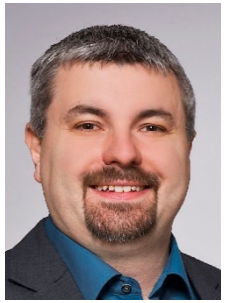
# Programming OpenMP

**Christian Terboven**

Michael Klemm



# Agenda (in total 7 Sessions)

- Session 1: OpenMP Introduction
- Session 2: Tasking
- **Session 3:** Optimization for **NUMA and SIMD**
  - →Review of Session 2 / homework assignments
  - →OpenMP and NUMA architectures
  - →Task Affinity
  - →SIMD
  - →Homework assignments ☺
- Session 4: What Could Possibly Go Wrong Using OpenMP
- Session 5: Introduction to Offloading with OpenMP
- Session 6: Advanced Offloading Topics
- Session 7: Selected / Remaining Topics

# Programming OpenMP

## *Review*

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RWTH AACHEN UNIVERSITY
OpenMP

OpenMP

# *Questions?*

# *Fibonacci*

# Fibonacci illustrated

```
 1  int main(int argc,
 2           char* argv[])
 3  {
 4      [...]
 5      #pragma omp parallel
 6      {
 7          #pragma omp single
 8          {
 9              fib(input);
10          }
11      }
12      [...]
13.}
```

```
14  int fib(int n)   {
15      if (n < 2) return n;
16      int x, y;
17      #pragma omp task shared(x)
18      {
19          x = fib(n - 1);
20      }
21      #pragma omp task shared(y)
22      {
23          y = fib(n - 2);
24      }
25      #pragma omp taskwait
26          return x+y;
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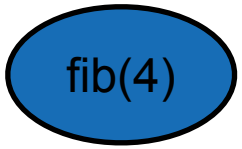
```

- Only one Task / Thread enters fib() from main(), it is responsible for creating the two initial work tasks
- Taskwait is required, as otherwise x and y would get lost

- **T1 enters fib(4)**




Task Queue

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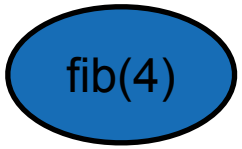
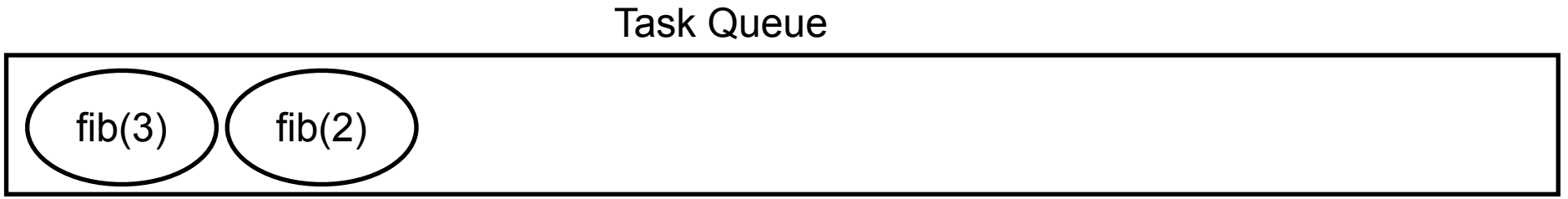
- **T1 creates tasks for fib(3) and fib(2)**



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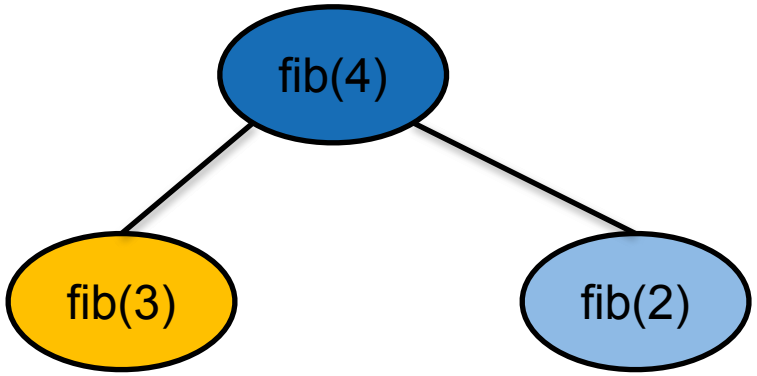


Task Queue

- T1 enters fib(4)

- T1 creates tasks for fib(3) and fib(2)
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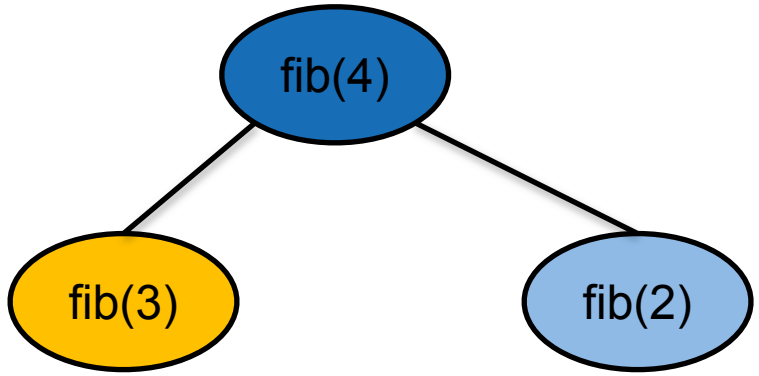


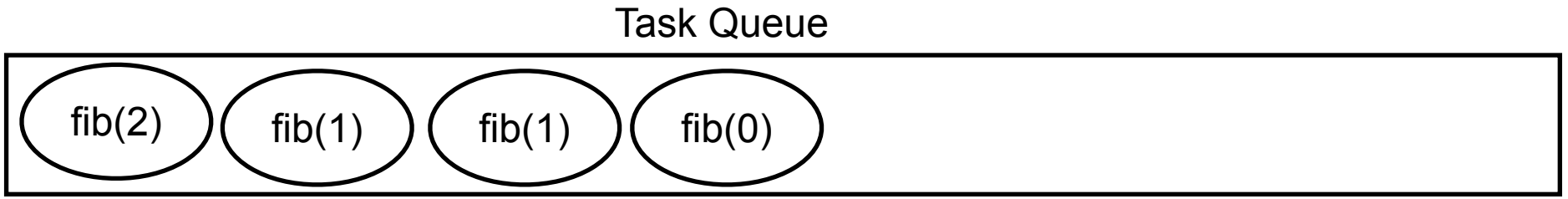

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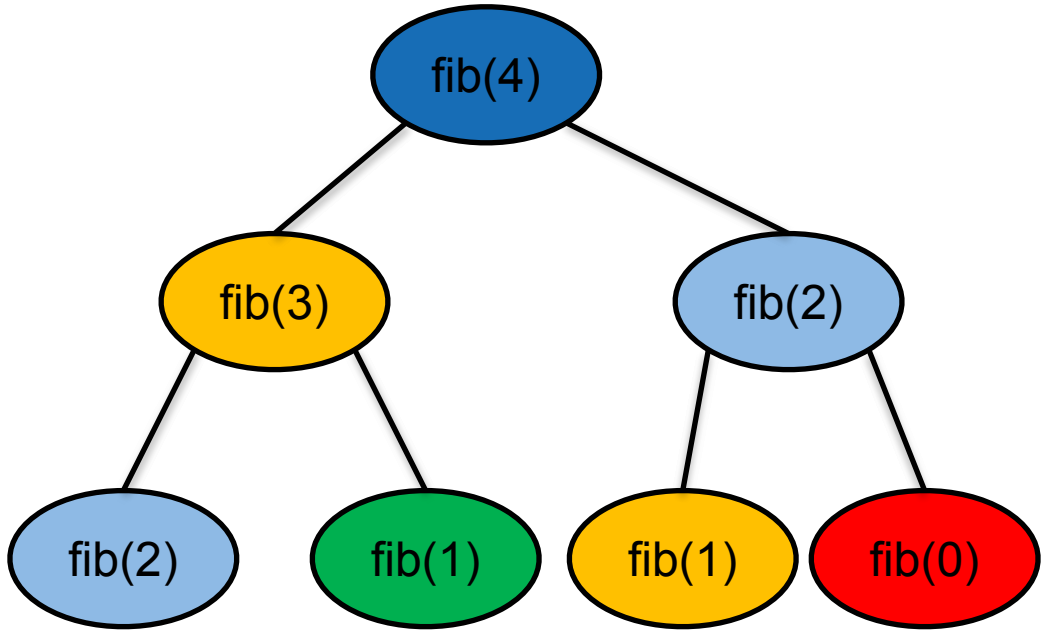


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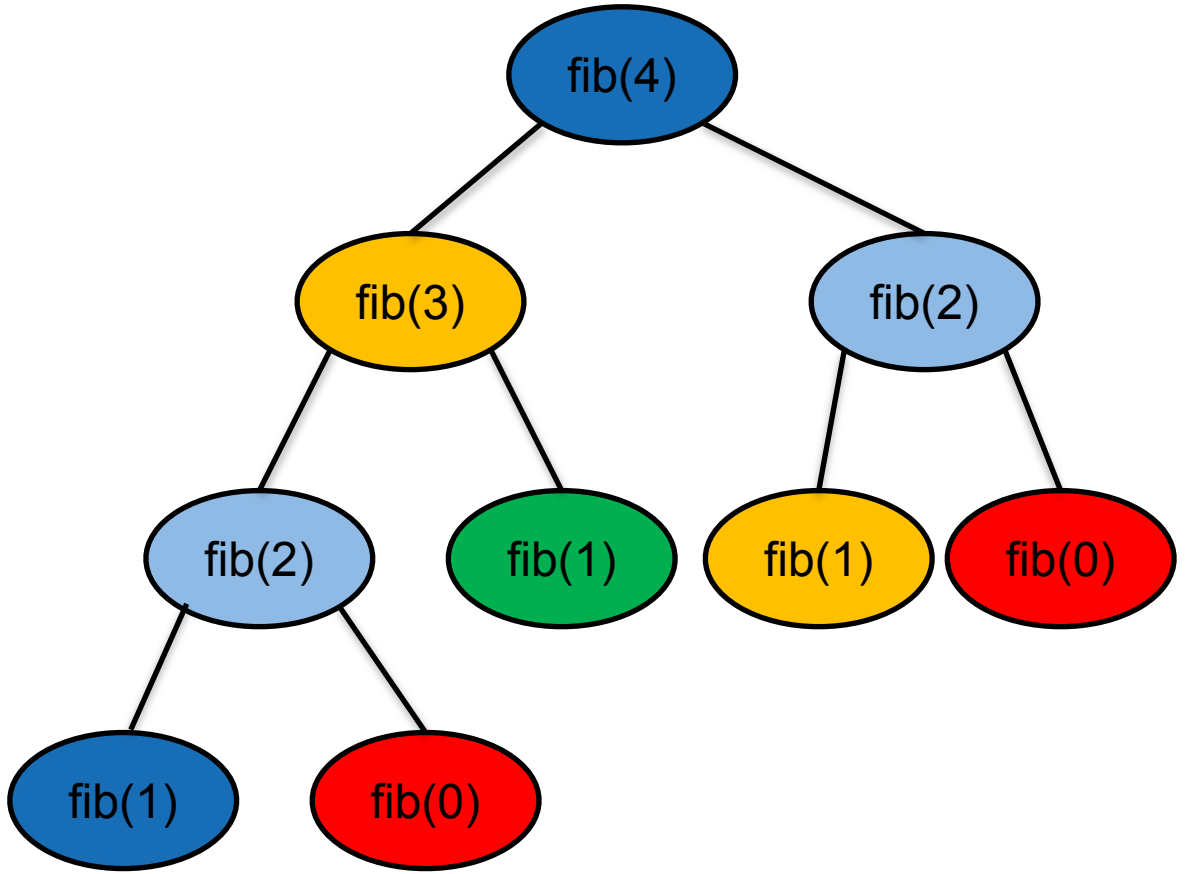

# For / Work-distribution

# Example solution: For w/ Tasking wo/ Red.

```
#pragma omp parallel firstprivate(presult)
{
#pragma omp single
{

        for (int i = 0; i < dimension; i++)
        {
#pragma omp task shared(presult)
{
                result += do_some_computation(i);
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        }

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#pragma omp critical
{
        result += presult;
}

} // end omp parallel
```

# Example solution: For w/ Tasking

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#pragma omp parallel reduction(task,+:result)
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}
        }

} // end omp single

} // end omp parallel
```

# Example solution: For w/ Taskloop

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{
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{

#pragma omp taskloop in_reduction(+:result)
        for (int i = 0; i < dimension; i++)
        {
                result += do_some_computation(i);
        }

} // end omp single

} // end omp parallel
```

