



703650 VO Parallel Systems WS2019/2020

OpenMP Advanced

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Overview

- ▶ task-based parallelism
- ▶ modern OpenMP features
 - ▶ affinity
 - ▶ vectorization
 - ▶ accelerators
- ▶ common OpenMP pitfalls
- ▶ Tales From the Proseminar

Motivation

- ▶ OpenMP offers constructs for parallelism and work sharing
 - ▶ `parallel`
 - ▶ `for`, `section`, `critical`, ...
- ▶ but they lack flexibility, e.g. because they
 - ▶ do not support nested work sharing (e.g. traversing branches of a tree in parallel) without explicit increase in parallelism
 - ▶ restrict data structures (e.g. try to process all elements of a linked list with a `for`...)

Motivation

- ▶ example scenario on the right
 - ▶ for directive will distribute work across all threads, including the one loading data from storage → leads to load imbalance
- ▶ How to improve this? Bad choices include:
 - ▶ `nowait` removes implicit barrier, but does not change load distribution
 - ▶ dynamic or guided loop scheduling reduces amount of work for the thread loading data from storage, but incurs overhead and doesn't fully solve the issue
 - ▶ `for` should be inside another `section`, but work share directives cannot be nested
 - ▶ nest multiple `parallel` directives and carefully control degree of parallelism

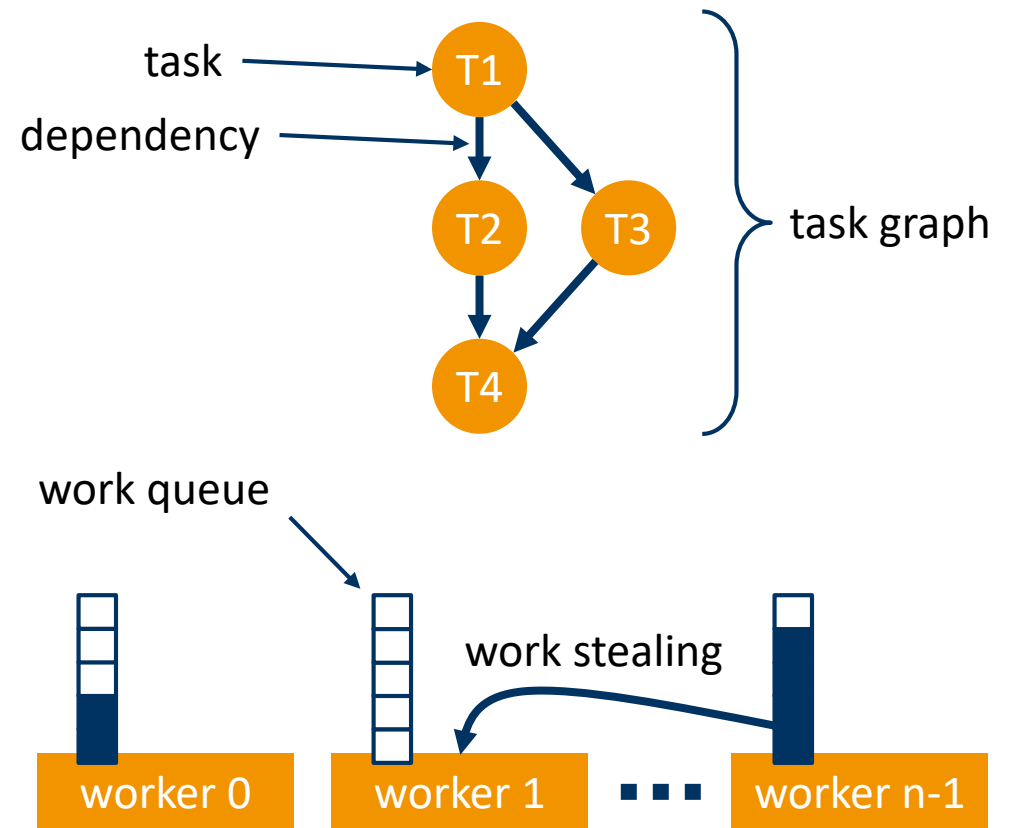
```
#pragma omp parallel
{
    #pragma omp sections
    {
        #pragma omp section
        { /*load part of data from storage*/ }
    }
    #pragma omp for
    { /*compute part of data on-the-fly*/ }
    // use both parts for processing
}
```

Task-based Parallelism

- ▶ offered by many programming models, including OpenMP
 - ▶ also used under the hood for `for`, `sections`, ...
- ▶ different from data parallelism
 - ▶ focuses on decomposing work ("*tasks*") rather than data
 - ▶ allows to evaluate dependencies between tasks and run parts of work in parallel
- ▶ offers many advantages, e.g.
 - ▶ supports easy nesting of parallel work
 - ▶ enables efficient load balancing strategies

Task-based Parallelism cont'd

- ▶ decompose tasks into sub-tasks and put in *work queues*
 - ▶ worker threads can take tasks from queue and execute them
 - ▶ if a worker runs empty, steal tasks from another worker
 - ▶ if queue is full, execute task immediately without further task generation



task Directive

- ▶ allows explicit specification of tasks
 - ▶ careful, `firstprivate` is the default
- ▶ whenever a thread encounters a task directive, a task is generated
 - ▶ task may be immediately executed
 - ▶ or execution may be deferred
- ▶ wait for completion using `taskwait`
 - ▶ waits for child tasks spawned by the current task

```
int fib(int n) {  
    int i, j;  
    if (n < 2)  
        return n;  
  
    #pragma omp task shared(i)  
    i = fib(n-1);  
  
    #pragma omp task shared(j)  
    j = fib(n-2);  
  
    #pragma omp taskwait  
    return i + j;  
}
```

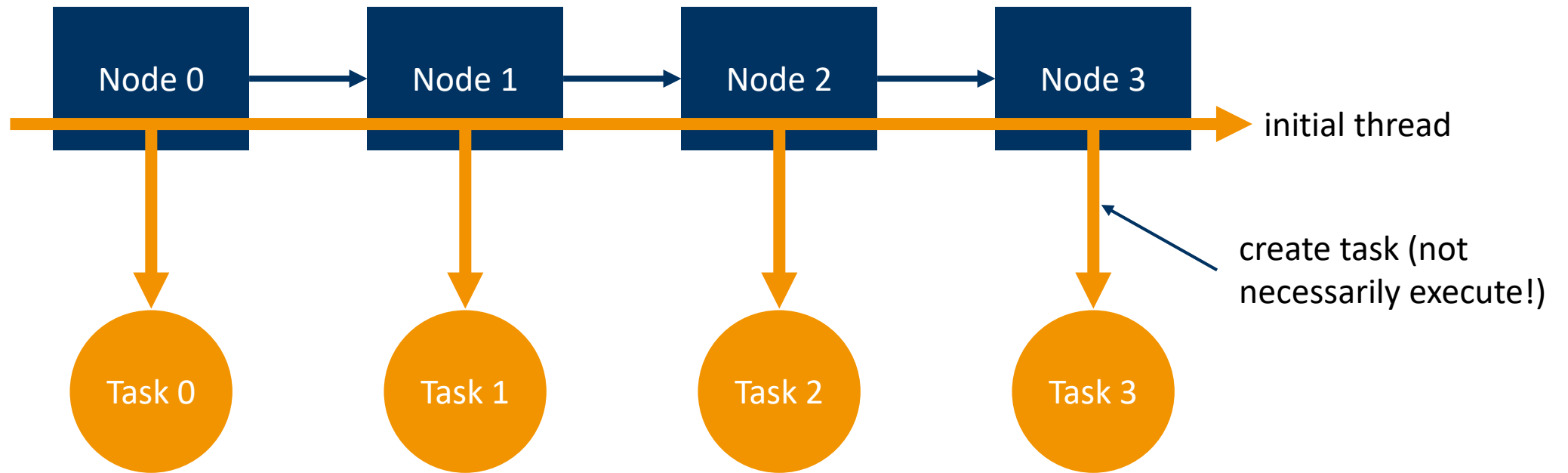
Example: Traversing a Linked List

```
struct Node {
    struct Node *next;
    struct Data *data;
};

void traverse(struct Node *p) {
    if (p->next) {
        #pragma omp task
        traverse(p->next);
    }
    process(p); // process work
}
```

```
int main(int argc, char **argv) {
    struct Node *head;
    head = ... // produce list
    #pragma omp parallel
    {
        #pragma omp single
        {
            traverse(head);
        }
    }
}
```


