 for other tasks that are cache bound
  - use cores 6-8 for MPI communication (I/O via PCI) if you do hybrid programming (i.e., combine MPI with OpenMP)

References

Recommended reading

(1) **OpenMP 4.5 standard and examples (currently 4.0.2) at**

http://openmp.org/wp/openmp-specifications/

(2) **Parallel programming in OpenMP**

Rohit Chandra et al; Morgan Kaufmann 2000

(3) **Using OpenMP - portable shared memory parallel programming**

B. Chapman, G. Jost, R. van der Pas; MIT Press 2008

(4) **J. Treibig, G. Hager, G. Wellein: LIKWID**

A lightweight performance-oriented tool suite for x86 multicore environments. PSTI2010, Sep 13-16, 2010, San Diego, CA DOI: 0.1109/ICPPW.2010.38; Preprint: http://arxiv.org/abs/1004.4431

(5) **G. Hager, J. Treibig, J. Habich, and G. Wellein:**
Exploring performance and power properties of modern multicore chips via simple machine models. Preprint: arXiv:1208.2908

(6) **G. Hager, G. Wellein:** Introduction to High Performance Computing for Scientists and Engineers. Chapman & Hall / CRC (2011)

Appendix:
Setting up Vtune Amplifier

Using Vtune Amplifier on x86-based systems

- **Tuning of serial and threaded programs**
  - performance counter access requires group rights
- **Start up GUI**
  - prerequisites: set up environment and possibly stack limit
  - then, invoke the GUI with

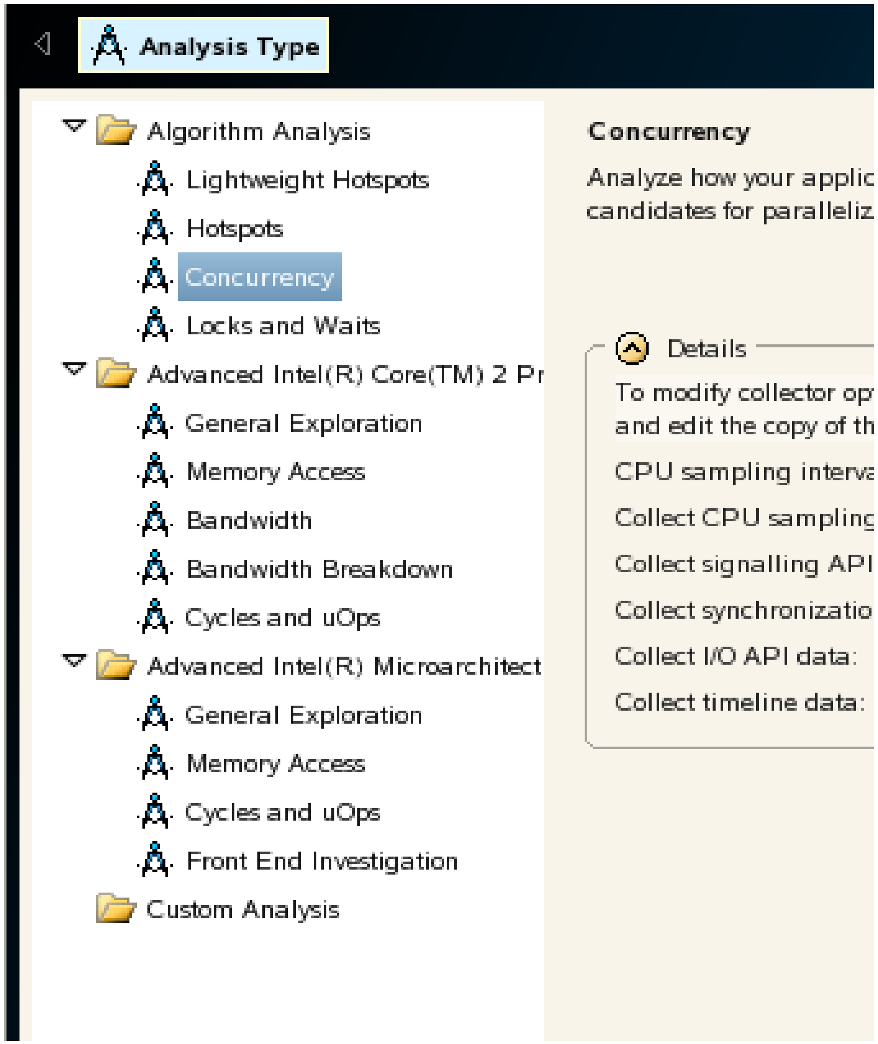
```
amplxe-gui &
```

  - command line `amplxe-cl` is also available, but will not be discussed
- **Project generation analogous to Intel Inspector**