# QuickSort

# Example solution: Quick Sort

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```
void quicksort(int * array, int first, int last){
        int pivotElement;
        if((last - first + 1) < 10000) {
                serial_quicksort(array, first, last);
        } else {
                pivotElement = pivot(array,first,last);
                #pragma omp task default(shared)
                {
                        quicksort(array,first,pivotElement-1);
                }
                #pragma omp task default(shared)
                {
                        quicksort(array,pivotElement+1,last);
                }
                #pragma omp taskwait
        }
}
```

# Programming OpenMP

## *Review*

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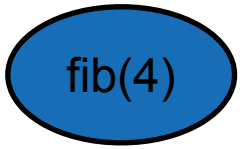


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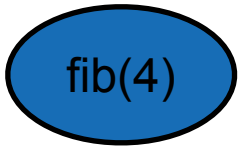


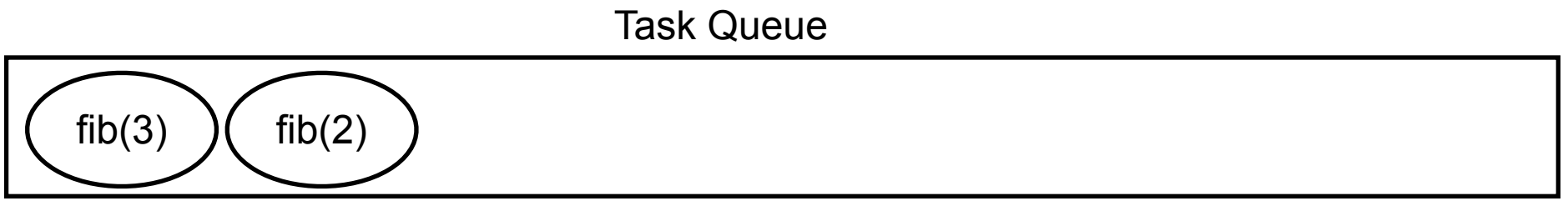

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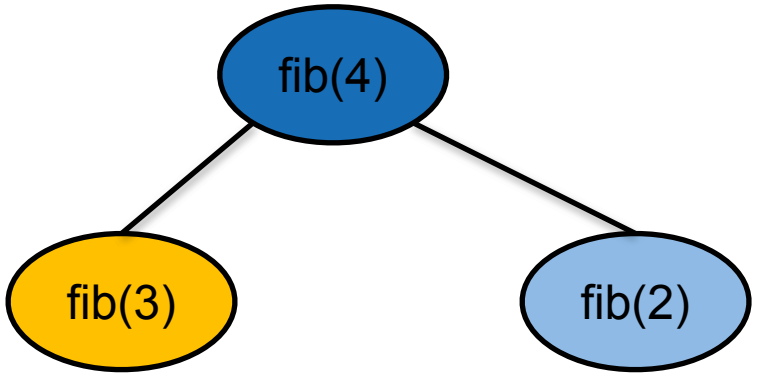


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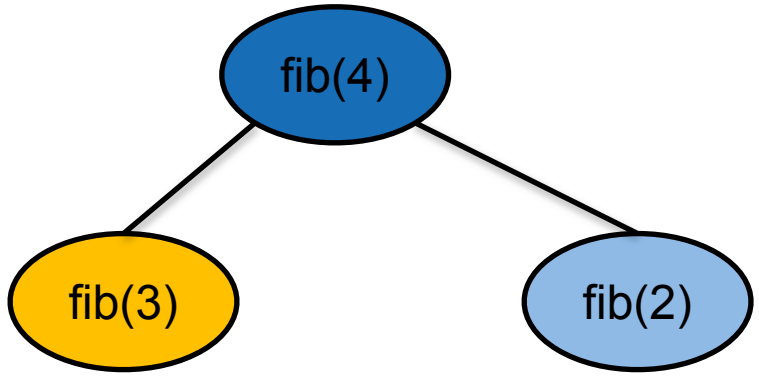


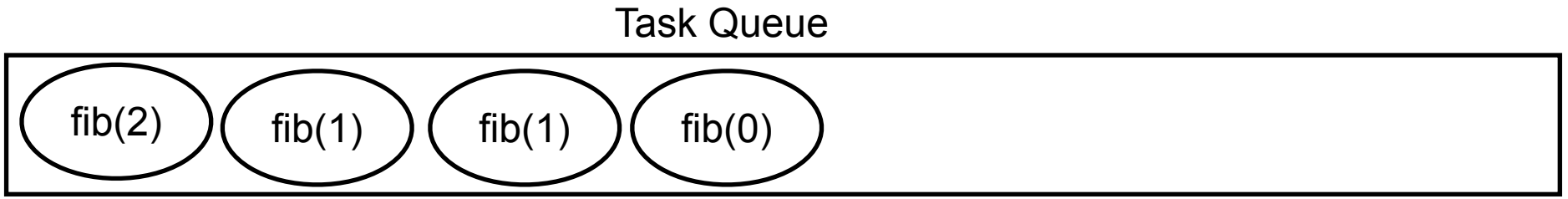

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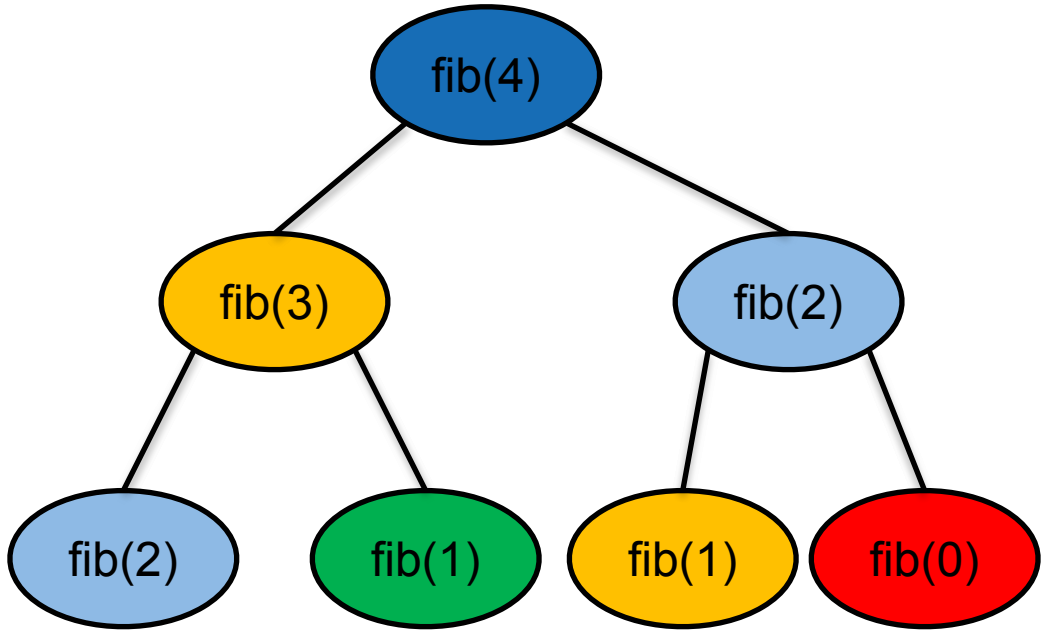


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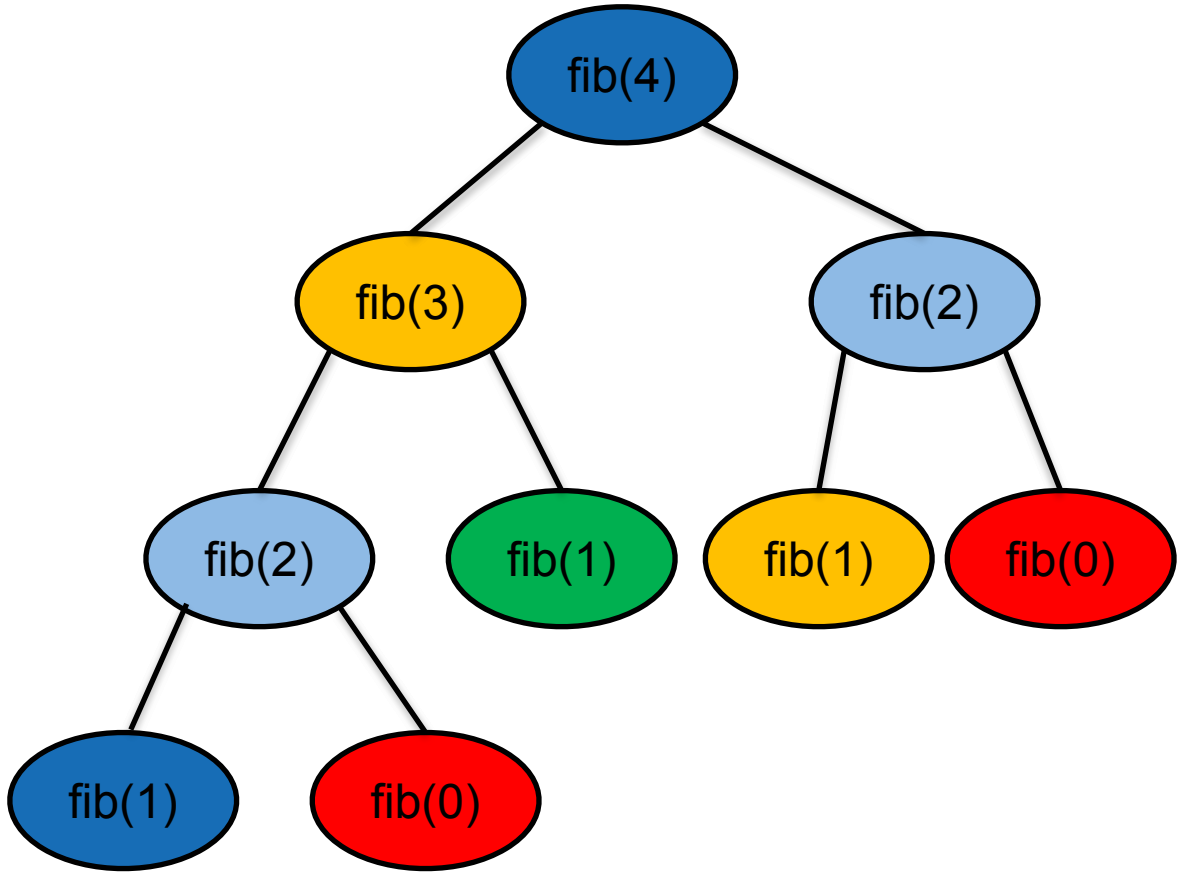

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```

# Example solution: For w/ Taskloop

```
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{

#pragma omp taskloop in_reduction(+:result)
        for (int i = 0; i < dimension; i++)
        {
                result += do_some_computation(i);
        }

} // end omp single

} // end omp parallel
```

# QuickSort

# Programming OpenMP

***NUMA***

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# Review: NUMA concept

# Non-uniform Memory

## *How To Distribute The Data ?*

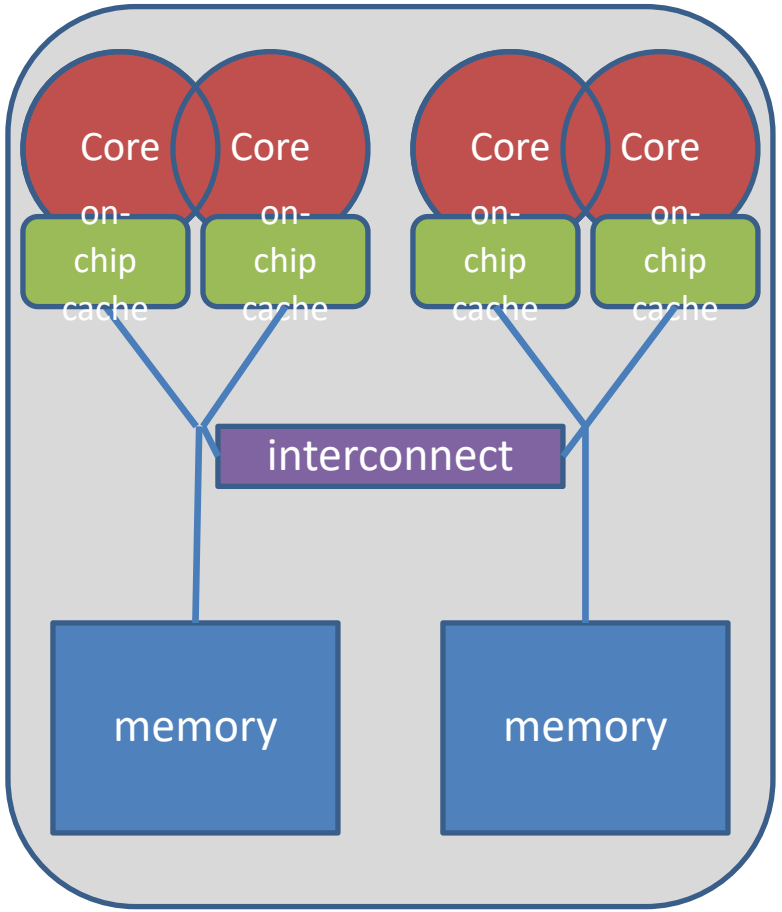
```
double* A;

A = (double*)
    malloc(N * sizeof(double));
```

```
for (int i = 0; i < N; i++) {

   A[i] = 0.0;

}
```



# Non-uniform Memory

- **Serial code: all array elements are allocated in the memory of the NUMA node closest to the core executing the initializer thread (first touch)**

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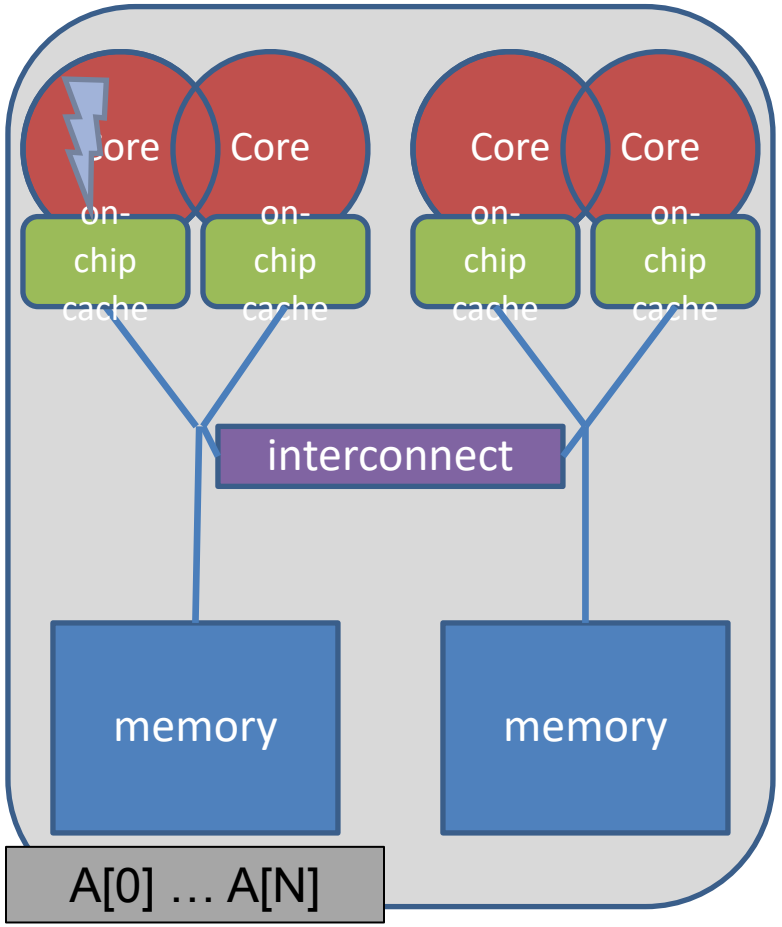
double* A;

A = (double*)
    malloc(N * sizeof(double));
```

```
for (int i = 0; i < N; i++) {

   A[i] = 0.0;

}
```



# About Data Distribution

- Important aspect on cc-NUMA systems
  - →If not optimal, longer memory access times and hotspots

- Placement comes from the Operating System
  - →This is therefore Operating System dependent

- Windows, Linux and Solaris all use the “First Touch” placement policy by default
  - →May be possible to override default (check the docs)

# Non-uniform Memory

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```
double* A;

A = (double*)
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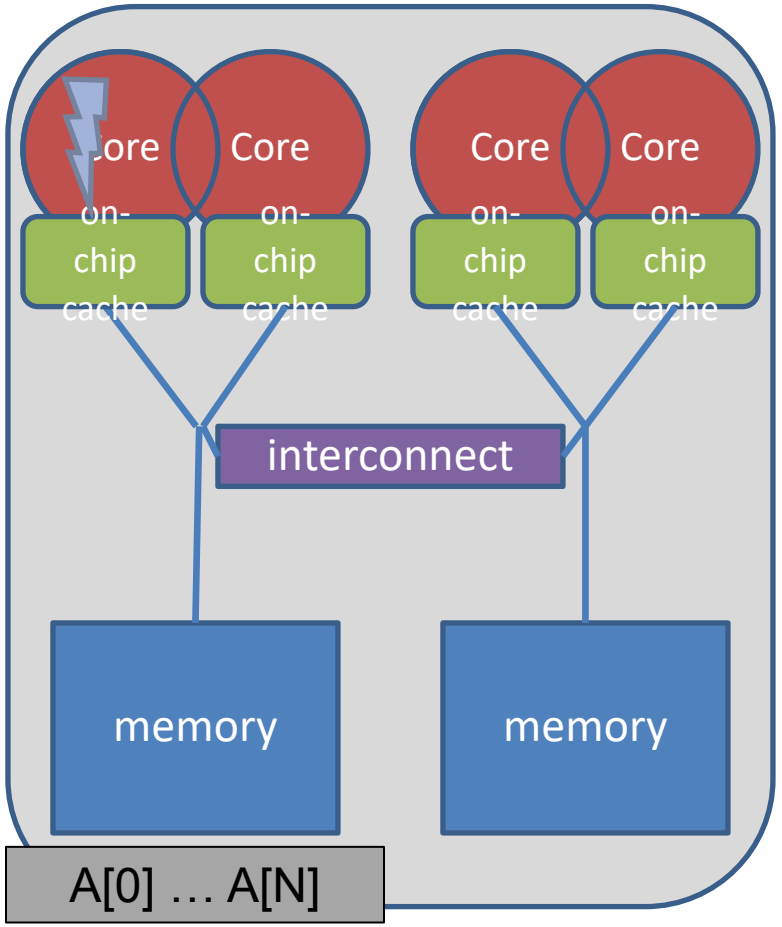