Example: Traversing a Linked List cont'd



Task Clauses

▶ **final**

- ▶ if expression evaluates to true: no more task generation but plain function calls
- ▶ useful for specifying “*cut-off*” and preventing excessive oversubscription
- ▶ e.g. `final(n < THRESHOLD)` for fibonacci

▶ **untied**

- ▶ if a task is suspended it can be resumed by any thread in the team (otherwise only by the same thread)
- ▶ useful if tasks hold no per-thread state information (e.g. allocated resources, MPI, ...)

▶ **depend**

- ▶ allows to specify data dependencies and establish a partial order on tasks
- ▶ useful for establishing task graphs

Task Dependencies

- ▶ OpenMP allows to establish partial task order using depends clause
 - ▶ allows to establish Read-after-Write, Write-after-Read, Write-after-Write, and Read-after-Read relationships task pairs
 - ▶ only applies to already generated sibling tasks → cannot re-order tasks
 - ▶ rather tells compiler how data is accessed to prevent race conditions and enable optimizations

```
void foo() {  
    #pragma omp task depend(out:x)  
    x = f();  
  
    #pragma omp task depend(in:x)  
    y = g(x);  
  
    ...  
}
```

Task Scheduling Points

- ▶ tasks can be suspended or resumed at task scheduling points
 - ▶ in the current task, immediately after generating a new task
 - ▶ at the end of a task region
 - ▶ in implicit and explicit barriers
 - ▶ at `taskwait`
 - ▶ when using `untied` clause: everywhere inside the untied task
- ▶ once commenced execution, a task will remain with the same thread unless it is an `untied` task

taskwait vs. taskgroup

- ▶ `taskwait` will wait for all children spawned by the current task
- ▶ `taskgroup` will wait at its end for all children spawned by the current task and their descendants

```
#pragma omp taskwait
// wait for all directly
// spawned children

#pragma omp taskgroup
{
// wait for all descendants
// at the end of this region
}
```

taskloop Directive

- ▶ allows to parallelize for loops using task parallelism
 - ▶ not a work sharing construct, should only be executed by one thread (like all other task constructs!)
 - ▶ loop must have canonical form (like with for directive)
 - ▶ can take all clauses that tasks or for can, except schedule, linear, ordered, nowait
 - ▶ reduction available with OpenMP 5.0

```
#pragma omp parallel
{
    #pragma omp single
    {
        #pragma omp taskloop
        for(i=0; i<30; i++) {
            a[i] = b[i] + f * (i+1);
        }
    }
}
```

taskloop Clauses

- ▶ **grainsize**
 - ▶ limits task size ($\text{grainsize} \leq \text{iterationsPerTask} \leq 2 \times \text{grainsize}$)
- ▶ **num_tasks**
 - ▶ specify number of tasks to create
- ▶ **nogroup**
 - ▶ optionally disable task group creation

Solving Motivation Example with `taskloop`

```
#pragma omp parallel
{
    #pragma omp sections
    {
        #pragma omp section
        { /*load part of data from storage*/ }
    }
    #pragma omp for
    { /*compute part of data on-the-fly*/ }
    // use both parts for processing
}
```

```
#pragma omp parallel
{
    #pragma omp single
    #pragma omp taskgroup
    {
        #pragma omp task
        { /*load from storage*/ }
        #pragma omp taskloop nogroup
        for (i=0; i<N; i++) { /*compute */ }
    }
    // use both parts for processing
}
```


OpenMP and Affinity

- ▶ knowing and controlling affinity is important
 - ▶ communication latencies, locality in data and instruction caches, etc.
- ▶ little guaranteed support before OpenMP 4.0
 - ▶ implementation dependent solutions, mostly environment variables, e.g.
 - ▶ GNU runtime: GOMP_CPU_AFFINITY=0-7
 - ▶ Intel runtime: KMP_CPU_AFFINITY=0-7
 - ▶ mostly enumerations of (possibly strided) core ranges, e.g.
 - ▶ 0-7
 - ▶ 0,1,18,19
 - ▶ 8-15:2
 - ▶ do explicit support for nested parallelism

OpenMP and Affinity cont'd

- ▶ OpenMP defines *places* consisting of one or more *processors*
 - ▶ pinning can be done on basis of places, threads are free to be migrated within a place
- ▶ controlled by env var OMP_PLACES
 - ▶ either using abstract names such as threads, cores, sockets
 - ▶ or using explicit but OS-dependent enumeration
(start : [number of entries] : [stride])
 - ▶ e.g. 4 places with 4 cores each
 - ▶ {0,1,2,3}, {4,5,6,7}, {8,9,10,11}, {12,13,14,15}
 - ▶ {0:4}, {4:4}, {8:4}, {12:4}
 - ▶ {0:4}:4:4