Example run: A badly performing solution of the histogram calculation

```
#pragma omp parallel private(seed,i,k,me)
  {
    me = omp_get_thread_num();
    seed = 123 + 159*me;
    for (k=0; k<100000; ++k) {
#pragma omp for
      for (i=0; i<10000; ++i) {
        ir[i] = rand_r(&seed) & 0xf;
      }
#pragma omp master
      for (i=0;i<10000; ++i) {
        hist[ir[i]]++;
      }
#pragma omp barrier
// prevents ir from being modified
// before hist update is done
    }
  }
```

Choose Analysis type

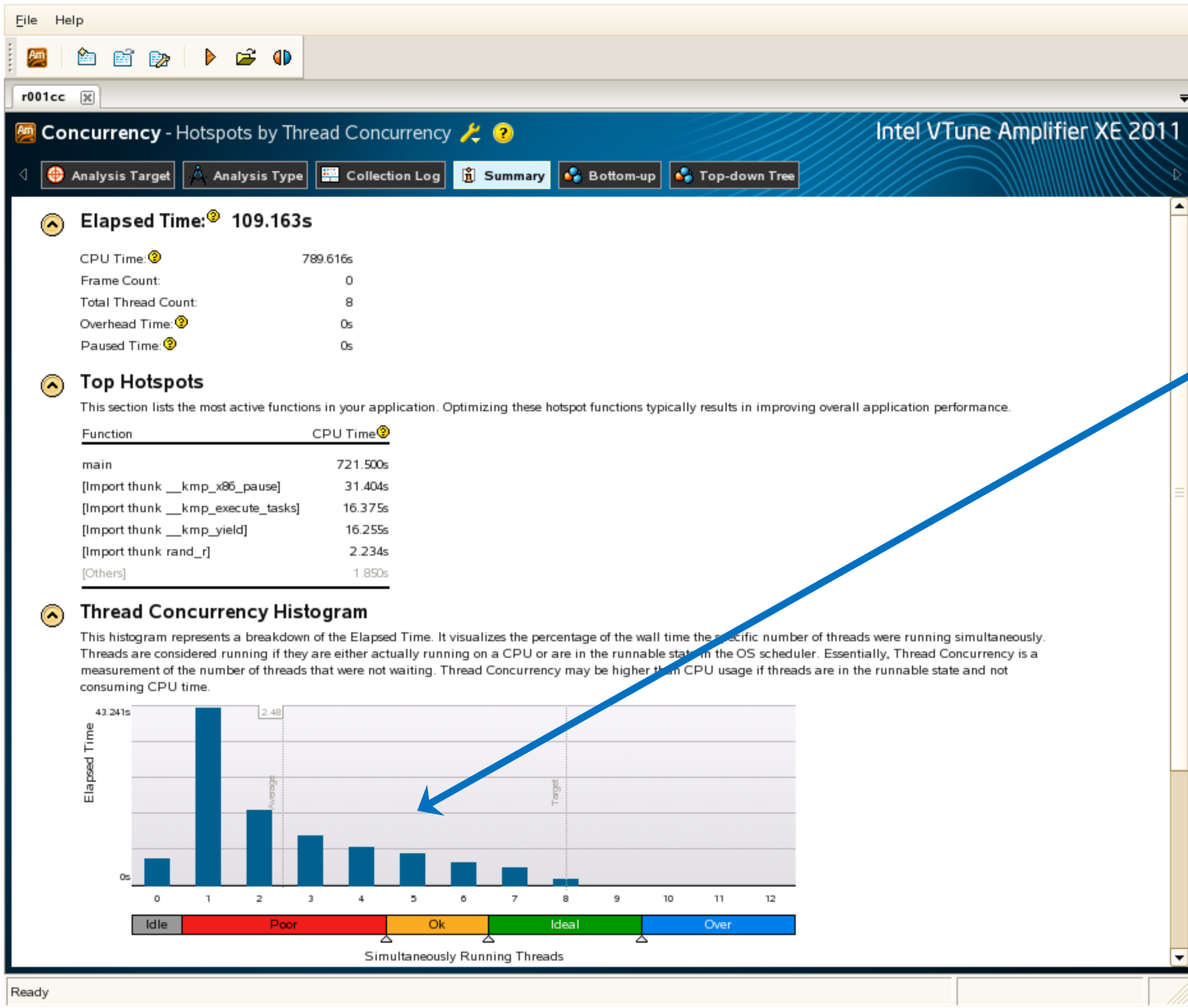


- **Various types are provided**
  - select „Concurrency“
  - in the project properties, set OMP_NUM_THREADS to number of physical cores