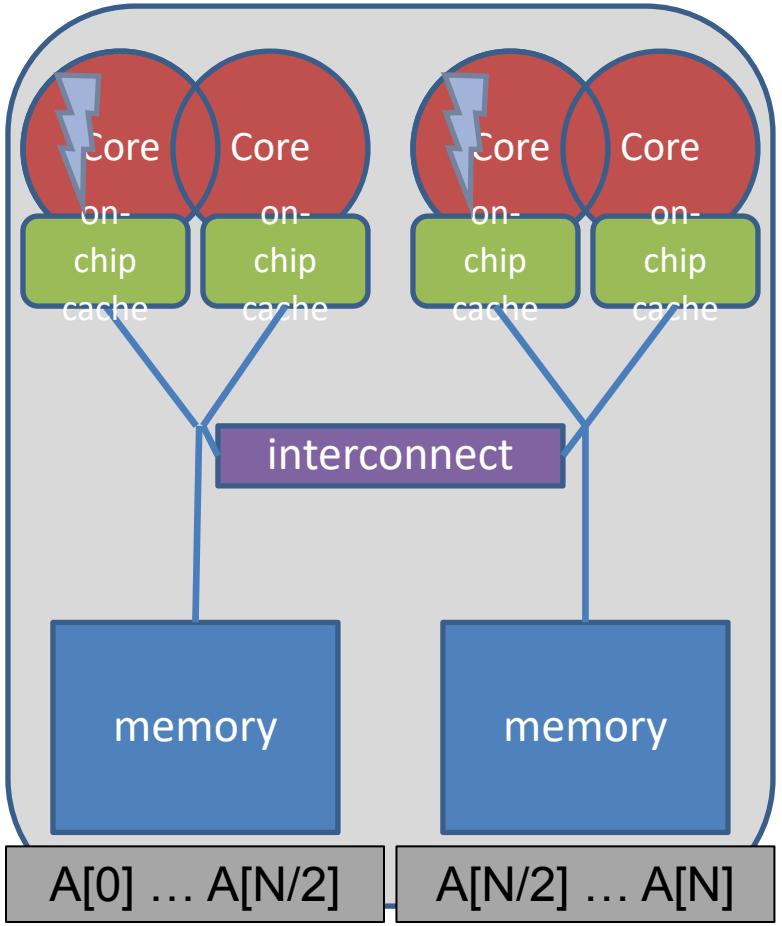
# First Touch Memory Placement

- **First Touch w/ parallel code: all array elements are allocated in the memory of the NUMA node that contains the core that executes the thread that initializes the partition**

```
double* A;
A = (double*)
    malloc(N * sizeof(double));

omp_set_num_threads(2);

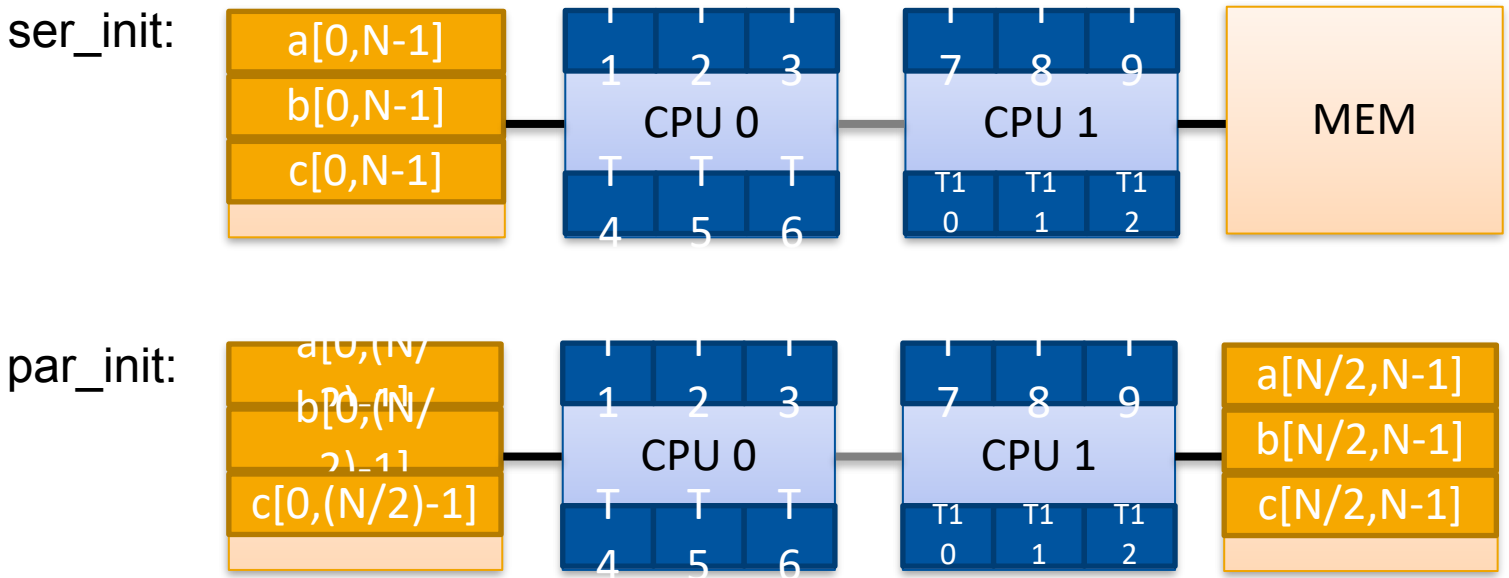
#pragma omp parallel for
for (int i = 0; i < N; i++) {
   A[i] = 0.0;
}
```



# Serial vs. Parallel Initialization

- Stream example on 2 socket sytem with Xeon X5675 processors, 12 OpenMP threads:

| | copy | scale | add | triad |
|---|---|---|---|---|
| ser_init | 18.8 GB/s | 18.5 GB/s | 18.1 GB/s | 18.2 GB/s |
| par_init | 41.3 GB/s | 39.3 GB/s | 40.3 GB/s | 40.4 GB/s |



# *Thread Binding and Memory Placement*

# Get Info on the System Topology

- Before you design a strategy for thread binding, you should have a basic understanding of the system topology. Please use one of the following options on a target machine:
  - → Intel MPI's `cpuinfo` tool
    - → `cpuinfo`
    - → Delivers information about the number of sockets (= packages) and the mapping of processor ids to cpu cores that the OS uses.
  - → hwlocs' `hwloc-ls` tool
    - → `hwloc-ls`
    - → Displays a (graphical) representation of the system topology, separated into NUMA nodes, along with the mapping of processor ids to cpu cores that the OS uses and additional info on caches.

# Decide for Binding Strategy

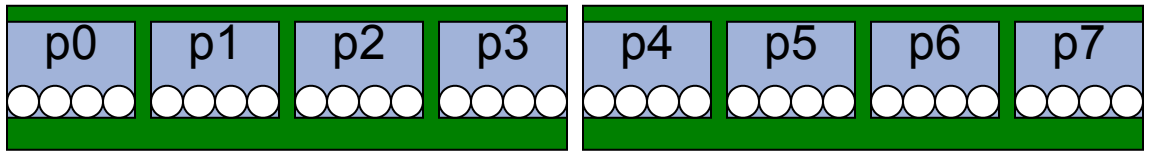
- Selecting the „right“ binding strategy depends not only on the topology, but also on application characteristics.
  - → Putting threads far apart, i.e., on different sockets
    - → May improve aggregated memory bandwidth available to application
    - → May improve the combined cache size available to your application
    - → May decrease performance of synchronization constructs
  - → Putting threads close together, i.e., on two adjacent cores that possibly share some caches
    - → May improve performance of synchronization constructs
    - → May decrease the available memory bandwidth and cache size

# Places + Binding Policies (1/2)

- Define OpenMP Places
  - → set of OpenMP threads running on one or more processors
  - → can be defined by the user, i.e. `OMP_PLACES=cores`
- Define a set of OpenMP Thread Affinity Policies
  - → SPREAD: spread OpenMP threads evenly among the places, partition the place list
  - → CLOSE: pack OpenMP threads near primary thread
  - → PRIMARY: collocate OpenMP thread with primary thread
- Goals
  - → user has a way to specify where to execute OpenMP threads
  - → locality between OpenMP threads / less false sharing / memory bandwidth

# OMP_PLACES env. variable

- Assume the following machine:




→ 2 sockets, 4 cores per socket, 4 hyper-threads per core

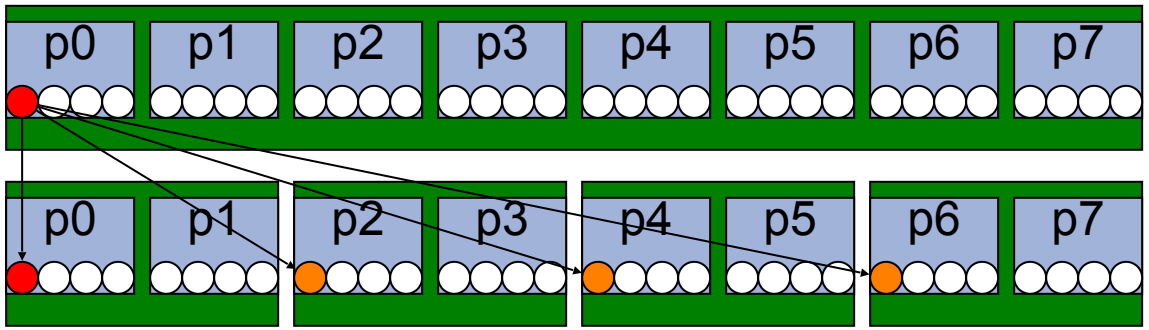
- Abstract names for OMP_PLACES:
  - → threads: Each place corresponds to a single hardware thread.
  - → cores: Each place corresponds to a single core (having one or more hardware threads).
  - → sockets: Each place corresponds to a single socket (consisting of one or more cores).
  - → ll_caches (5.1): Each place corresponds to a set of cores that share the last level cache.
  - → numa_domains (5.1): Each places corresponds to a set of cores for which their closest memory is: the same memory; and at a similar distance from the cores.

# OpenMP 4.0: Places + Policies

- Example‘s Objective:
  - → separate cores for outer loop and near cores for inner loop
- Outer Parallel Region: proc_bind(spread), Inner: proc_bind(close)
  - → spread creates partition, compact binds threads within respective partition

```
OMP_PLACES=(0,1,2,3), (4,5,6,7), ... = (0-4):4:8    = cores
#pragma omp parallel proc_bind(spread) num_threads(4)
#pragma omp parallel proc_bind(close) num_threads(4)
```

- Example
  - → initial
  - → spread 4
  - → close 4



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- Example
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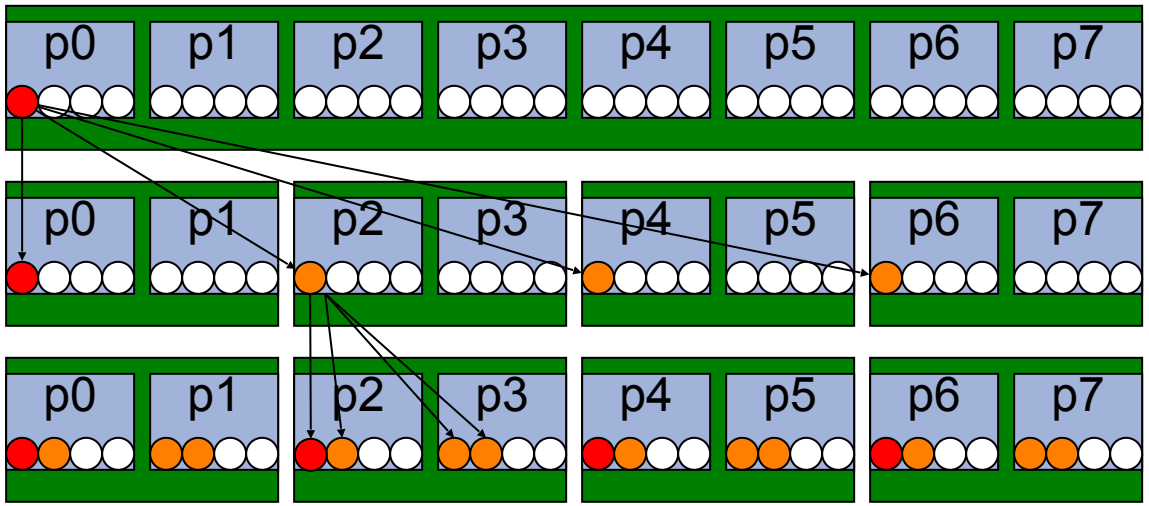
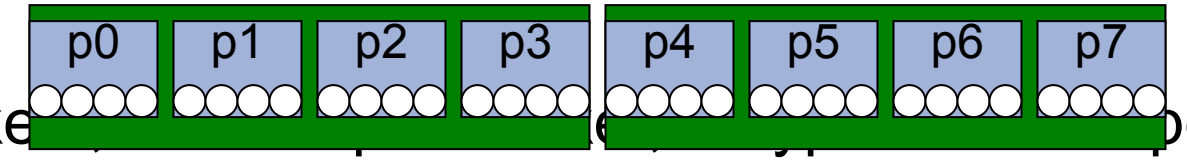


# More Examples (1/3)

- Assume the following machine:




→2 socke per core

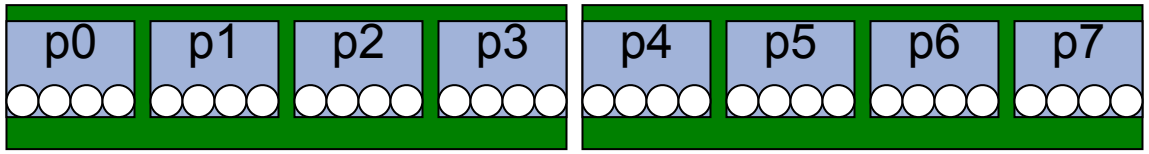
- Parallel Region with two threads, one per socket

→`OMP_PLACES=sockets`

→`#pragma omp parallel num_threads(2) proc_bind(spread)`

# More Examples (2/3)

- Assume the following machine:




- Parallel Region with four threads, one per core, but only on the first socket
  - → `OMP_PLACES=cores`
  - → `#pragma omp parallel num_threads(4) proc_bind(close)`

# More Examples (3/3)

- Spread a nested loop first across two sockets, then among the cores within each socket, only one thread per core
  - → `OMP_PLACES=cores`
  - → `#pragma omp parallel num_threads(2) proc_bind(spread)`
  - → `#pragma omp parallel num_threads(4) proc_bind(close)`

- Places API routines allow to
  - → query information about binding…
  - → query information about the place partition…

# Places API: Example

- Simple routine printing the processor ids of the place the calling thread is bound to:

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```
void print_binding_info() {
     int my_place = omp_get_place_num();
     int place_num_procs = omp_get_place_num_procs(my_place);

     printf("Place consists of %d processors: ", place_num_procs);

     int *place_processors = malloc(sizeof(int) * place_num_procs);
     omp_get_place_proc_ids(my_place, place_processors)

     for (int i = 0; i < place_num_procs - 1; i++) {
             printf("%d ", place_processors[i]);
     }
     printf("\n");

     free(place_processors);
}
```

# OpenMP 5.0 way to do this

- Set `OMP_DISPLAY_AFFINITY=TRUE`
  - → Instructs the runtime to display formatted affinity information
  - → Example output for two threads on two physical cores:
  - → Output can be formatted with `OMP_AFFINITY_FORMAT` env var or corresponding routine
  - → Formatted affinity information can be printed with `omp_display_affinity(const char* format)`

# OpenMP 5.0 way to do this

- Set `OMP_DISPLAY_AFFINITY=TRUE`
  - → Instructs the runtime to display formatted affinity information
  - → Example output for two threads on two physical cores:

```
nesting_level=   1,   thread_num=   0,   thread_affinity=   0,1
nesting_level=   1,   thread_num=   1,   thread_affinity=   2,3
```

  - → Output can be formatted with `OMP_AFFINITY_FORMAT` or the corresponding routine
  - → Formatted affinity information can be printed with

```
omp_display_affinity(const char* format)
```

# Affinity format specification

| | | | |
|---|---|---|---|
| t | omp_get_team_num() | a | omp_get_ancestor_thread_num() at level-1 |
| T | omp_get_num_teams() | H | hostname |
| L | omp_get_level() | P | process identifier |
| n | omp_get_thread_num() | i | native thread identifier |
| N | omp_get_num_threads() | A | thread affinity: list of processors (cores) |

- Example:

→Possible output:

# Affinity format specification

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| N | omp_get_num_threads() | A | thread affinity: list of processors (cores) |

- Example:

```
OMP_AFFINITY_FORMAT="Affinity: %0.3L %.8n %.15{A} %.12H"
```

→Possible output:

```
Affinity: 001          0       0-1,16-17       host003
Affinity: 001          1       2-3,18-19       host003
```

# Fine-grained control of Memory Affinity

- Explicit NUMA-aware memory allocation:
  - → By carefully touching data by the thread which later uses it
  - → By changing the default memory allocation strategy
    - → Linux: `numactl` command
  - → By explicit migration of memory pages
    - → Linux: `move_pages()`

- Example: using numactl to distribute pages round-robin:
  - → `numactl -interleave=all ./a.out`

# Managing Memory Spaces

# Different kinds of memory

- Traditional DDR-based memory
- High-bandwidth memory
- Non-volatile memory
- …

**Cascade Lake (Leonide at INRIA)**