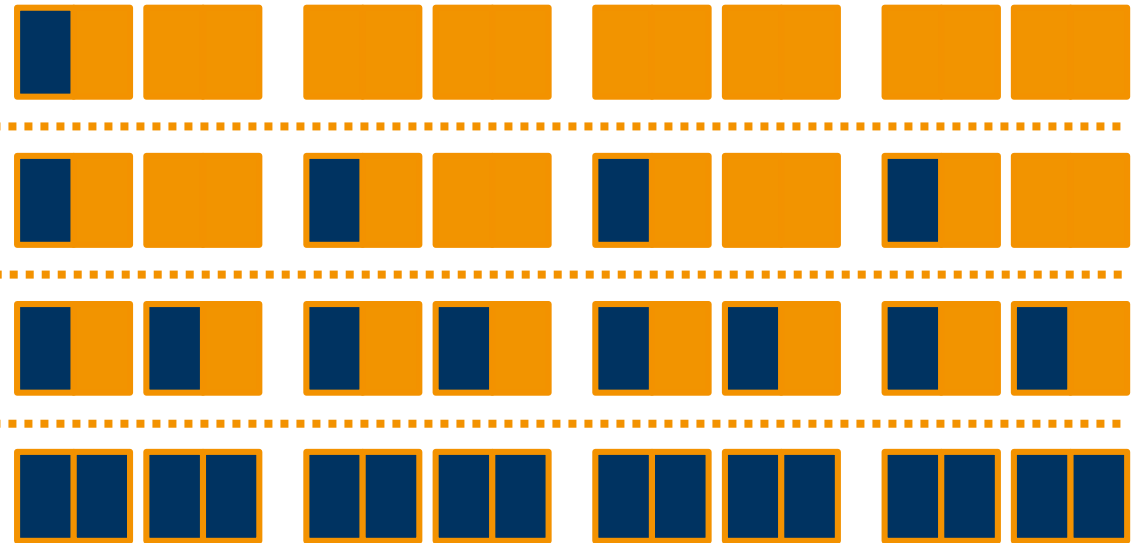
OpenMP and Affinity cont'd

- ▶ binding is controlled with `OMP_PROC_BIND`
 - ▶ `true`: don't move at all
 - ▶ `false`: free to move
 - ▶ `spread`: distribute across places first
 - ▶ `close`: fill places first
 - ▶ `master`: same place as master thread
- ▶ nested degree of parallelism controlled with `OMP_NUM_THREADS`
 - ▶ e.g. 4, 2, 2
 - ▶ first `#pragma omp parallel` spawns 4 threads, the next nested ones 2 and 2

OpenMP Nested Affinity Example

```
// OMP_PLACES=threads
// OMP_NUM_THREADS=4,2,2
// OMP_PROC_BIND=spread,spread,close

#pragma omp parallel .....
{
    #pragma omp parallel .....
    {
        #pragma omp parallel .....
        {
            // work ...
        }
    }
}
```



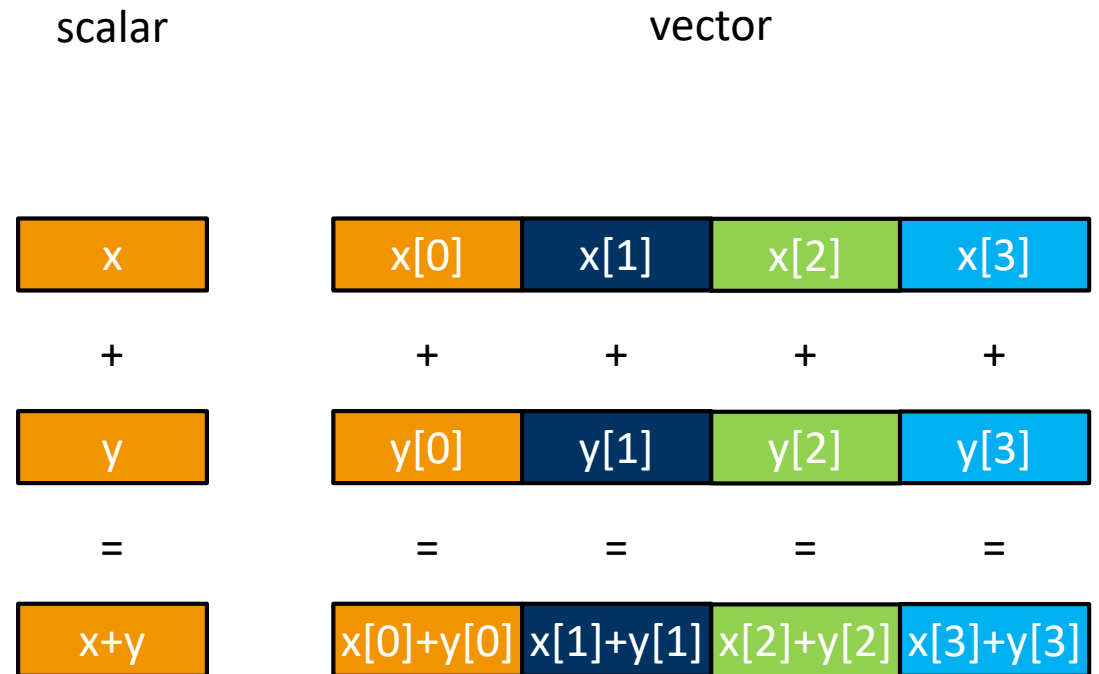


Modern Features of OpenMP ≥ 4.0



Vectorization

- ▶ modern CPUs have vector units
 - ▶ allow multiple operands per operation
 - ▶ performance gains of up to e.g. 4x without any thread- or process-based parallelism
 - ▶ Intel/AMD MMX/SSE/AVX, ARM NEON, IBM AltiVec, ...
- ▶ available operations and number of operands (“vector width”) depend on your software/hardware stack
 - ▶ hard to code manually (compiler intrinsics or assembler)



What Could go Wrong With Automatic Vectorization?

- ▶ compiler-based auto-vectorization (e.g. GCC's `-ftree-vectorize`)
 - ▶ requires analysis and heuristics
 - ▶ has lots of points of failure
 - ▶ loop-carried dependencies
 - ▶ pointer aliasing
 - ▶ memory alignment
 - ▶ data type mixing
 - ▶ overly conservative heuristics
 - ▶ numerical stability issues

```
void foo(double* a, double* b) {  
    for(int i=0; i<32; ++i) {  
        a[i] = a[i+1] + b[i];  
    }  
}
```

simd directive

- ▶ portable vectorization without compiler- or hardware-specific intrinsics
 - ▶ no need to know about GCC/LLVM/Intel/ARM...
- ▶ not the be-all end-all solution to vectorization but helps a lot
- ▶ can be combined with for directive
 - ▶ distributes vectorized loop iteration chunks among threads