> **Note:**
> performance quality evaluation assumes complete system is used

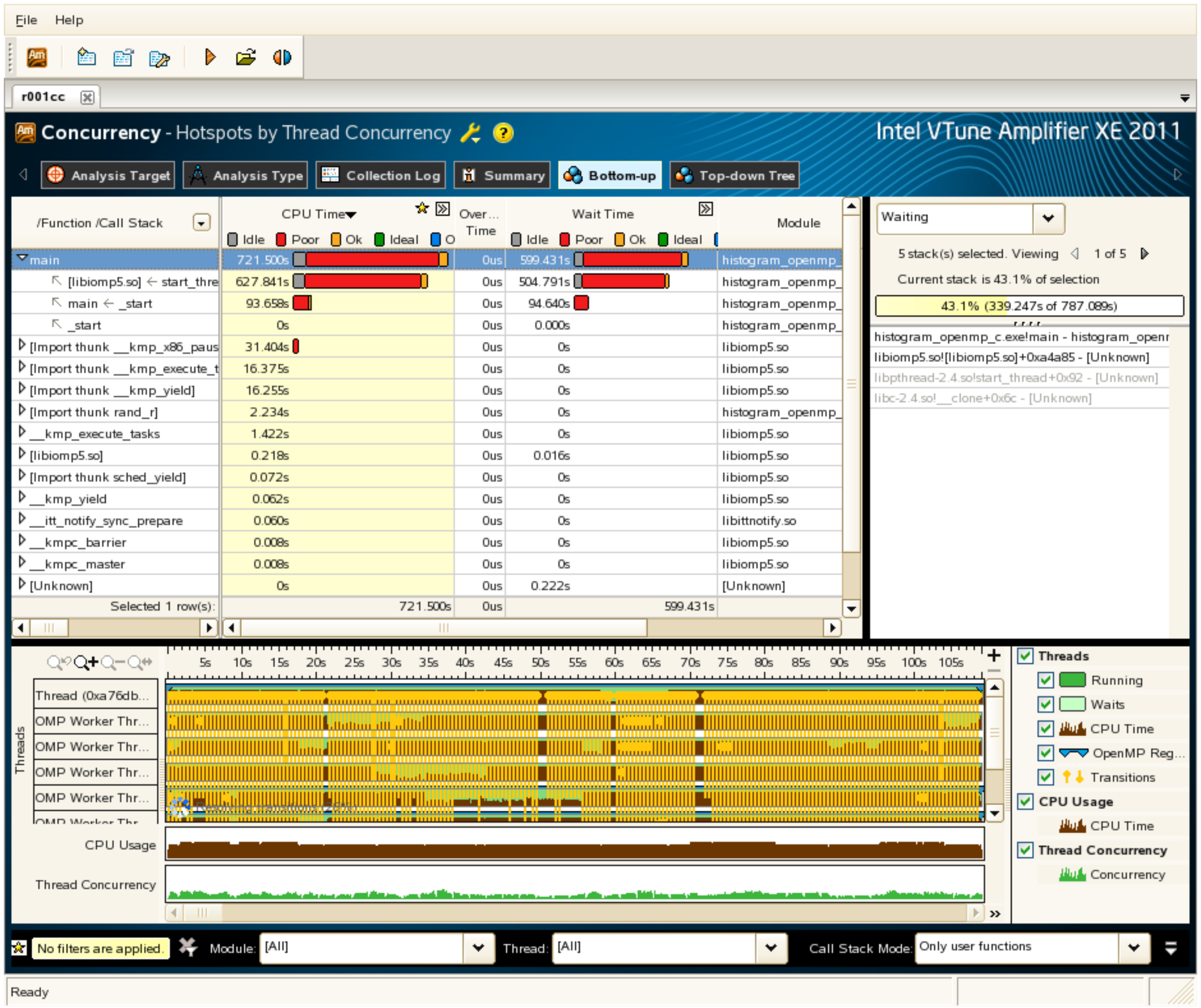
- **Note:**
  - analysis may take quite a long time to run, even for programs of small size

Result tabs: Summary



- **Result:**
  - thread concurrency very low although CPU usage is high

Result tabs: Bottom-up view



Observation:

- much time spent in OpenMP run time library
- lots of transitions indicated → have false sharing

Drill down to source

- **Click on routine with significant resource usage**