```
CPU: Intel(R) Xeon(R) Gold 6230 CPU @ 2.10GHz
Freq Govenor: performance
---------------------
available: 4 nodes (0-3)
node 0 cpus: 0 2 4 6 8 10 12 14 16 18
             20 22 24 26 28 30 32 34 36 38
node 0 size: 191936 MB
node 0 free: 178709 MB
node 1 cpus: 1 3 5 7 9 11 13 15 17 19 21 23
             25 27 29 31 33 35 37 39
node 1 size: 192016 MB
node 1 free: 179268 MB
node 2 cpus:
node 2 size: 759808 MB
node 2 free: 759794 MB
node 3 cpus:
node 3 size: 761856 MB
node 3 free: 761851 MB
node distances:
node   0   1   2   3
  0:  10  21  17  28
  1:  21  10  28  17
  2:  17  28  10  28
  3:  28  17  28  10
```

**DRAM + Optane**

# Memory Management

- Allocator := an OpenMP object that fulfills requests to allocate and deallocate storage for program variables
- OpenMP allocators are of type `omp_allocator_handle_t`
- Default allocator for Host
  - →via `OMP_ALLOCATOR` env. var. or corresponding API
- OpenMP 5.0 supports a set of memory allocators

# OpenMP allocators

- Selection of a certain kind of memory

| Allocator name | Storage selection intent |
|---|---|
| omp_default_mem_alloc | use default storage |
| omp_large_cap_mem_alloc | use storage with large capacity |
| omp_const_mem_alloc | use storage optimized for read-only variables |
| omp_high_bw_mem_alloc | use storage with high bandwidth |
| omp_low_lat_mem_alloc | use storage with low latency |
| omp_cgroup_mem_alloc | use storage close to all threads in the contention group of the thread requesting the allocation |
| omp_pteam_mem_alloc | use storage that is close to all threads in the same parallel region of the thread requesting the allocation |
| omp_thread_local_mem_alloc | use storage that is close to the thread requesting the allocation |

# Using OpenMP Allocators

- New clause on all constructs with data sharing clauses:
  - → `allocate( [allocator:] list )`
- Allocation:
  - → `omp_alloc(size_t size, omp_allocator_handle_t allocator)`
- Deallocation:
  - → `omp_free(void *ptr, const omp_allocator_handle_t allocator)`
  - → `allocator` argument is optional
- `allocate` directive: standalone directive for allocation, or declaration of allocation stmt.

# OpenMP allocator traits / 1

- Allocator traits control the behavior of the allocator

| | |
|---|---|
| sync_hint | contended, uncontended, serialized, private<br>default: contended |
| alignment | positive integer value that is a power of two<br>default: 1 byte |
| access | all, cgroup, pteam, thread<br>default: all |
| pool_size | positive integer value |
| fallback | default_mem_fb, null_fb, abort_fb, allocator_fb<br>default: default_mem_fb |
| fb_data | an allocator handle |
| pinned | true, false<br>default: false |
| partition | environment, nearest, blocked, interleaved<br>default: environment |

# OpenMP Allocator Traits / 2

- `fallback`: describes the behavior if the allocation cannot be fulfilled
  - → `default_mem_fb`: return system's default memory
  - → Other options: null, abort, or use different allocator
- `pinned`: request pinned memory, i.e. for GPUs

# OpenMP Allocator Traits / 3

- `partition`: partitioning of allocated memory of physical storage resources (think of NUMA)
  - → `environment`: use system's default behavior
  - → `nearest`: most closest memory
  - → `blocked`: partitioning into approx. same size with at most one block per storage resource
  - → `interleaved`: partitioning in a round-robin fashion across the storage resources

# OpenMP Allocator Traits / 4

- Construction of allocators with traits via
  - →
```
omp_allocator_handle_t   omp_init_allocator(
  omp_memspace_handle_t memspace,
  int ntraits, const omp_alloctrait_t traits[]);
```
  - →Selection of memory space mandatory
  - →Empty traits set: use defaults
- Allocators have to be destroyed with `*_destroy_*`
- Custom allocator can be made default with `omp_set_default_allocator(omp_allocator_handle_t allocator)`

# OpenMP Memory Spaces

- Storage resources with explicit support in OpenMP:

| | |
|---|---|
| omp_default_mem_space | System's default memory resource |
| omp_large_cap_mem_space | Storage with larg(er) capacity |
| omp_const_mem_space | Storage optimized for variables with constant value |
| omp_high_bw_mem_space | Storage with high bandwidth |
| omp_low_lat_mem_space | Storage with low latency |

→Exac

→Pre-d

# Memory Management Status

- **LLVM OpenMP runtime internally already uses libmemkind (libnuma, numactl)**
  - → Support for various kinds of memory: DDR, HBW and Persistent Memory (Optane)
  - → Library loaded at initialization (checks for availability)
  - → If requested memory space for allocator is not available → fallback to DDR

- **Memory Management implementation in LLVM still not complete**
  - → Some allocator traits not implemented yet
  - → Some `partition` values not implemented yet (environment, interleaved, nearest, blocked)
  - → Semantics of `omp_high_bw_mem_space and omp_large_cap_mem_space` unclear. Which memory should be used?
    - → Explicitly target HBM → currently implemented in LLVM

- **LLVM has custom implementation of aligned memory allocation**
  - → Allocation covers → {Allocator Information + Requested Size + Buffer based on alignment}

# Programming OpenMP

***NUMA***

**Christian Terboven**
Michael Klemm

RWTH AACHEN UNIVERSITY
OpenMP

# Improving Tasking Performance: Task Affinity

# Motivation

- Techniques for process binding & thread pinning available
  - →OpenMP thread level: `OMP_PLACES & OMP_PROC_BIND`
  - →OS functionality: `taskset -c`

OpenMP Tasking:

- In general: Tasks may be executed by any thread in the team
  - →Missing task-to-data affinity may have detrimental effect on performance

OpenMP 5.0:

- `affinity` clause to express affinity to data

# `affinity` clause

- New clause: `#pragma omp task affinity (list)`
  - → Hint to the runtime to execute task closely to physical data location
  - → Clear separation between dependencies and affinity
- Expectations:
  - → Improve data locality / reduce remote memory accesses
  - → Decrease runtime variability
- Still expect task stealing
  - → In particular, if a thread is under-utilized

# Code Example

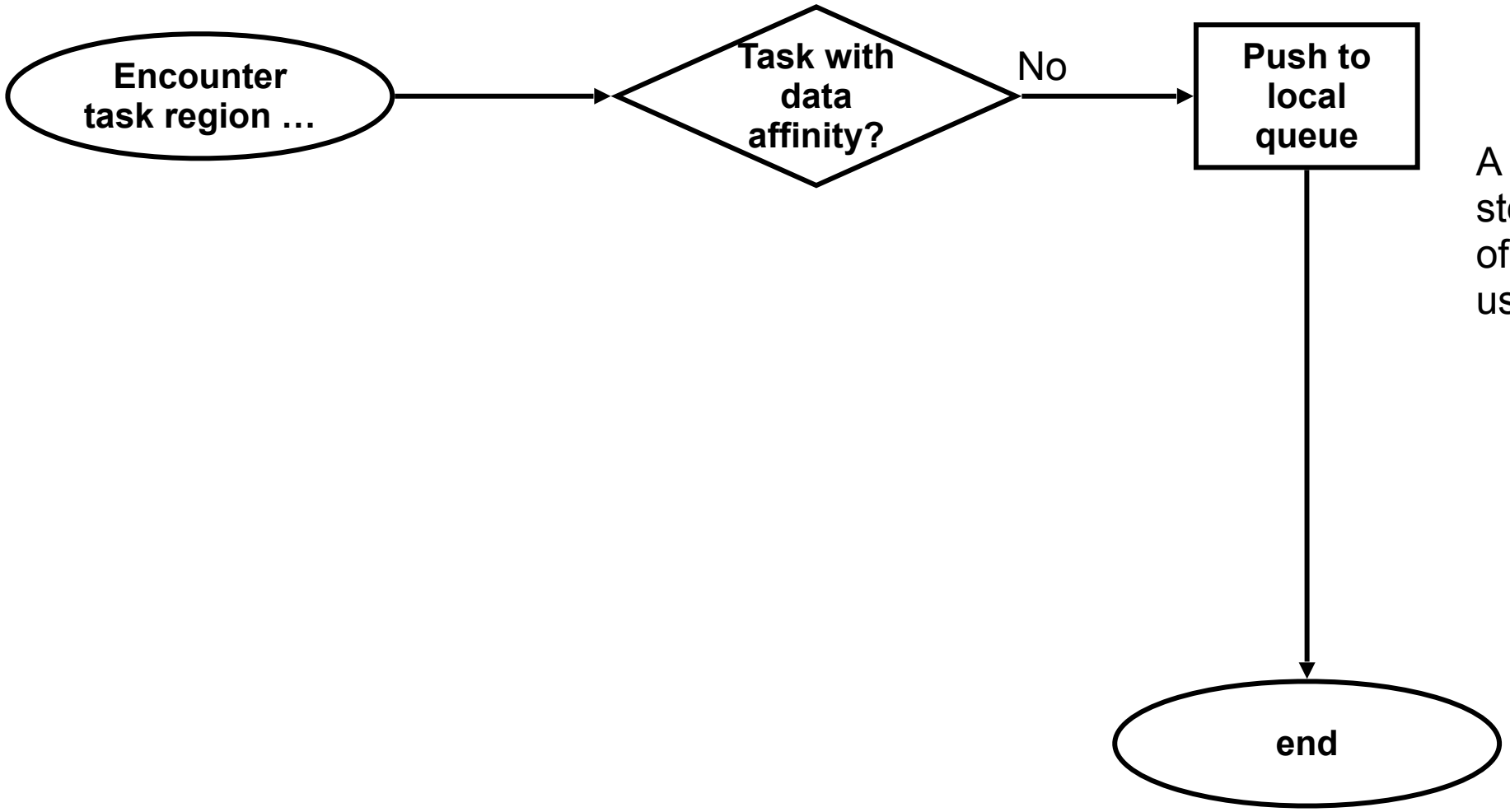
- Excerpt from task-parallel STREAM