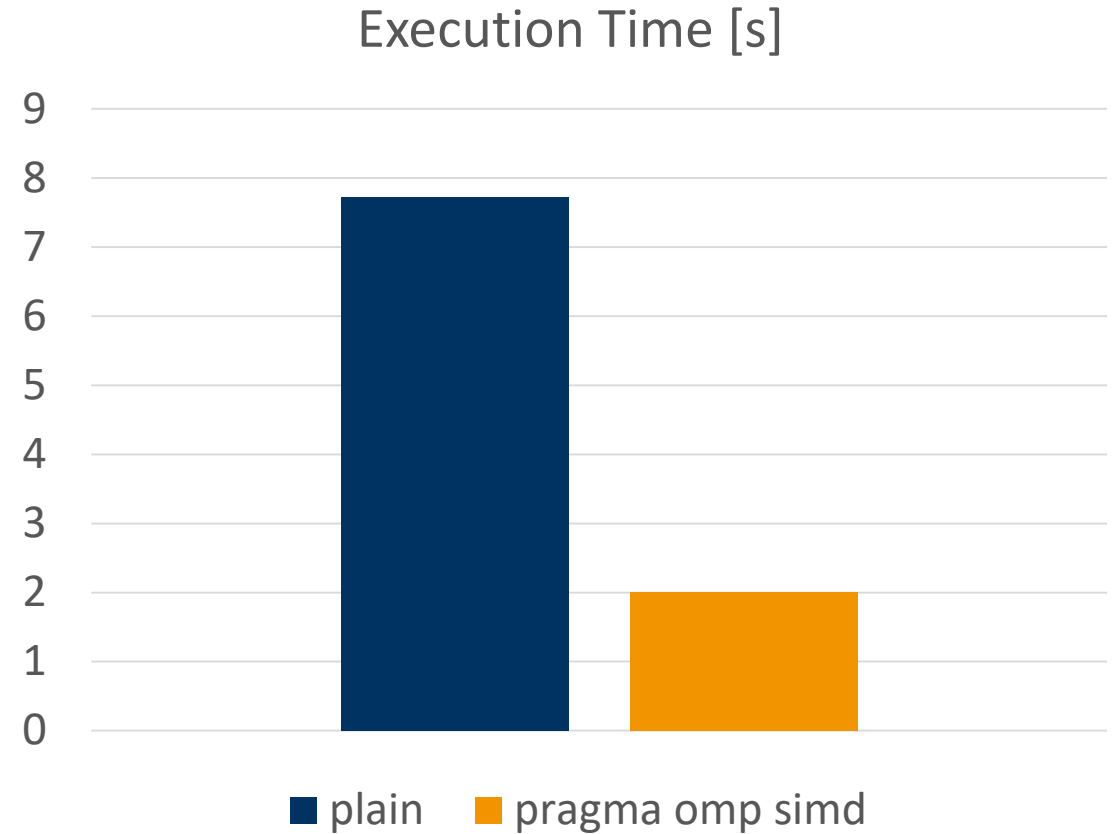
```
// note: aligned_alloc requires -std=c11
int* a = aligned_alloc(32,
                      sizeof(int)*SIZE);
int* b = aligned_alloc(32,
                      sizeof(int)*SIZE);

// initialize a, b, and f...

#pragma omp simd aligned(a,b:32)
for(int i = 0; i < SIZE; ++i) {
    b[i] += a[i] * f;
}
```


Vectorization Performance Comparison

- ▶ LCC2, gcc/8.2.0, single-threaded,
 - ▶ -march=native
 - ▶ -mtune=native
 - ▶ -O2
- ▶ 10^8 vector sums of length 64 integers
 - ▶ code example of previous slide
- ▶ execution time reduced by 3.84x
 - ▶ 4 integers per operation with incl. some overhead



simd clauses

▶ safelen

- ▶ maximum number of iterations with no dependencies to be vectorized
- ▶ increases loop coverage that can be vectorized

▶ aligned

- ▶ specify memory alignment in bytes after aligned allocation with e.g. `aligned_alloc()`
- ▶ required for additional compiler optimizations

```
#pragma omp simd safelen(4)
for(int i=0; i<N; i++) {
    a[i] = a[i+4] * f;
}
```

```
#pragma omp simd aligned(a,b:32)
for(int i = 0; i < SIZE; ++i) {
    b[i] += a[i] * f;
}
```

Vectorization and Functions

- ▶ function calls are problematic
 - ▶ function definition could be too complex for auto-vectorization or hidden in another object file only visible during linking
 - ▶ solution: specify SIMD-capable functions with `declare simd`

```
#pragma omp declare simd  
int max(int a, int b) {  
    return a > b ? a : b;  
}
```

declare simd Clauses

- ▶ **aligned**
 - ▶ specify memory alignment of arguments
- ▶ **inbranch/notinbranch**
 - ▶ specifies that function will always/never be called inside a conditional branch of an SIMD loop
 - ▶ required due to masking (conditionally loading arguments in vector registers)
- ▶ **simdlen**
 - ▶ specify preferred SIMD-length, i.e. the number of loop iterations per SIMD invocation

Accelerator Support in OpenMP

- ▶ programming accelerators is difficult
 - ▶ usually completely different hardware architecture and ISA (e.g. GPUs)
 - ▶ new/additional software stack
 - ▶ requires copying data from/to device memory
 - ▶ often lack of debugging tools (I'm looking at you, OpenCL!)
- ▶ OpenMP tries to add abstraction layer to improve usability
 - ▶ c.f. SIMD support
- ▶ already present in 4.0 (2013!), some clarifications in 4.5, usability improvements in 5.0
 - ▶ but check compiler/runtime implementation support!

target directive

- ▶ creates a target task to be executed on device and maps variables to data environment on device
 - ▶ map clause: specify mapping of original data on host to data on device (to), vice versa (from), or both (tofrom)

```
void vadd_omp(float *a, float *b, float *c, int size)
{
    #pragma omp target \
        map(to:a[0:size],b[0:size],size) \
        map(from:c[0:size])
    {
        #pragma omp parallel for
        for (int i = 0; i < size; i++)
            c[i] = a[i] + b[i];
    }
}
```

Additional Accelerator Directives and Clauses

- ▶ **teams**

- ▶ creates a collection of teams (a single team is always implicitly created if teams is not specified)
- ▶ relevant for performance: barriers only done among threads of the same team

- ▶ **parallel for**

- ▶ distribute loop iterations to threads of a team

- ▶ **distribute**

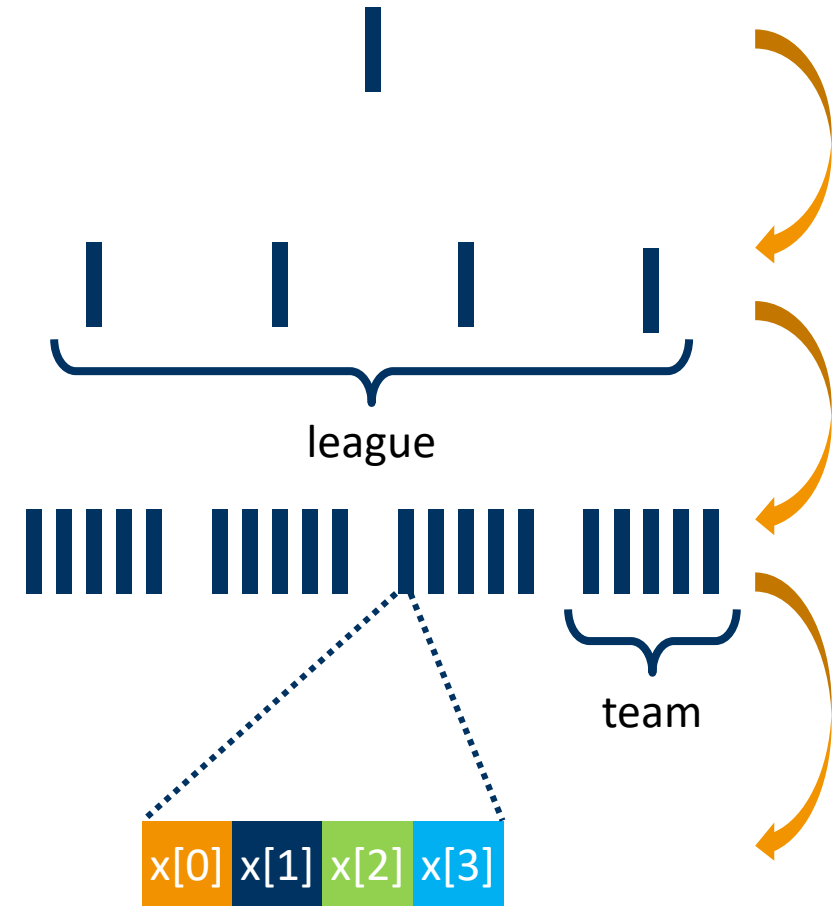
- ▶ similar to work share constructs but distributes iterations to different teams