```
1   #pragma omp task \
2       shared(a, b, c, scalar) \
3       firstprivate(tmp_idx_start, tmp_idx_end) \
4       affinity( a[tmp_idx_start] )
5   {
6      int i;
7      for(i = tmp_idx_start; i <= tmp_idx_end; i++)
8           a[i] = b[i] + scalar * c[i];
9   }
```

→Loops have been blocked manually (see `tmp_idx_start/end`)

→Assumption: initialization and computation have same blocking and same affinity

# Selected LLVM implementation details




A map is introduced to store location information of data that was previously used

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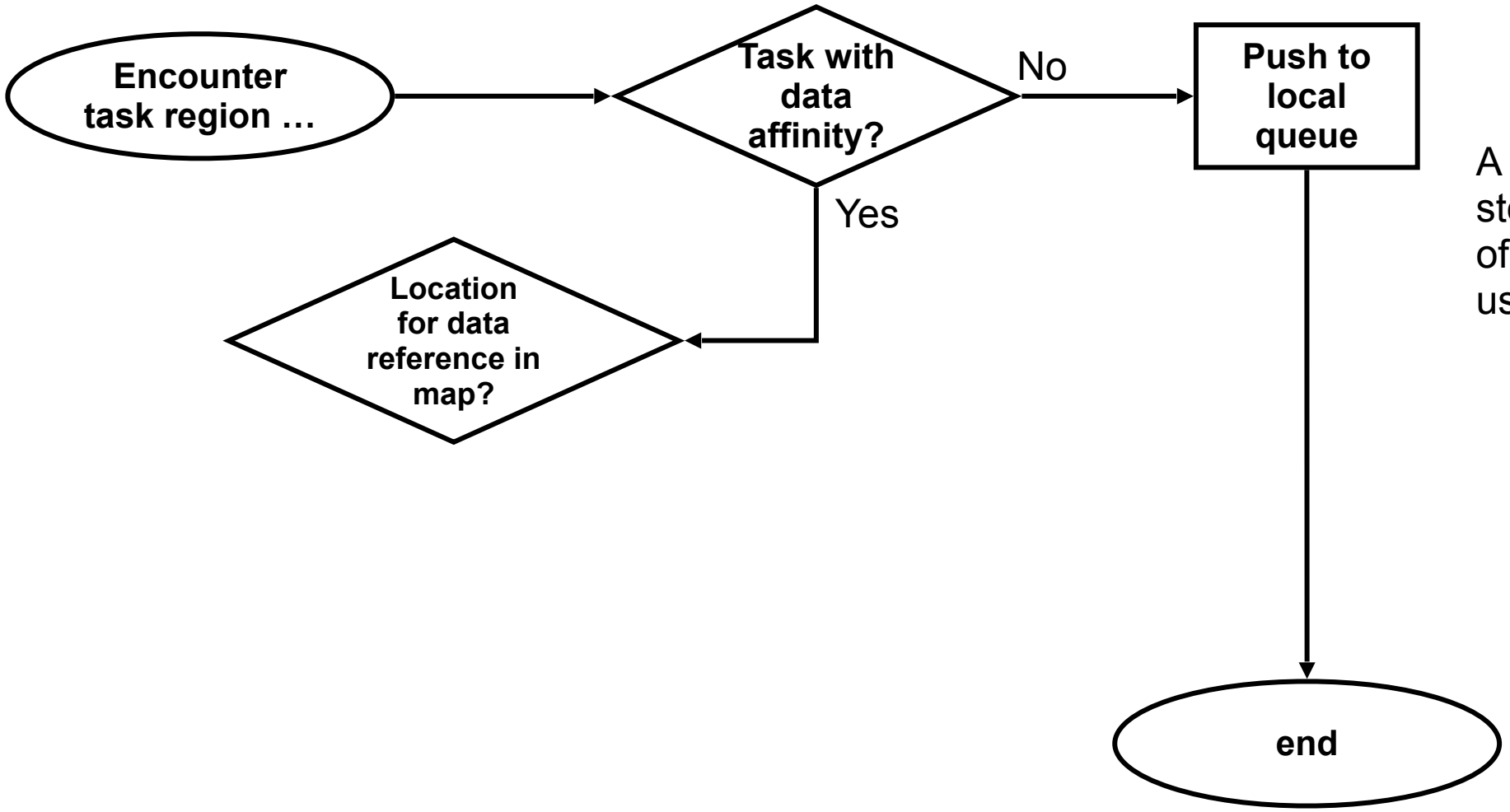


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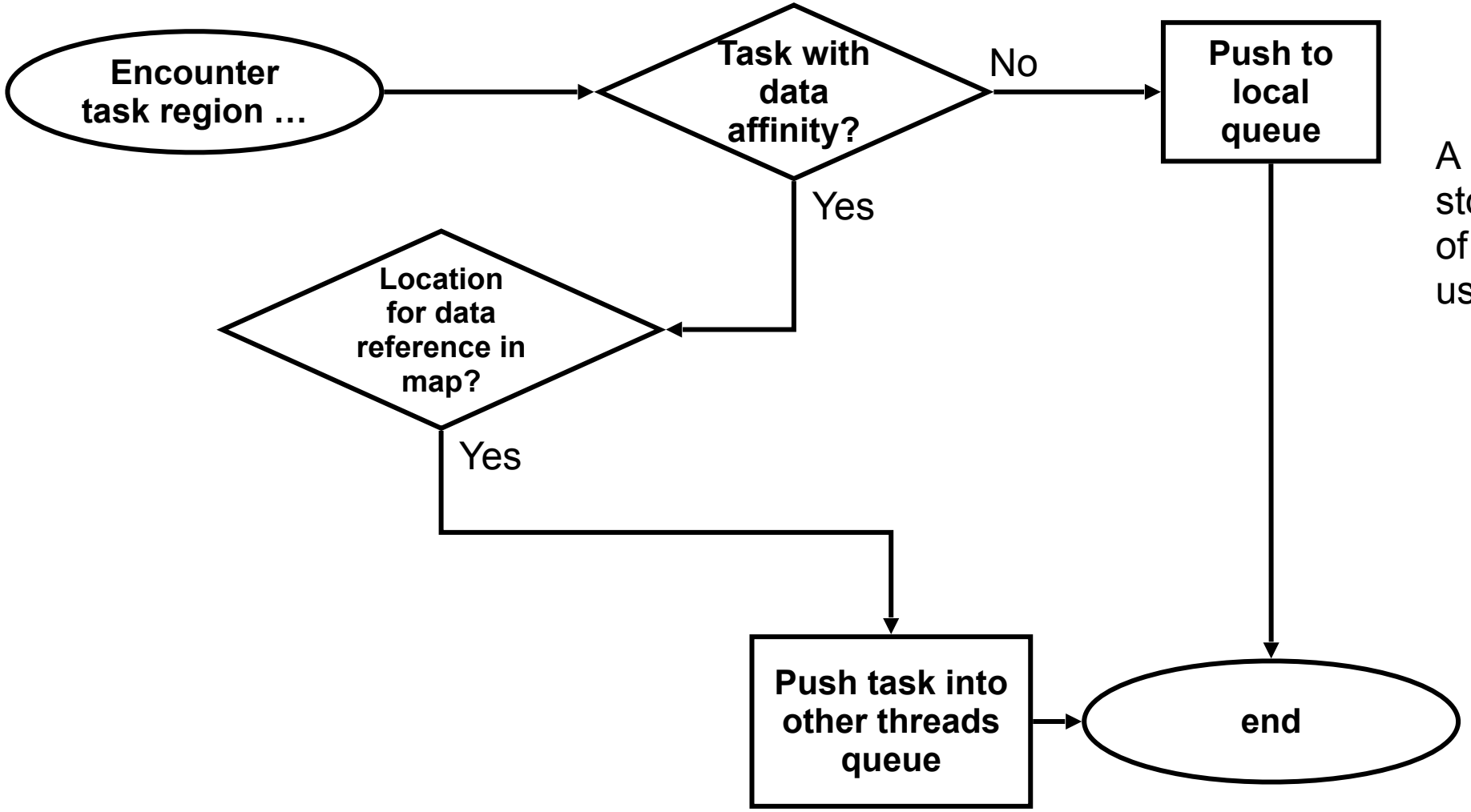


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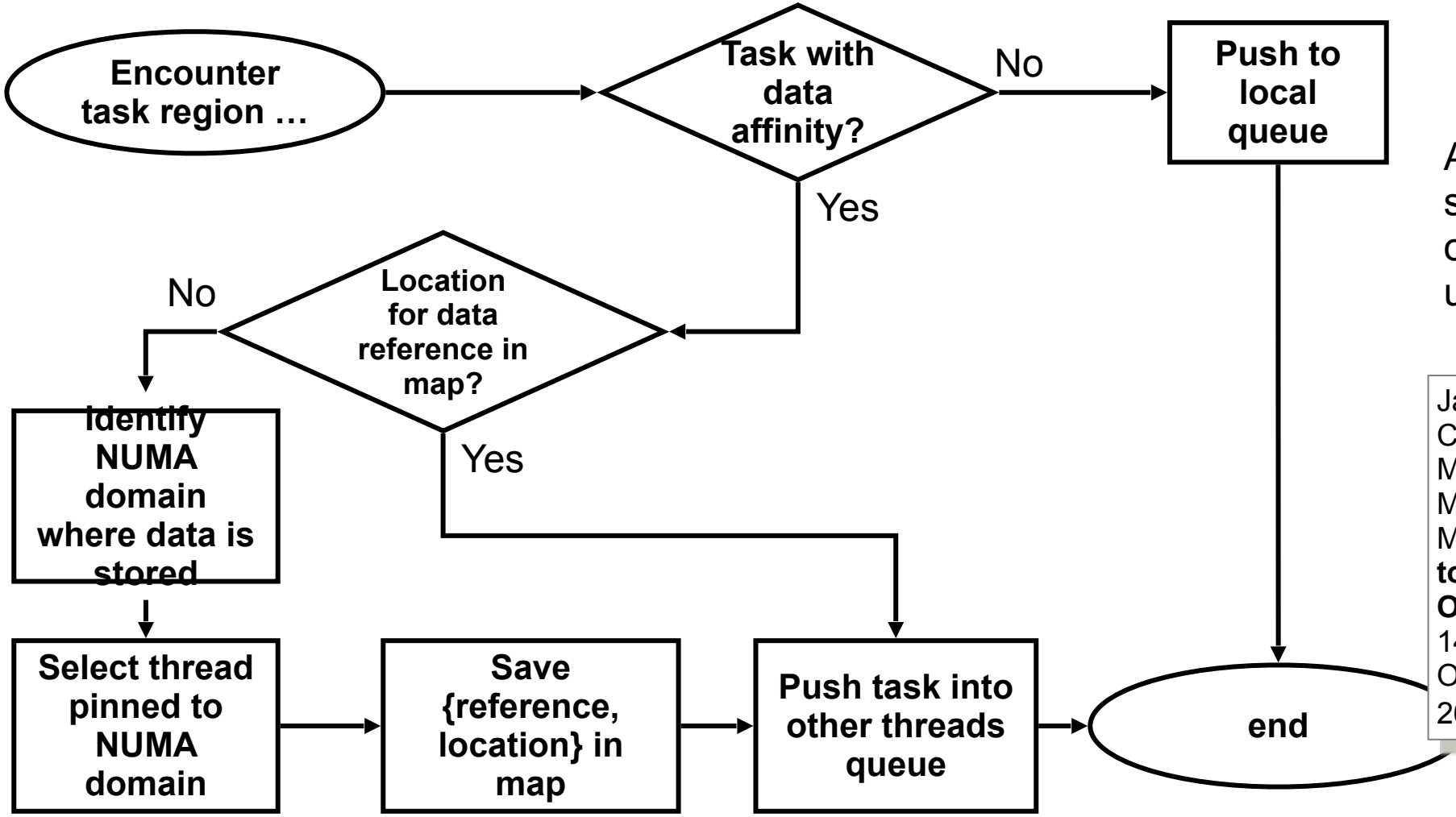


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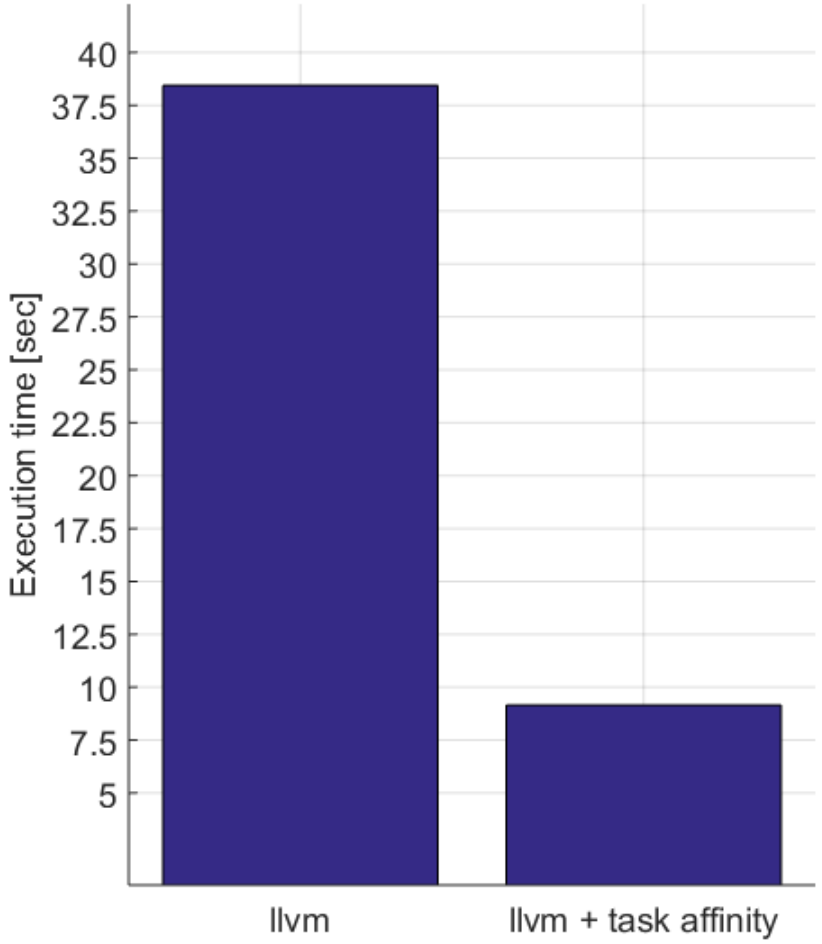
Jannis Klinkenberg, Philipp Samfass, Christian Terboven, Alejandro Duran, Michael Klemm, Xavier Teruel, Sergi Mateo, Stephen L. Olivier, and Matthias S. Müller. **Assessing Task-to-Data Affinity in the LLVM OpenMP Runtime**. Proceedings of the 14th International Workshop on OpenMP, IWOMP 2018. September 26-28, 2018, Barcelona, Spain.

# Evaluation

## Program runtime
## Median of 10 runs



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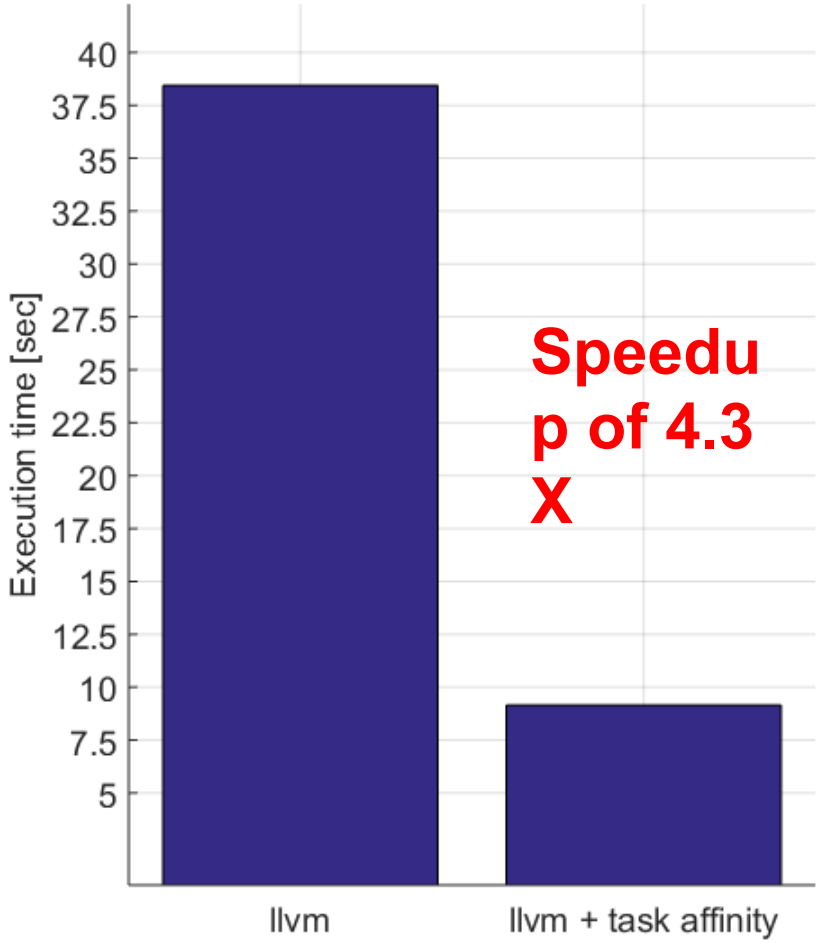

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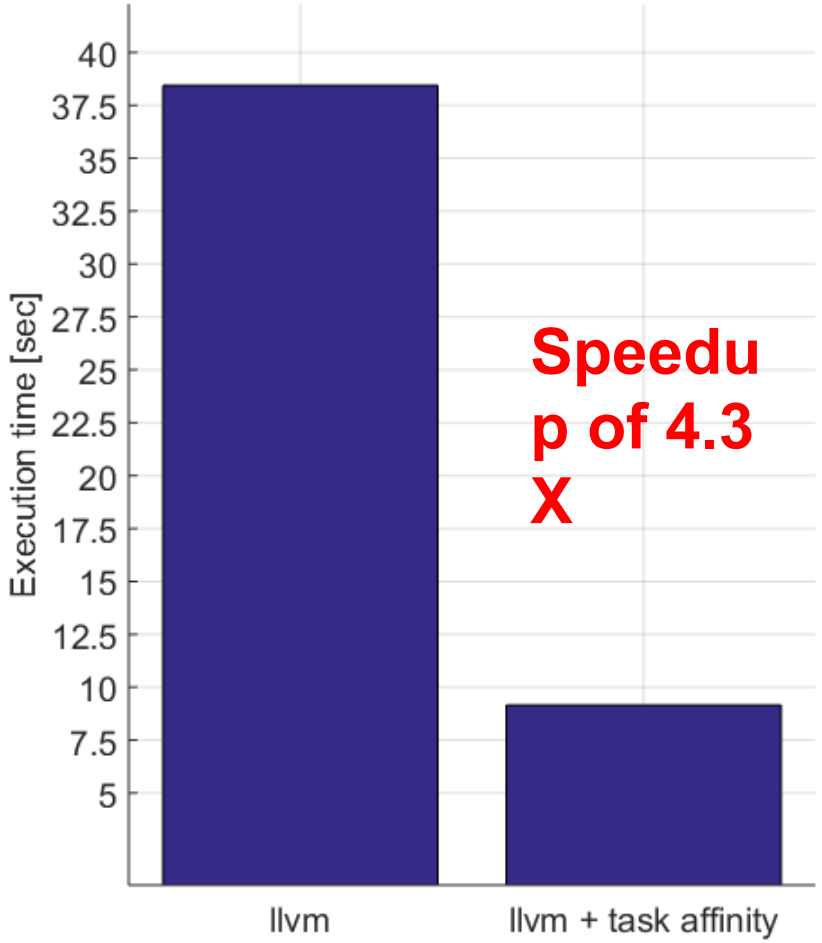


**Speedup of 4.3X**

**LIKWID: reduction of remote data volume from 69% to 13%**

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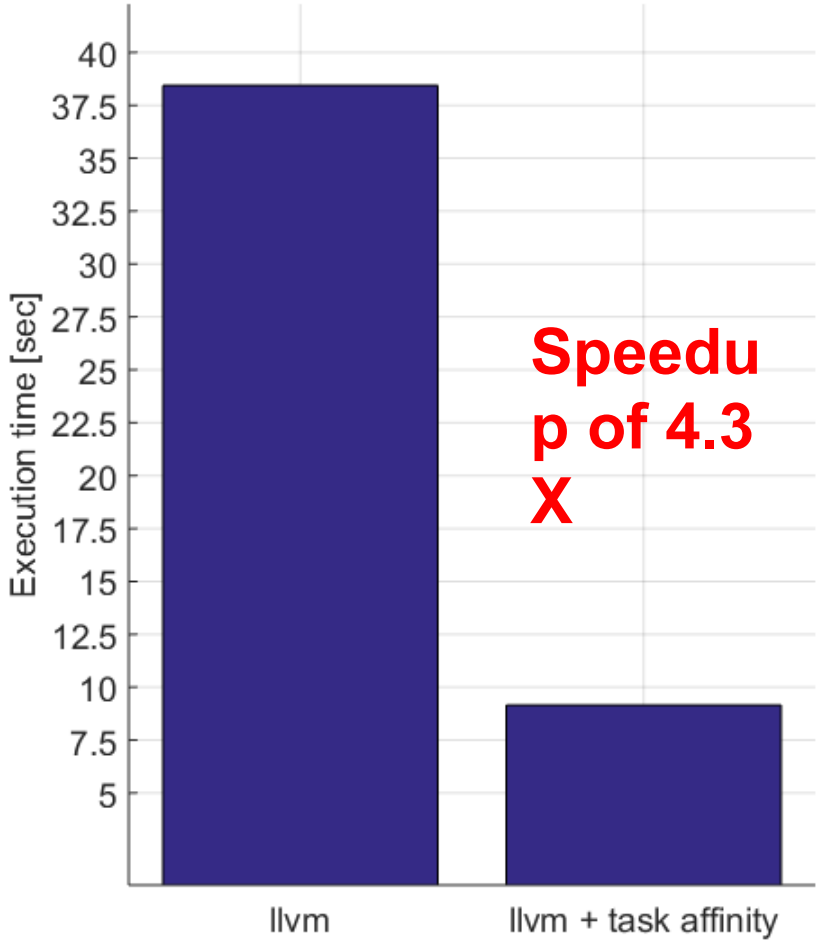
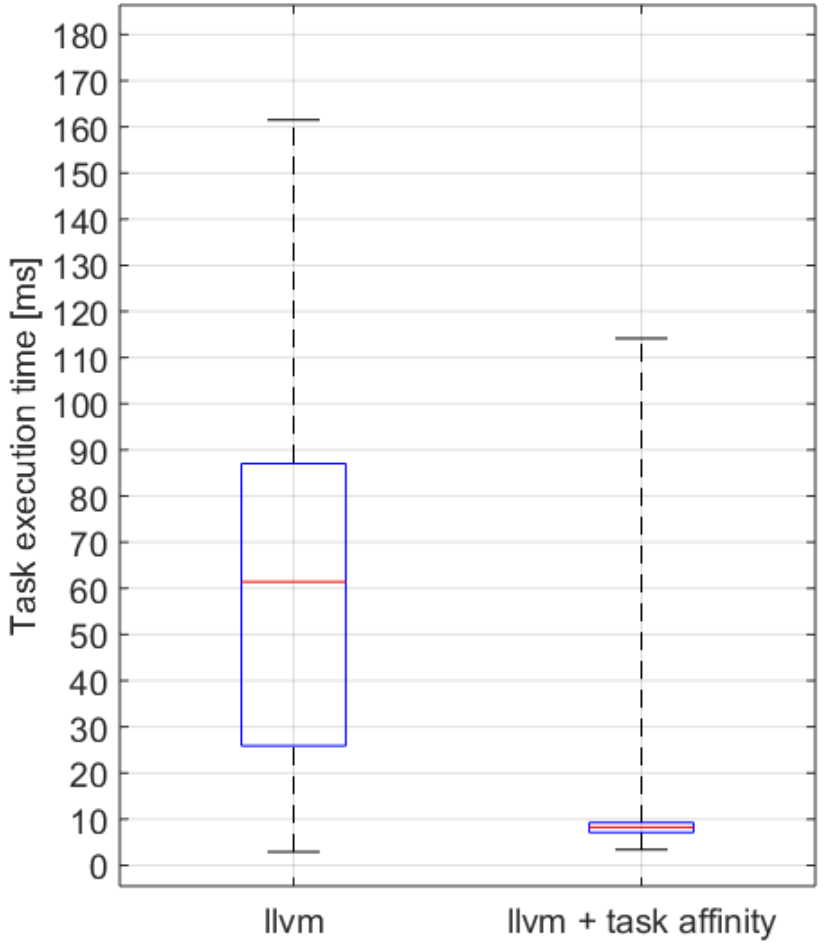



**Speedup of 4.3X**

## Distribution of single task execution times




**LIKWID: reduction of remote data volume from 69% to 13%**

# Summary

- Requirement for this feature: thread affinity enabled

- The `affinity` clause helps, if
  - →tasks access data heavily
  - →single task creator scenario, or task not created with data affinity
  - →high load imbalance among the tasks

- Different from thread binding: task stealing is absolutely allowed

# Programming OpenMP

***SIMD***

Christian Terboven

**Michael Klemm**

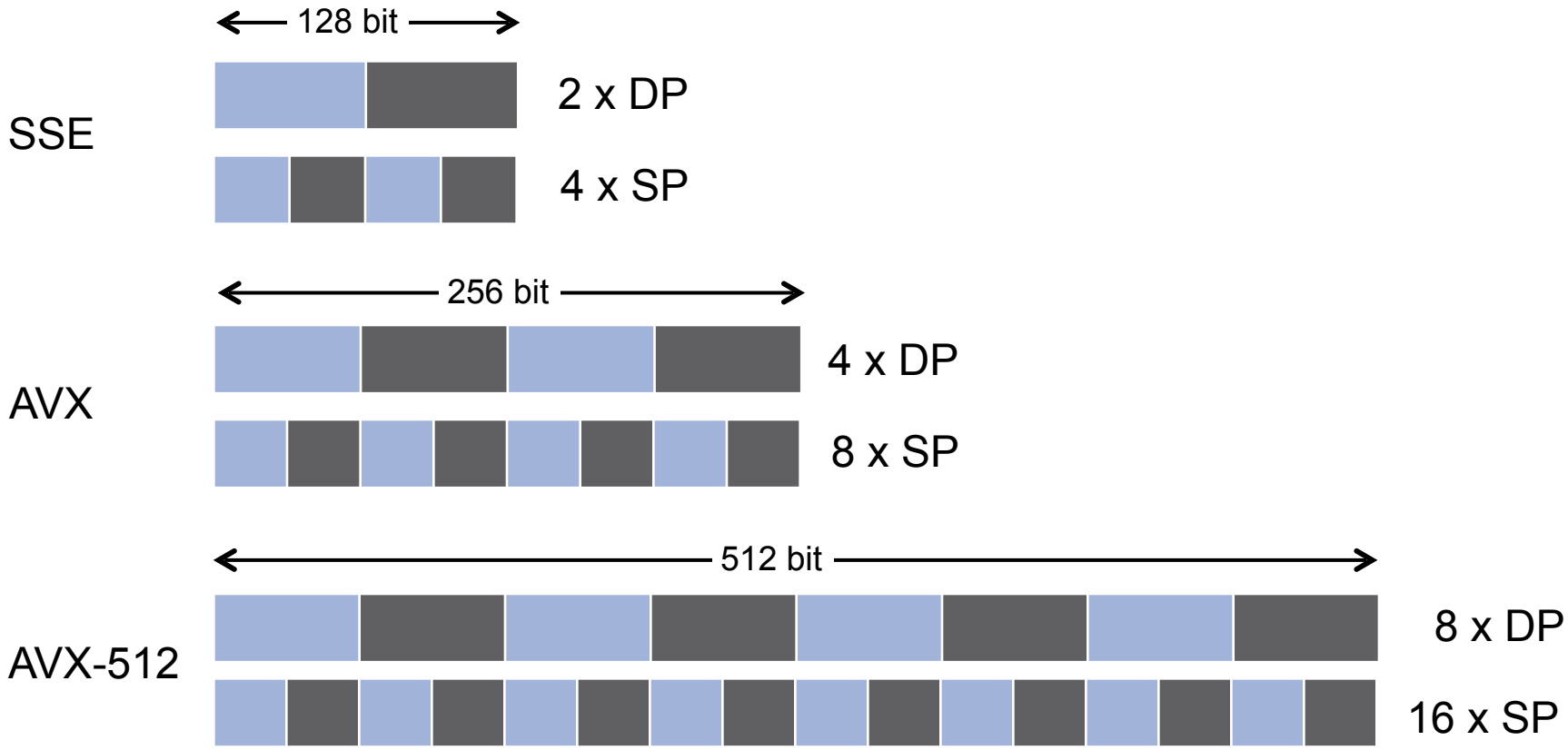
RWTH AACHEN UNIVERSITY

# Topics

- Exploiting SIMD parallelism with OpenMP
- Using SIMD directives with loops
- Creating SIMD functions

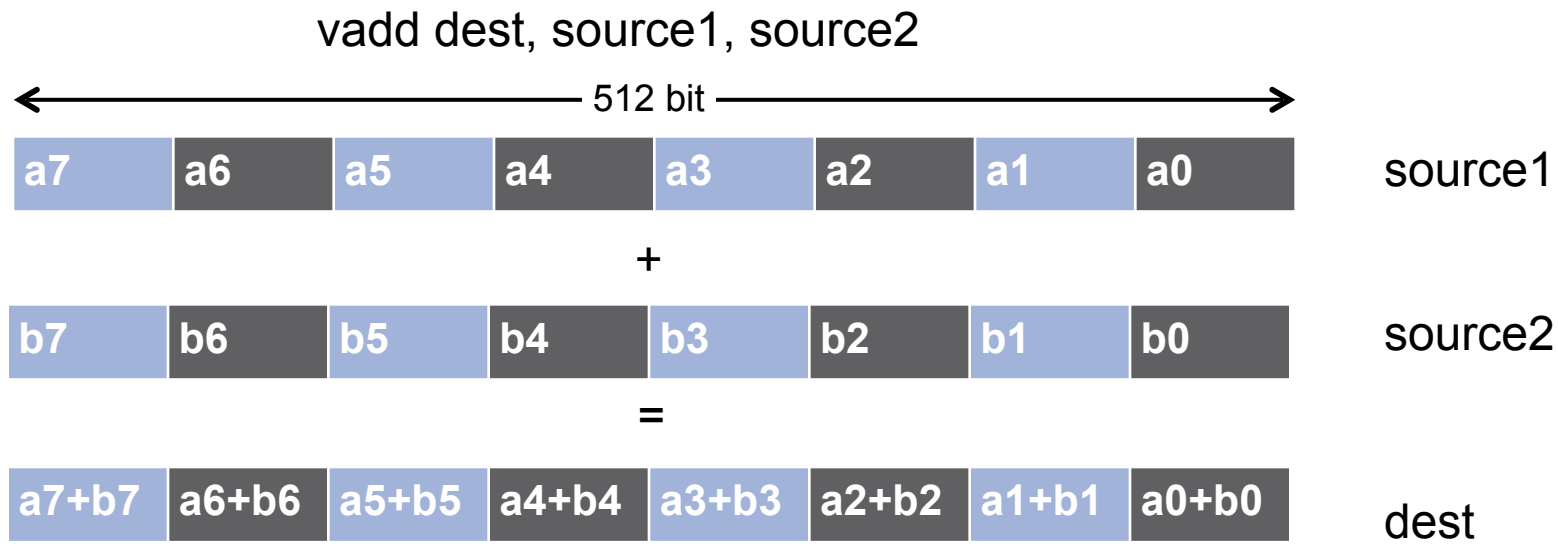
# SIMD on x86 Architectures

- Width of SIMD registers has been growing in the past:



# More Powerful SIMD Units

- SIMD instructions become more powerful



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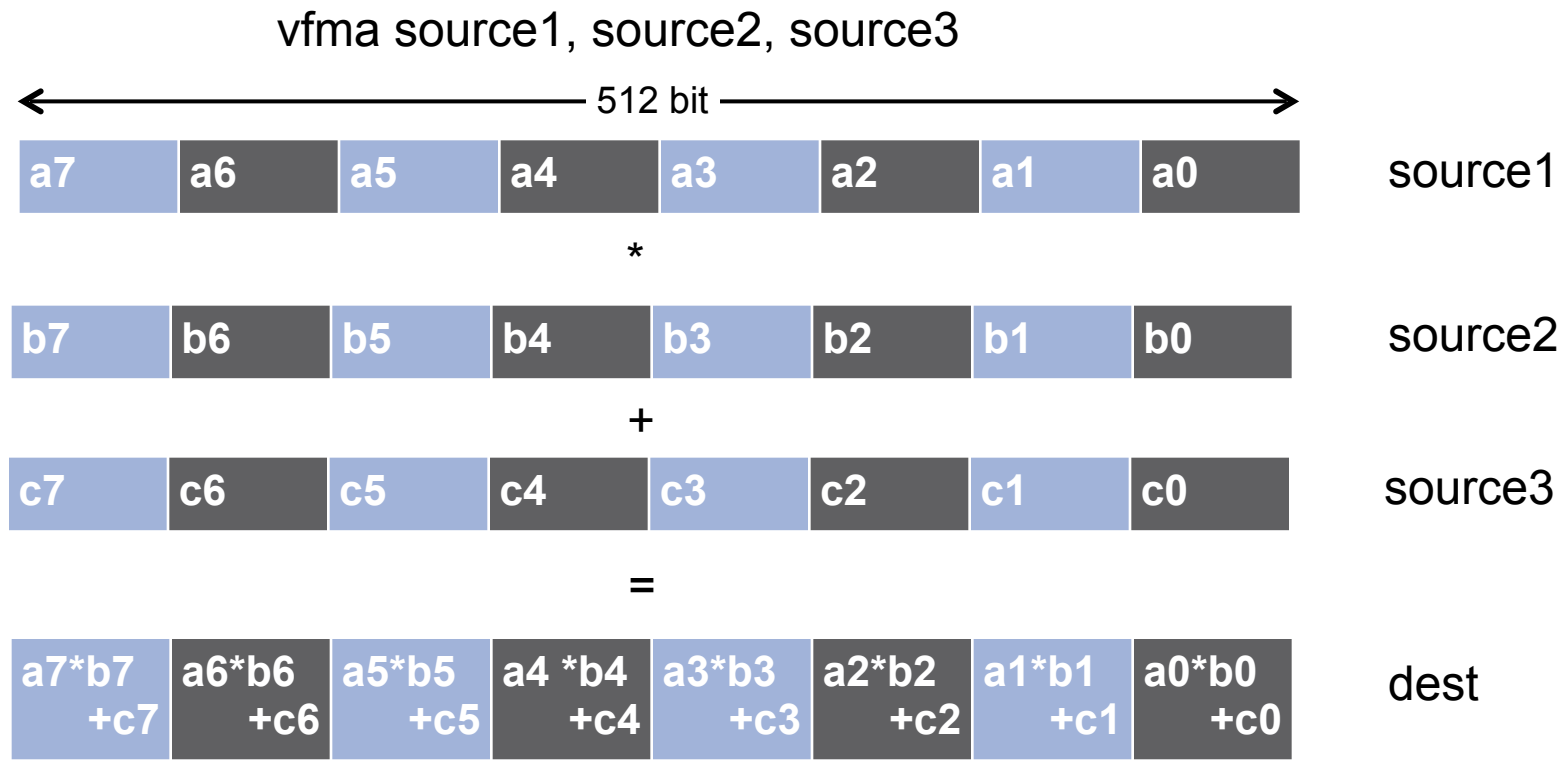

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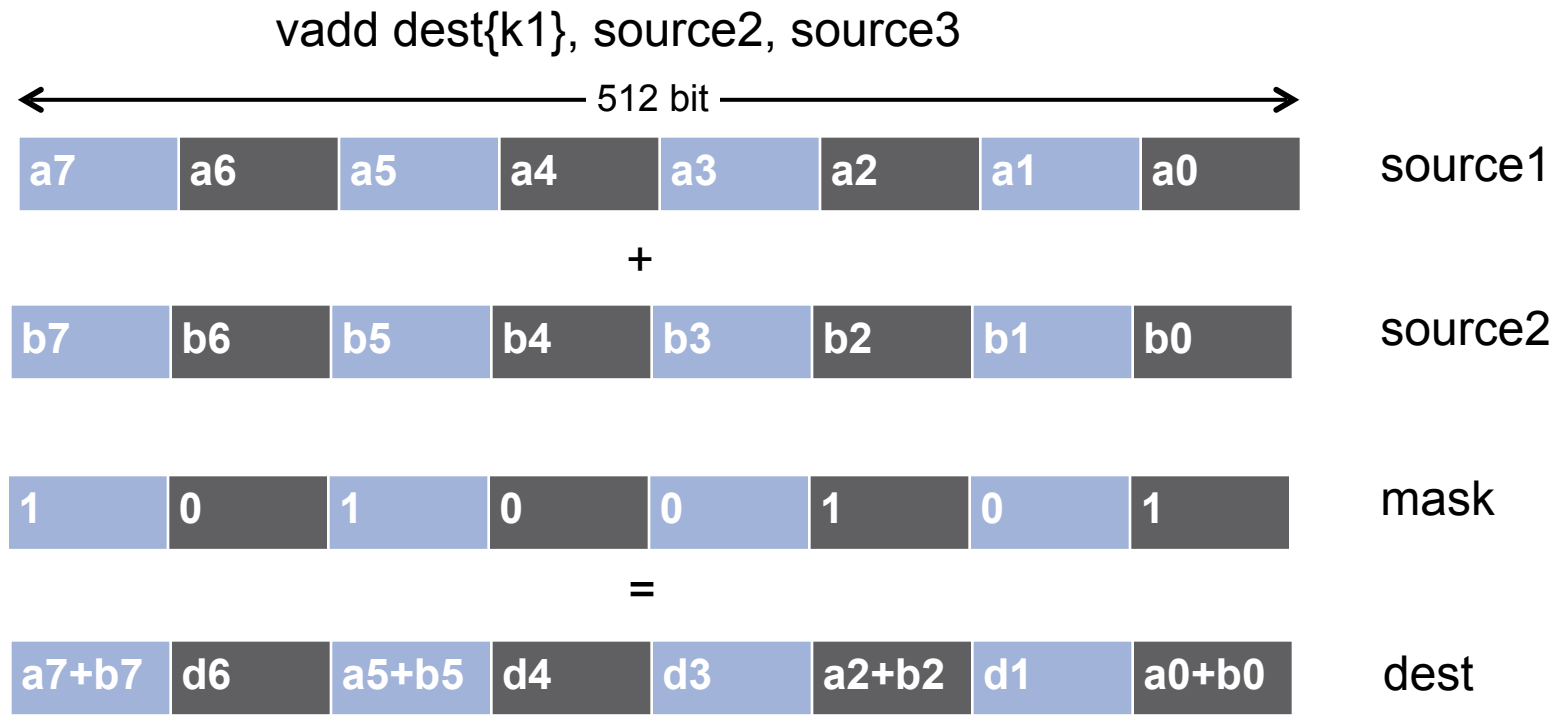

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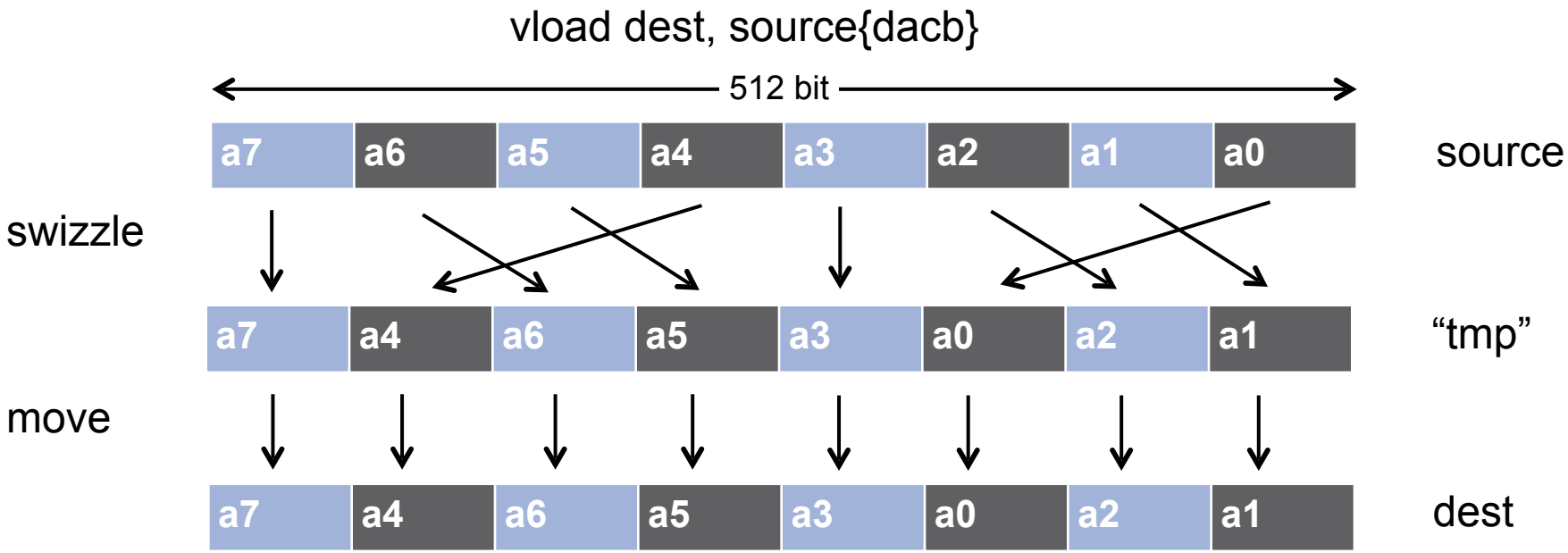

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- Example: clang/LLVM
  - → -fvectorize
  - → -Rpass=loop-.*
  - → -mprefer-vector-width=<*width*>

GCC
-ftree-vectorize
-ftree-loop-vectorize
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# Why Auto-vectorizers Fail

- Data dependencies
- Other potential reasons
  - → Alignment
  - → Function calls in loop block
  - → Complex control flow / conditional branches
  - → Loop not “countable”
    - → e.g., upper bound not a runtime constant
  - → Mixed data types
  - → Non-unit stride between elements
  - → Loop body too complex (register pressure)
  - → Vectorization seems inefficient
- Many more … but less likely to occur

# Data Dependencies

- Suppose two statements S1 and S2
- S2 depends on S1, iff S1 must execute before S2
  - → Control-flow dependence
  - → Data dependence
  - → Dependencies can be carried over between loop iterations
- Important flavors of data dependencies

FLOW