- ▶ additional, known clauses can be used, e.g. SIMD

- ▶ leads to e.g. `#pragma omp teams distribute parallel for SIMD`

OpenMP `target` Thread Hierarchy

- ▶ `target` creates a single, initial thread on target
- ▶ `teams` creates a *league* of several teams, each with a single, initial thread
- ▶ `parallel` creates several threads within each team
- ▶ SIMD vectorizes code executed by each thread of each team in the league



Other Neat OpenMP 5.0 Features and Fixes

- ▶ reductions in `taskloop`
 - ▶ also reductions in `task_group`
- ▶ range-based for loops in C++ and `!=` as loop condition
- ▶ many new combined directives
- ▶ tool support
 - ▶ e.g. callback functions

```
#pragma omp taskloop reduction(+:sum)
  for(int i = 0; i < N; i++)
    sum += ..;

#pragma omp parallel for
for(const auto& x : vec)
  ...

#pragma omp parallel master taskloop
...
```

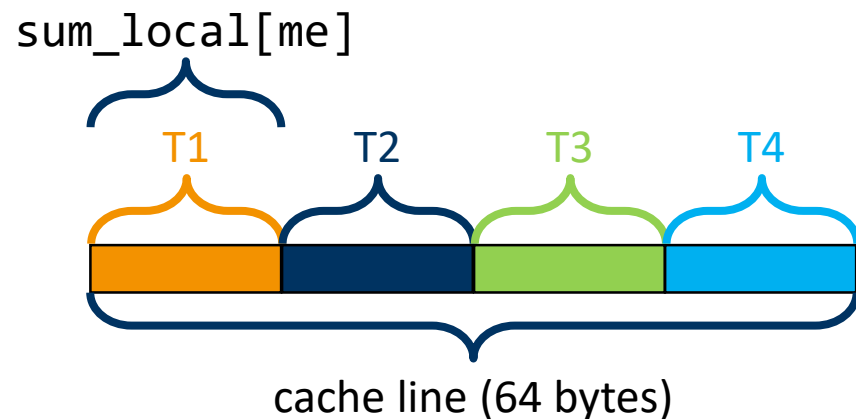


Common OpenMP Pitfalls



False Sharing

- ▶ common performance pitfall in OpenMP
 - ▶ cache coherence tries to keep all data up-to-date and valid for all threads
 - ▶ causes unnecessary coherence traffic and cache misses



```
double sum = 0.0;
double sum_local[MAX_NUM_THREADS];

#pragma omp parallel
{
    int me = omp_get_thread_num();
    sum_local[me] = 0.0;

    #pragma omp for
    for (i = 0; i < N; i++)
        sum_local[me] += x[i] * y[i];

    #pragma omp atomic
    sum += sum_local[me];
}
```

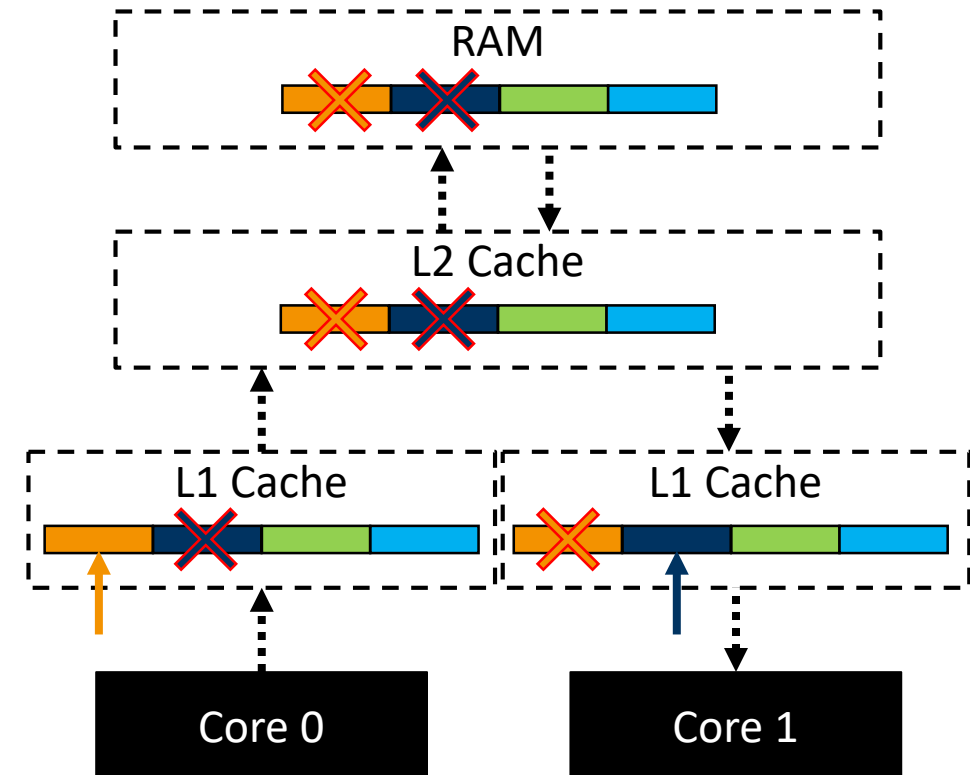
False Sharing cont'd

▶ thread 1

- ▶ reads first 8 bytes
 - ▶ causes entire cache line to be fetched
- ▶ writes first 8 bytes
 - ▶ entire cache line invalidated for thread 2

▶ thread 2

- ▶ reads second 8 bytes
 - ▶ causes entire cache line to be fetched
- ▶ writes second 8 bytes
 - ▶ entire cache line invalidated for thread 1



False Sharing Solution

```
double sum = 0.0;
double sum_local[MAX_NUM_THREADS];

#pragma omp parallel
{
    int me = omp_get_thread_num();
    sum_local[me] = 0.0;

    #pragma omp for
    for (i = 0; i < N; i++)
        sum_local[me] += x[i] * y[i];

    #pragma omp atomic
    sum += sum_local[me];
}
```

```
double sum = 0.0;
double sum_local[MAX_NUM_THREADS][8];

#pragma omp parallel
{
    int me = omp_get_thread_num();
    sum_local[me][0] = 0.0;

    #pragma omp for
    for (i = 0; i < N; i++)
        sum_local[me][0] += x[i] * y[i];

    #pragma omp atomic
    sum += sum_local[me][0];
}
```