```
s1: a = 40

    b = 21

s2: c = a + 2
```

ANTI

```
    b = 40

s1: a = b + 1

s2: b = 21
```

# Loop-Carried Dependencies

- Dependencies may occur across loop iterations
  → Loop-carried dependency

- The following code contains such a dependency:

```
void lcd_ex(float* a, float* b, size_t n, float c1, float c2)
{
    size_t i;
    for (i = 0; i < n; i++) {
        a[i] = c1 * a[i + 17] + c2 * b[i];
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```

- Some iterations of the loop have to complete before the next iteration can run
  → Simple trick: Can you reverse the loop w/o getting wrong results?

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Loop-carried dependency for a[i] and a[i+17]; distance is 17.

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# Loop-carried Dependencies

- Can we parallelize or vectorize the loop?

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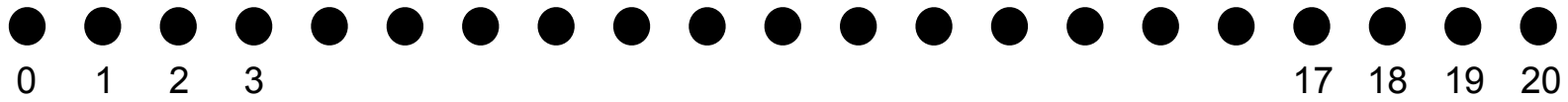

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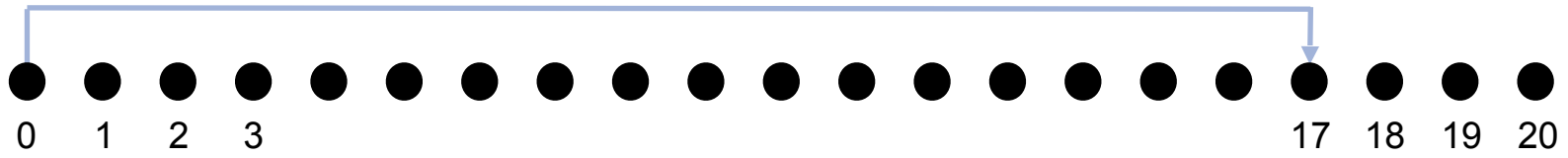

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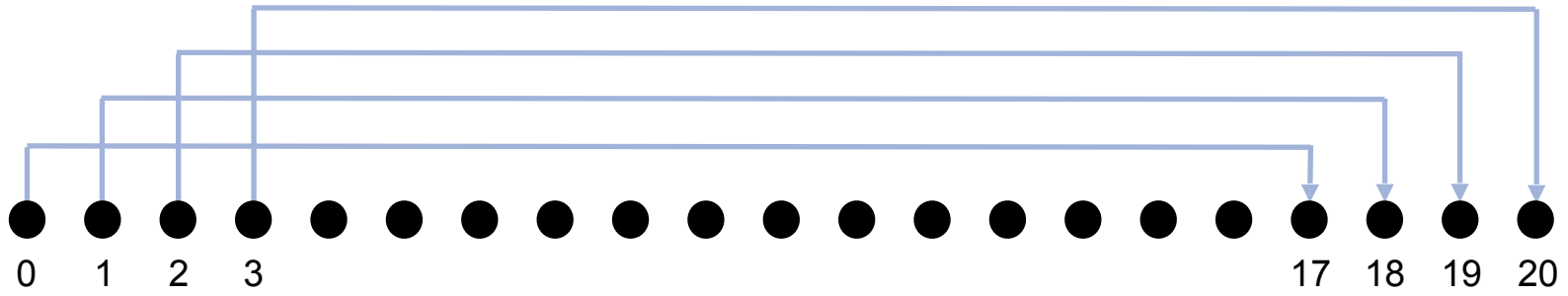

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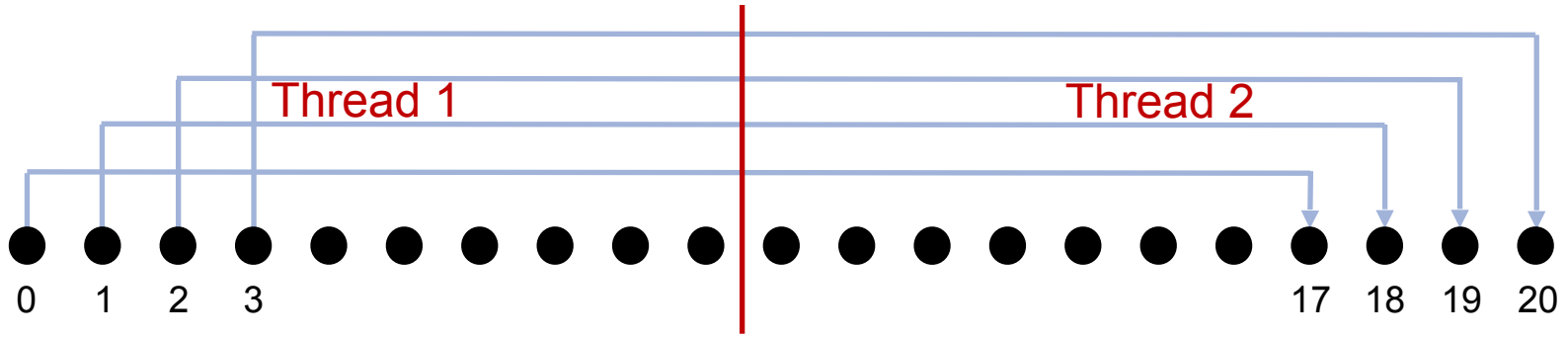

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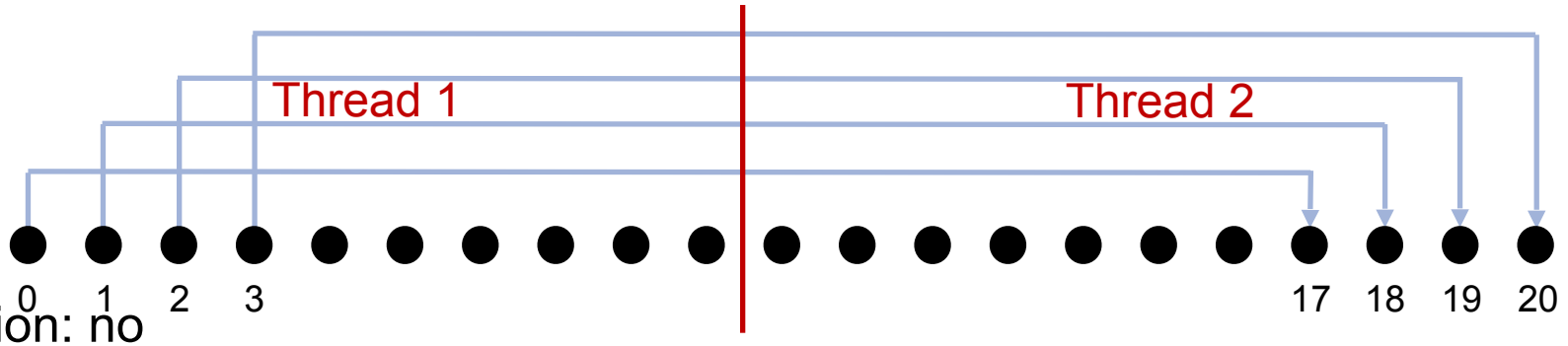


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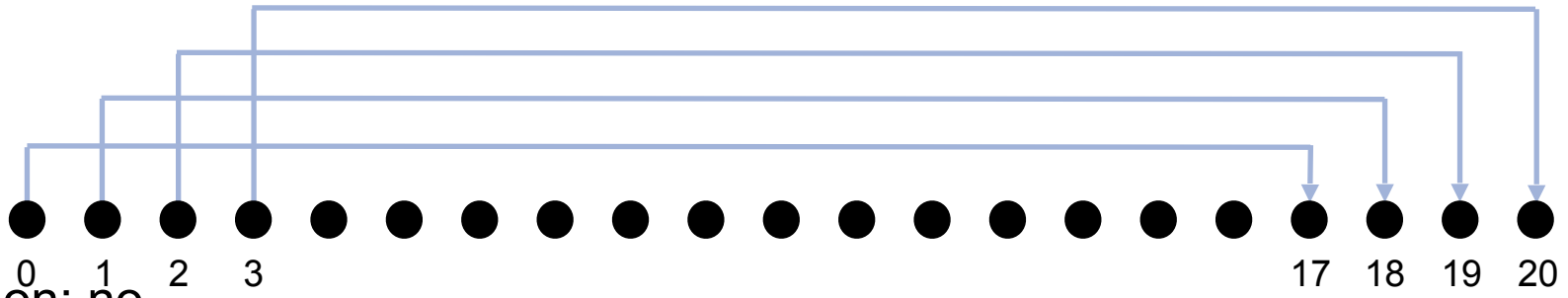


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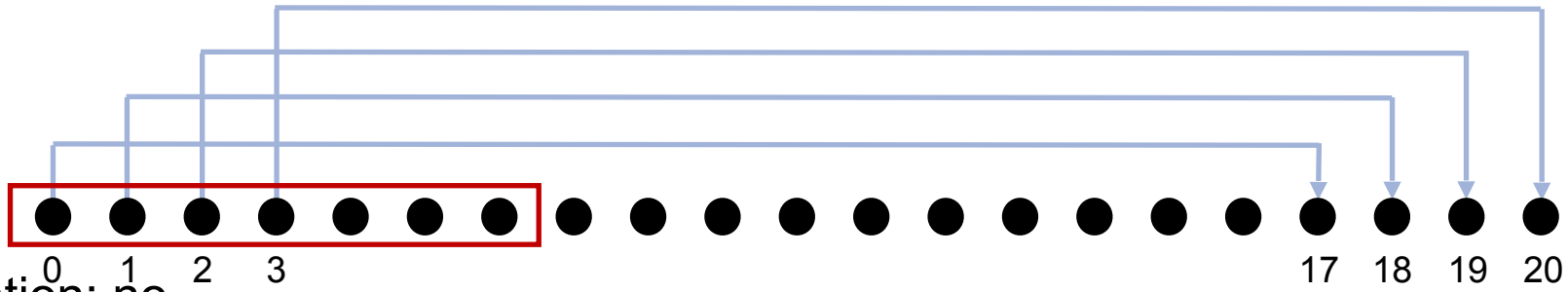


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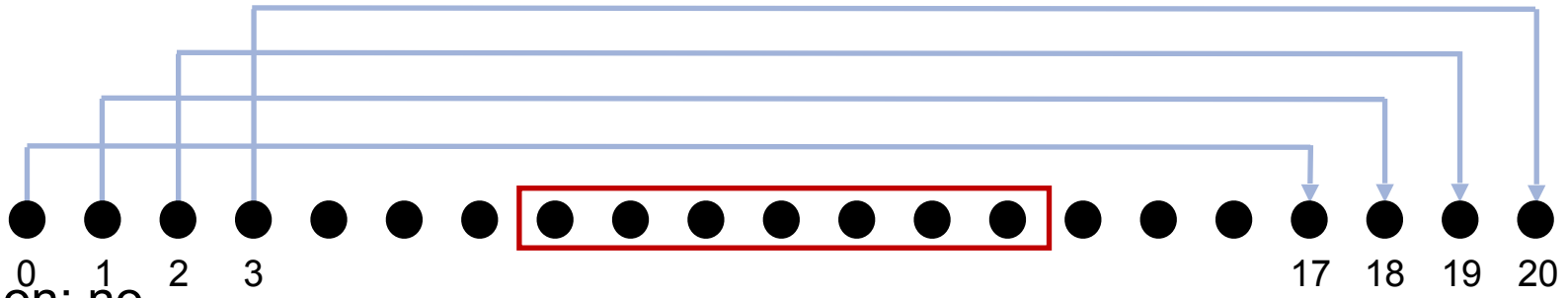
# Loop-carried Dependencies

- Can we parallelize or vectorize the loop?

```
void lcd_ex(float* a, float* b, size_t n, float c1, float c2) {
    for (int i = 0; i < n; i++) {
        a[i] = c1 * a[i + 17] + c2 * b[i];
}   }
```

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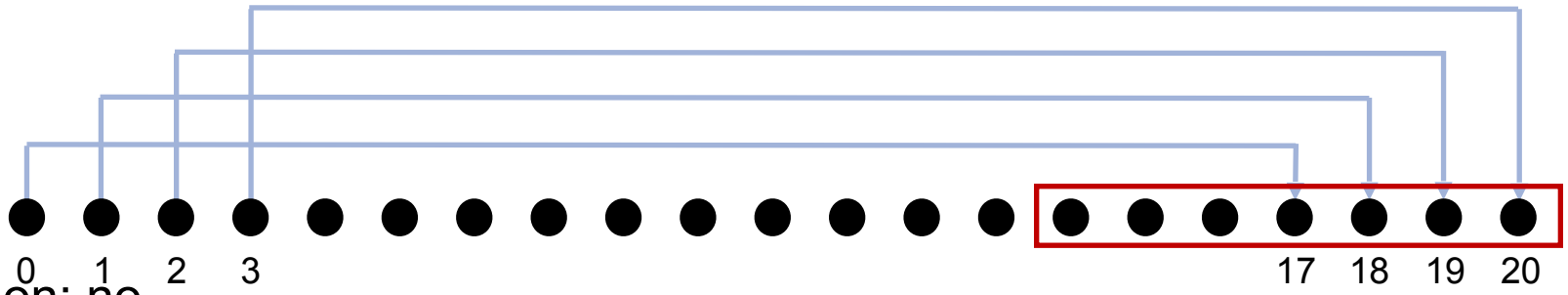


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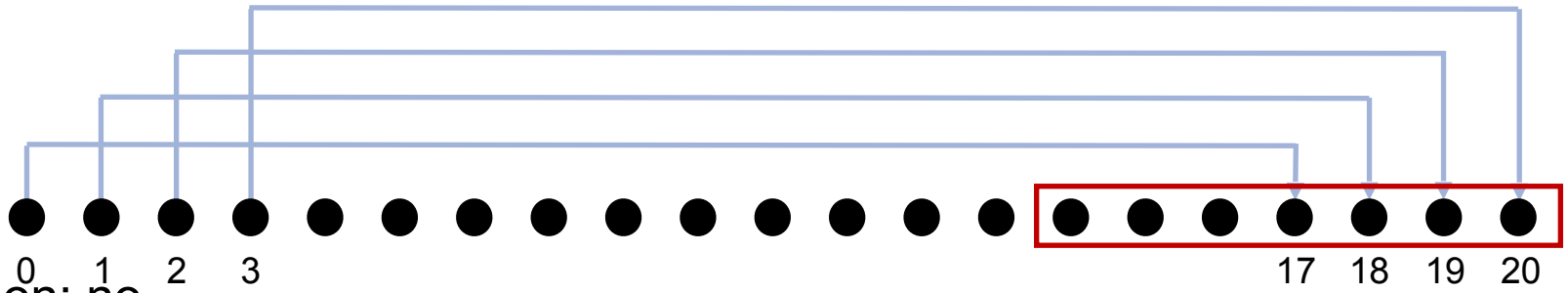


→ Parallelization: no

(except for very specific loop schedules)

→ Vectorization: yes

(iff vector length is shorter than any distance of any dependency)

# In a Time Before OpenMP 4.0

- Support required vendor-specific extensions
  - →Programming models (e.g., Intel® Cilk Plus)
  - →Compiler pragmas (e.g., `#pragma vector`)
  - →Low-level constructs (e.g., `_mm_add_pd()`)

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#pragma omp parallel for
#pragma vector always
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}
```

# SIMD Loop Construct

- Vectorize a loop nest
  - →Cut loop into chunks that fit a SIMD vector register
  - →No parallelization of the loop body

- Syntax (C/C++)

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

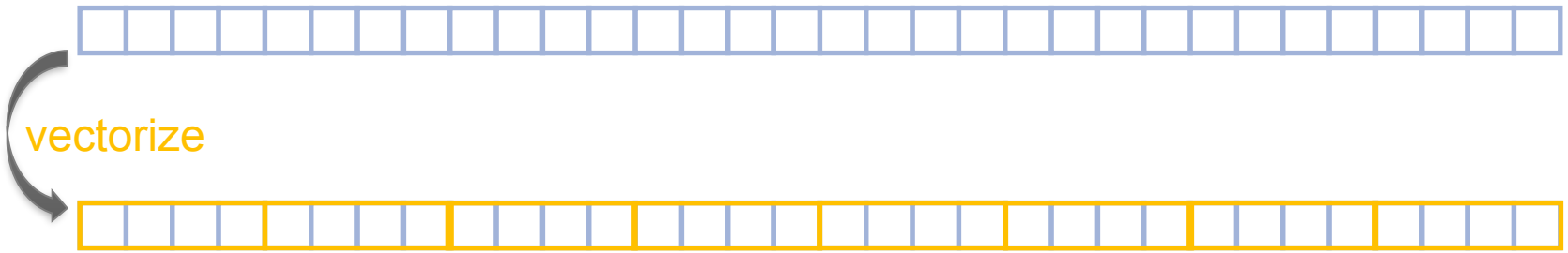
- Syntax (Fortran)

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

# Example

# Example

```
float 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];
  return sum;
}
```



# Data Sharing Clauses

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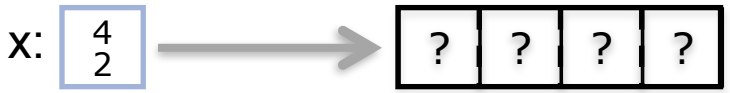
- `private(var-list)`:
  Uninitialized vectors for variables in *var-list*



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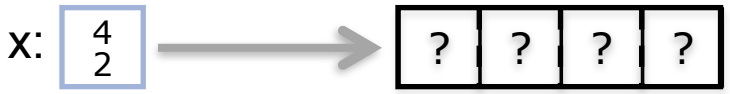


- `firstprivate(var-list):`
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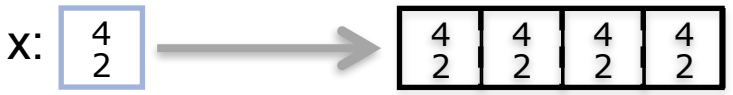

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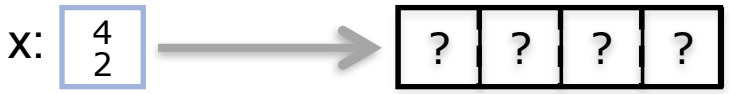


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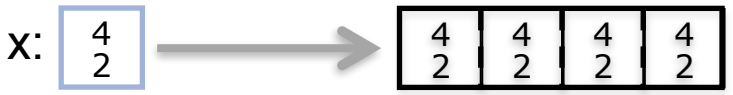


- `reduction(op:var-list):`
  Create private variables for *var-list* and apply reduction operator *op* at the end of the construct

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  - → Maximum number of iterations that can run concurrently without breaking a dependence
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- `collapse (n)`

# SIMD Worksharing Construct

- Parallelize and vectorize a loop nest
  - → Distribute a loop's iteration space across a thread team
  - → Subdivide loop chunks to fit a SIMD vector register

- Syntax (C/C++)

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

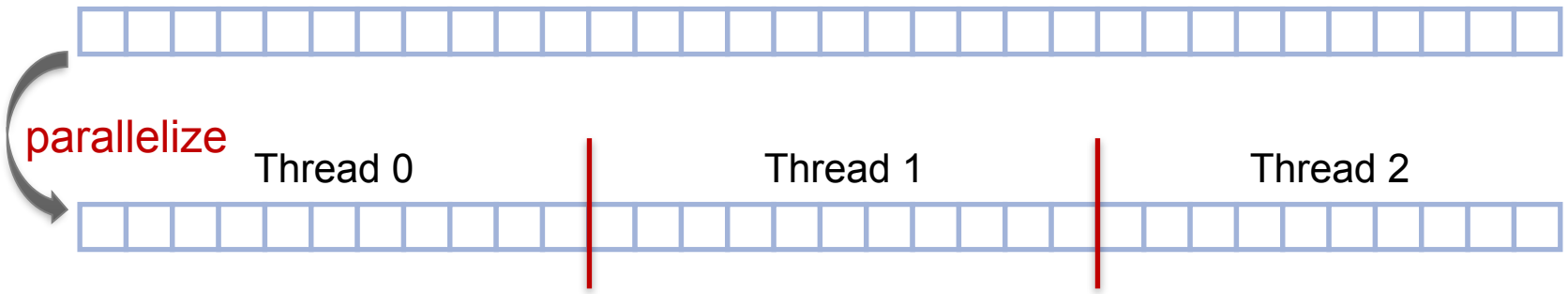
- Syntax (Fortran)

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

# Example

# Example

```
float 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];
  return sum;
}
```



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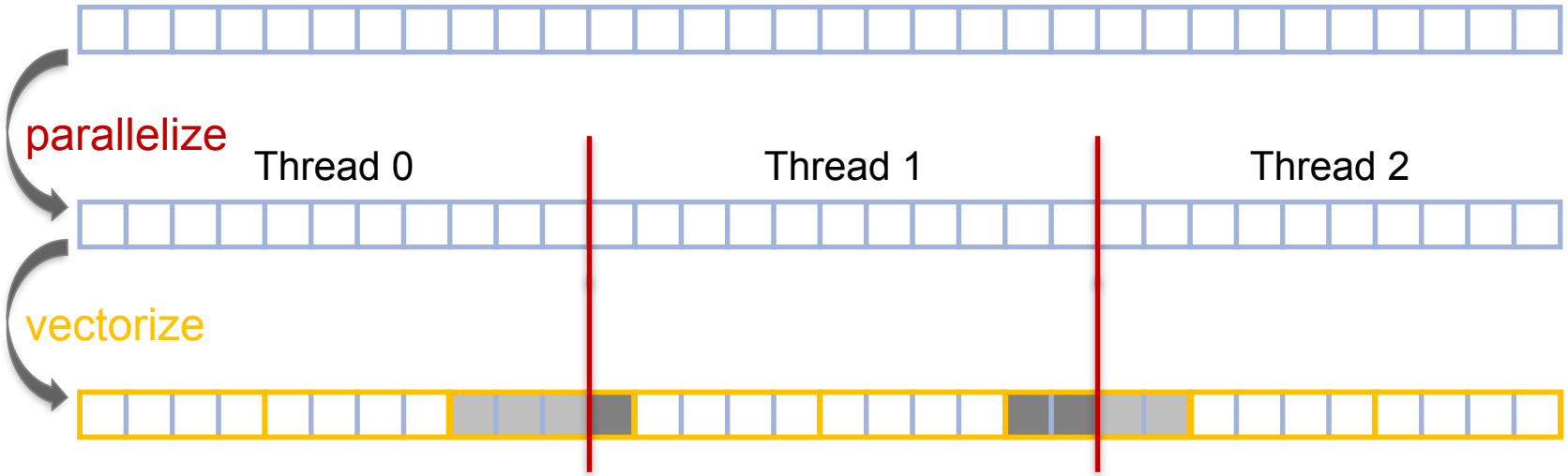

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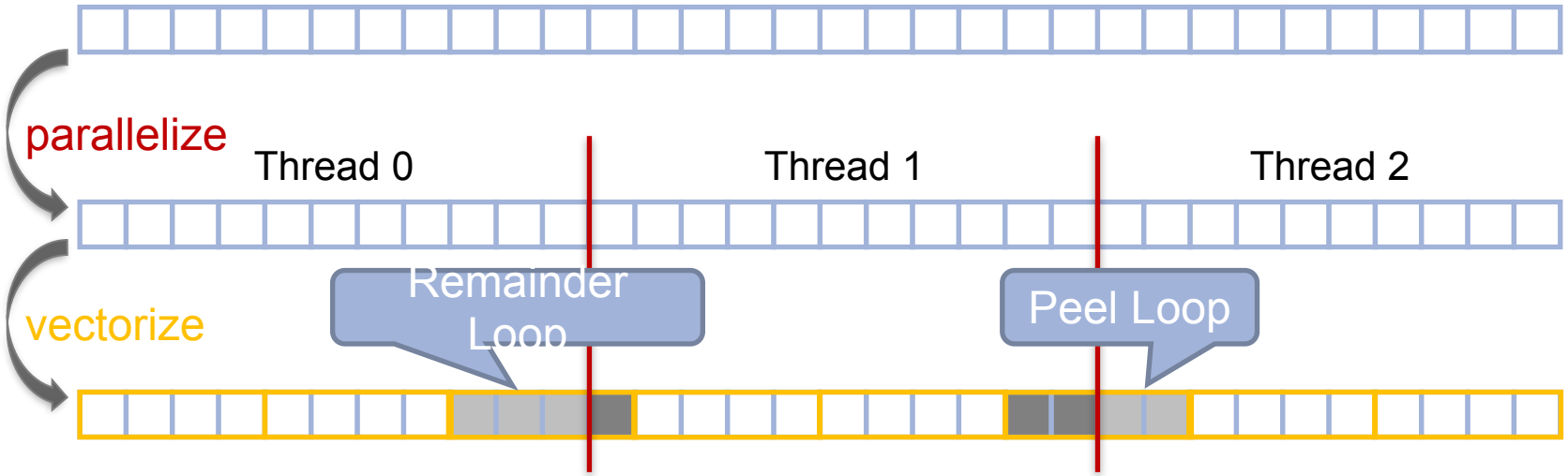

# Be Careful What You Wish For…

- You should choose chunk sizes that are multiples of the SIMD length
  - → Remainder loops are not triggered
  - → Likely better performance

# Be Careful What You Wish For…

```
float sprod(float *a, float *b, int n) {
  float sum = 0.0f;
#pragma omp for simd reduction(+:sum) \
                     schedule(static, 5)
  for (int k=0; k<n; k++)
    sum += a[k] * b[k];
  return sum;
}
```

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  return sum;
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```

- You should choose chunk sizes that are multiples of the SIMD length
  - → Remainder loops are not triggered
  - → Likely better performance
- In the above example …
  - → and AVX2, the code will only execute the remainder loop!
  - → and SSE, the code will have one iteration in the SIMD loop plus one in the remainder loop!

# OpenMP 4.5 Simplifies SIMD Chunks

- Chooses chunk sizes that are multiples of the SIMD length
  - →First and last chunk may be slightly different to fix alignment and to handle loops that are not exact multiples of SIMD width
  - →Remainder loops are not triggered
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- Chooses chunk sizes that are multiples of the SIMD length
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# SIMD Function Vectorization

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```
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 parallel for simd
    for (i=0; i<N; i++) {
        d[i] = min(distsq(a[i], b[i]), c[i]);
}   }
```

# SIMD Function Vectorization

- Declare one or more functions to be compiled for calls from a SIMD-parallel loop

- Syntax (C/C++):

```
#pragma omp declare simd [clause[[,] clause],…]

[#pragma omp declare simd [clause[[,] clause],…]]

[…]

function-definition-or-declaration
```

- Syntax (Fortran):

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

# SIMD Function Vectorization

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#pragma omp parallel for simd
    for (i=0; i<N; i++) {
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}   }
```

```
_ZGVZN16vv_min(%zmm0, %zmm1):
    vminps %zmm1, %zmm0, %zmm0
    ret
```

```
_ZGVZN16vv_distsq(%zmm0, %zmm1):
    vsubps %zmm0, %zmm1, %zmm2
    vmulps %zmm2, %zmm2, %zmm0
    ret
```

```
vmovups (%r14,%r12,4), %zmm0
vmovups (%r13,%r12,4), %zmm1
call _ZGVZN16vv_distsq
vmovups (%rbx,%r12,4), %zmm1
call _ZGVZN16vv_min
```

# SIMD Function Vectorization

- `simdlen (`*`length`*`)`
  - → generate function to support a given vector length

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# SIMD Function Vectorization

- `simdlen (length)`
  - → generate function to support a given vector length
- `uniform (argument-list)`
  - → argument has a constant value between the iterations of a given loop
- `inbranch`
  - → function always called from inside an if statement
- `notinbranch`
  - → function never called from inside an if statement

# SIMD Function Vectorization

- `simdlen (length)`
  → generate function to support a given vector length
- `uniform (argument-list)`
  → argument has a constant value between the iterations of a given loop
- `inbranch`
  → function always called from inside an if statement
- `notinbranch`
  → function never called from inside an if statement
- `linear (argument-list[:linear-step])`
- `aligned (argument-list[:alignment])`

# inbranch & notinbranch

```
#pragma omp declare simd inbranch
float do_stuff(float x) {
    /* do something */
    return x * 2.0;
}

void example() {
#pragma omp simd
    for (int i = 0; i < N; i++)
        if (a[i] < 0.0)
            b[i] = do_stuff(a[i]);
}
```

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#pragma omp declare simd inbranch
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}
```

```
vec8 do_stuff_v(vec8 x, mask m) {
    /* do something */
    vmulpd x{m}, 2.0, tmp
    return tmp;
}
```

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}
```

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vec8 do_stuff_v(vec8 x, mask m) {
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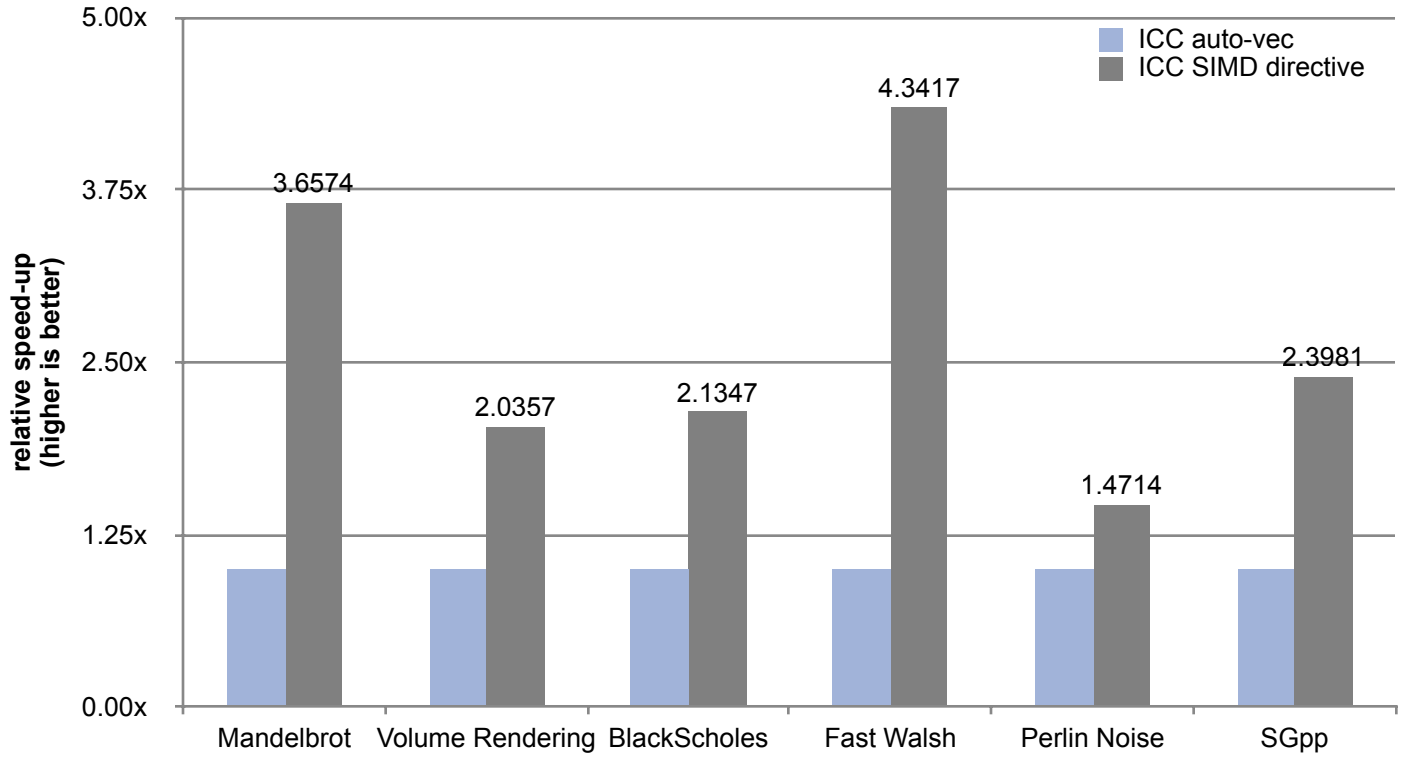
    vmulpd x{m}, 2.0, tmp
    return tmp;
}
```

```
for (int i = 0; i < N; i+=8) {
    vcmp_lt &a[i], 0.0, mask
    b[i] = do_stuff_v(&a[i], mask);
}
```

# SIMD Constructs & Performance




M.Klemm, A.Duran, X.Tian, H.Saito, D.Caballero, and X.Martorell. Extending OpenMP with Vector Constructs for Modern Multicore SIMD Architectures. In Proc. of the Intl. Workshop on OpenMP, pages 59-72, Rome, Italy, June 2012. LNCS 7312.

# Programming OpenMP

***Hands-on Exercises***

**Christian Terboven**
Michael Klemm
Yun (Helen) He

# Exercises

- We have implemented a series of small hands-on examples that you can use and play with.
  - → Download: `git clone https://github.com/NERSC/openmp-series-2024`
  - → Subfolder: `Session-3-NUMA_SIMD/exercises`, with instructions in `Exercises_OMP_2024.pdf`
  - → Build: `make` (or follow README files)
  - → You can then find the compiled executable to run with sample Slurm commands
  - → We use the GCC compiler mostly

- Each hands-on exercise has a folder “solution”
  - → It shows the OpenMP directive that we have added
  - → You can use it to cheat ☺, or to check if you came up with the same solution

# Exercises: Overview

| Exercise no. | Exercise name | OpenMP Topic | Day / Order (proposal) |
|---|---|---|---|
| 1 | PI | Apply OpenMP SIMD | Third day |
| 2 | xthi | Review for NUMA | Third day |
| 3 | Stream | Optimize / review for NUMA | Third day |
| 4 | Jacobi | Optimize / review for NUMA | Third day |