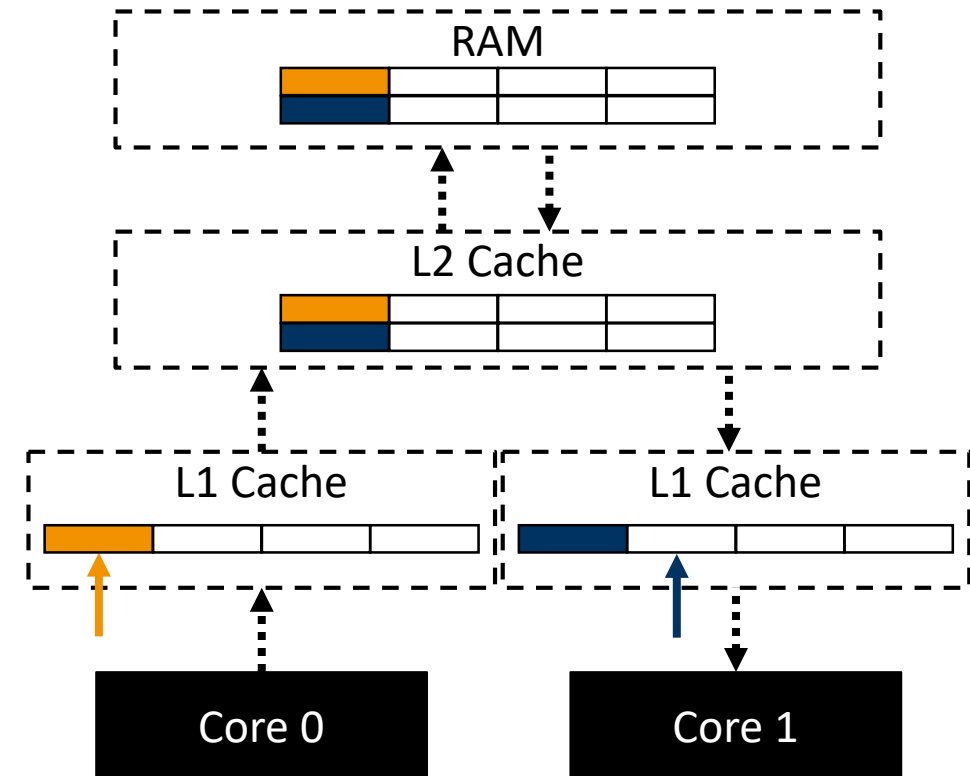
False Sharing Solution cont'd

▶ thread 1

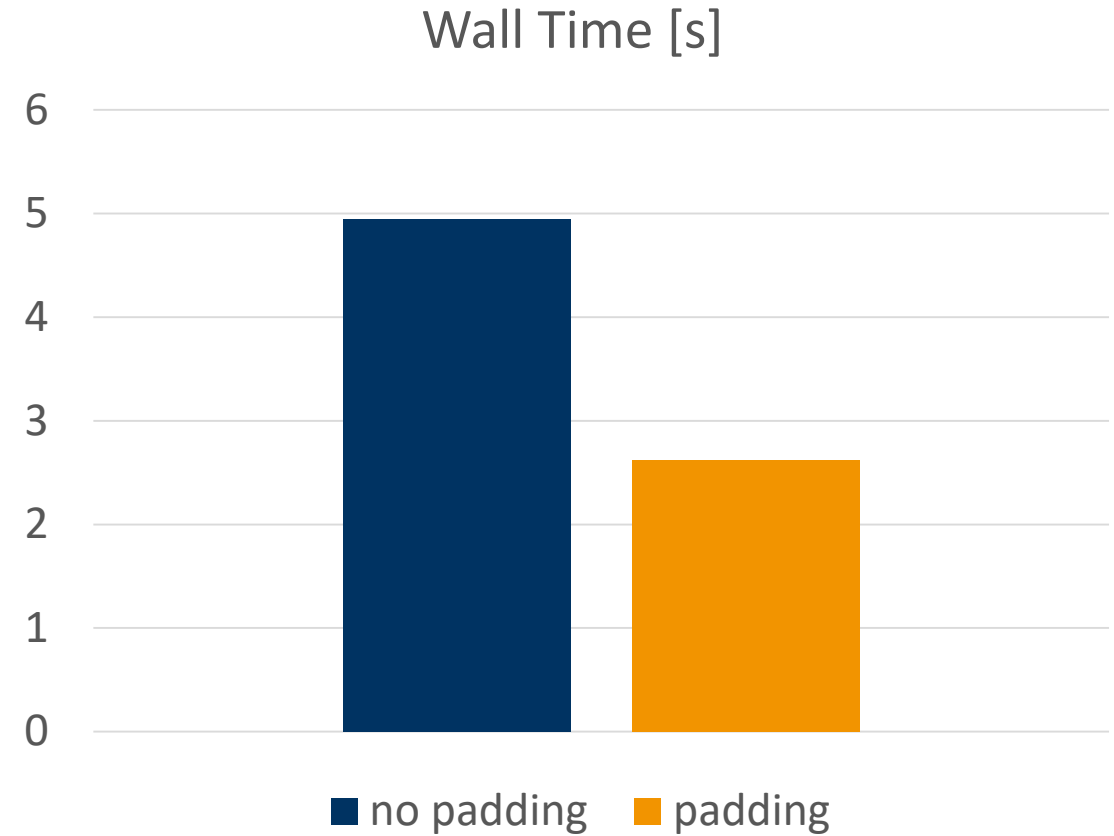
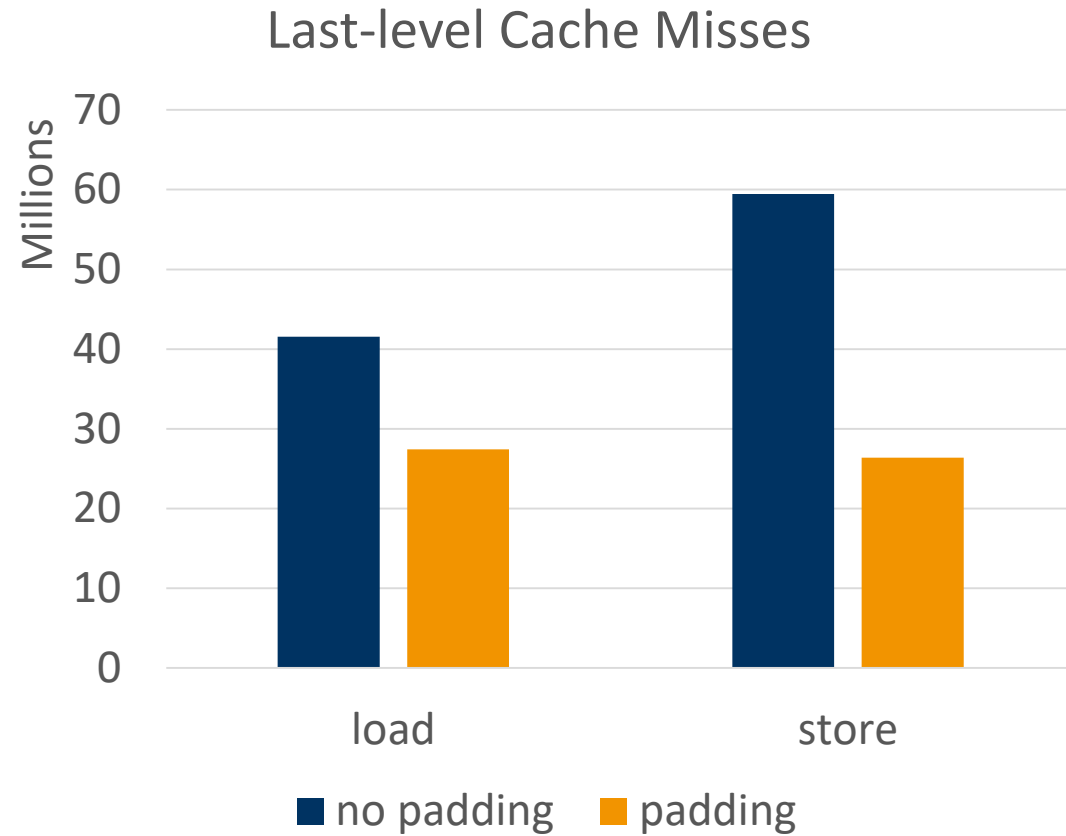
- ▶ reads first 8 bytes of first cache line
 - ▶ causes first cache line to be fetched
- ▶ writes first 8 bytes

▶ thread 2

- ▶ reads first 8 bytes of second cache line
 - ▶ causes second cache line to be fetched
- ▶ writes second 8 bytes



False Sharing Performance Comparison (LCC2, 10^9 iterations)



First Touch & NUMA – How to Initialize Your Data?

```
double* x = malloc(sizeof(double)*SIZE);
double* y = malloc(sizeof(double)*SIZE);

for(int i = 0; i < SIZE; ++i) {
    x[i] = 0.0; y[i] = 1.0;
}

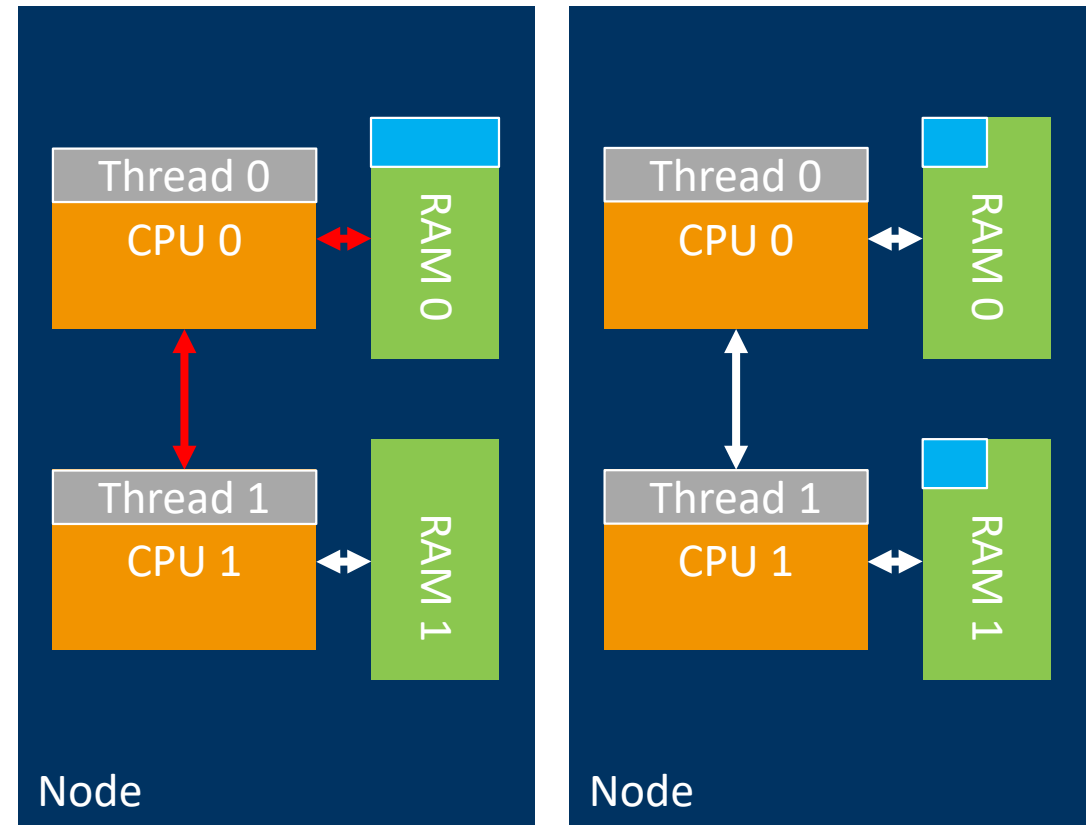
#pragma omp parallel
{
    #pragma omp for schedule(static)
    for(int i = 0; i < SIZE; ++i) {
        x[i] += y[i];
    }
}
```

```
double* x = malloc(sizeof(double)*SIZE);
double* y = malloc(sizeof(double)*SIZE);

#pragma omp parallel
{
    #pragma omp for schedule(static)
    for(int i = 0; i < SIZE; ++i) {
        x[i] = 0.0; y[i] = 1.0;
    }
    #pragma omp for schedule(static)
    for(int i = 0; i < SIZE; ++i) {
        x[i] += y[i];
    }
}
```

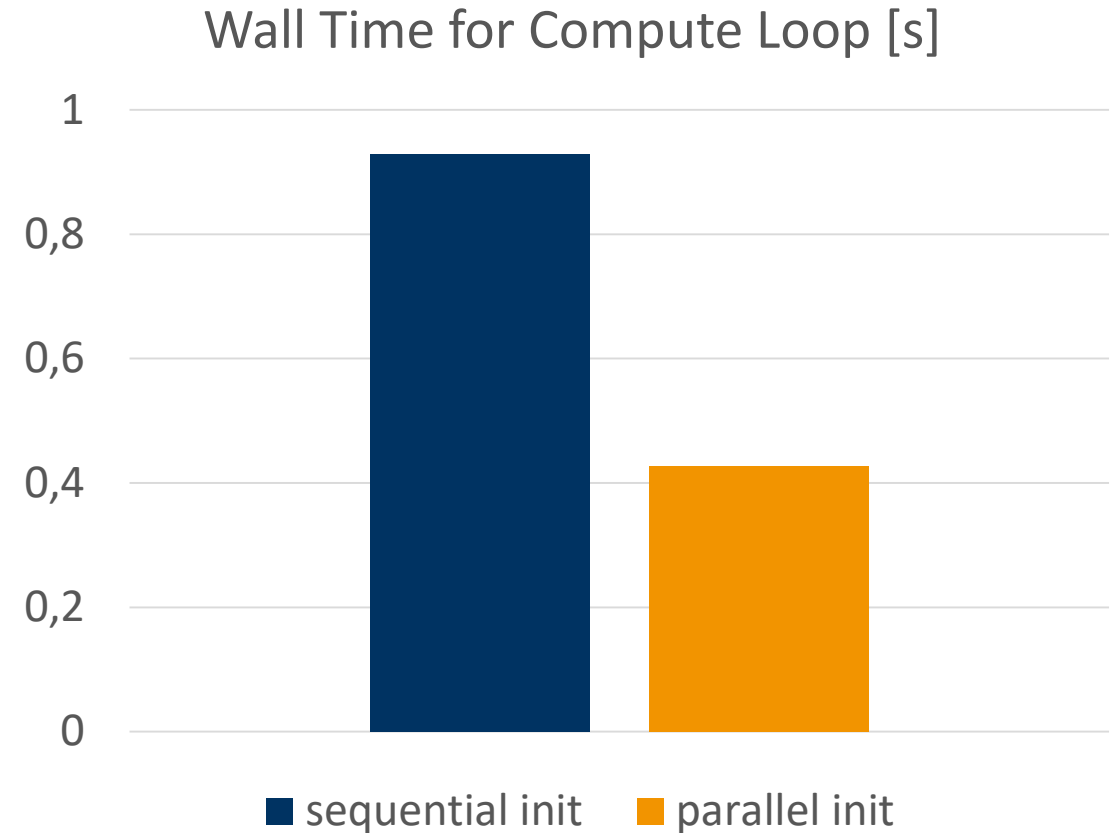

Sequential vs. Parallel Initialization on NUMA

- ▶ data is not allocated upon allocation but upon first access (*"first touch"*)
 - ▶ happens when you initialize data in the memory of the initializing thread
- ▶ sequential initialization
 - ▶ all data resides with RAM modules of core processing initial thread
 - ▶ causes bottleneck on single memory bus, additional inter-CPU traffic and higher latency for core 1
- ▶ parallel initialization
 - ▶ data resides with RAM of the threads initializing the respective chunk of data
 - ▶ only downside: one more pragma



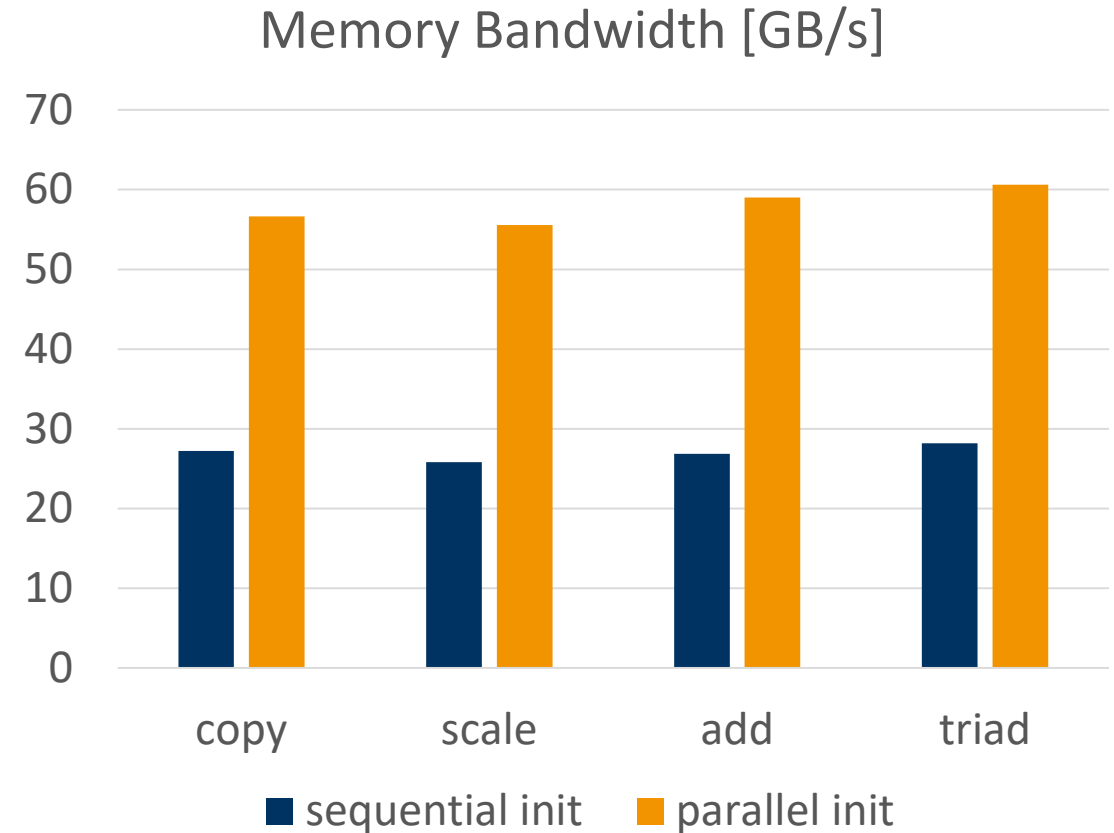
Performance Impact of First Touch and NUMA

- ▶ hudson server (2x Intel Xeon E5-2699 v3 18-core), gcc 6.3.0, 10^8 double elements, 10 repetitions
- ▶ performance improvement of compute loop (not initialization!) of 2.17x



Performance Impact of First Touch and NUMA cont'd

- ▶ same platform, stream memory benchmark, 3 threads per CPU
 - ▶ <https://www.cs.virginia.edu/stream/>
- ▶ between 2.08x and 2.20x higher bandwidth





Tales From the Proseminar



Performance Difference Between `if/else` & Ternary Operator?

```
for (long long i = 0; i < N; i++) {  
    for (long long j = 0; j < N; j++) {  
        tc = A[i][j];  
        t_above = (i != 0) ? A[i-1][j] : tc;  
    }  
}
```

```
for (long long i = 0; i < N; i++) {  
    for (long long j = 0; j < N; j++) {  
        tc = A[i][j];  
        if(i != 0) {  
            t_above = A[i-1][j];  
        } else {  
            t_above = tc;  
        }  
    }  
}
```



Nope! (gcc 9.1, -O3)

```
foo(double**):  
    mov rsi, rdi  
    xor ecx, ecx  
  
.L5:  
    mov eax, 1  
    test rcx, rcx  
    cmove rcx, rax  
    mov rax, QWORD PTR [rsi-8+rcx*8]  
    lea rdx, [rax+400]  
  
.L3:  
    movsd xmm0, QWORD PTR [rax]  
    add rax, 8  
    cmp rax, rdx  
    jne .L3  
    add rcx, 1  
    cmp rcx, 50  
    jne .L5  
    cvtsd2si eax, xmm0  
    ret
```

```
foo(double**):  
    mov rsi, rdi  
    xor ecx, ecx  
  
.L5:  
    mov eax, 1  
    test rcx, rcx  
    cmove rcx, rax  
    mov rax, QWORD PTR [rsi-8+rcx*8]  
    lea rdx, [rax+400]  
  
.L3:  
    movsd xmm0, QWORD PTR [rax]  
    add rax, 8  
    cmp rax, rdx  
    jne .L3  
    add rcx, 1  
    cmp rcx, 50  
    jne .L5  
    cvtsd2si eax, xmm0  
    ret
```



Summary

- ▶ task-based parallelism
- ▶ modern OpenMP features
 - ▶ affinity
 - ▶ vectorization
 - ▶ accelerators
- ▶ common OpenMP pitfalls
- ▶ Tales From the Proseminar
 - ▶ in compilers, we trust