Programming OpenMP

Tasking

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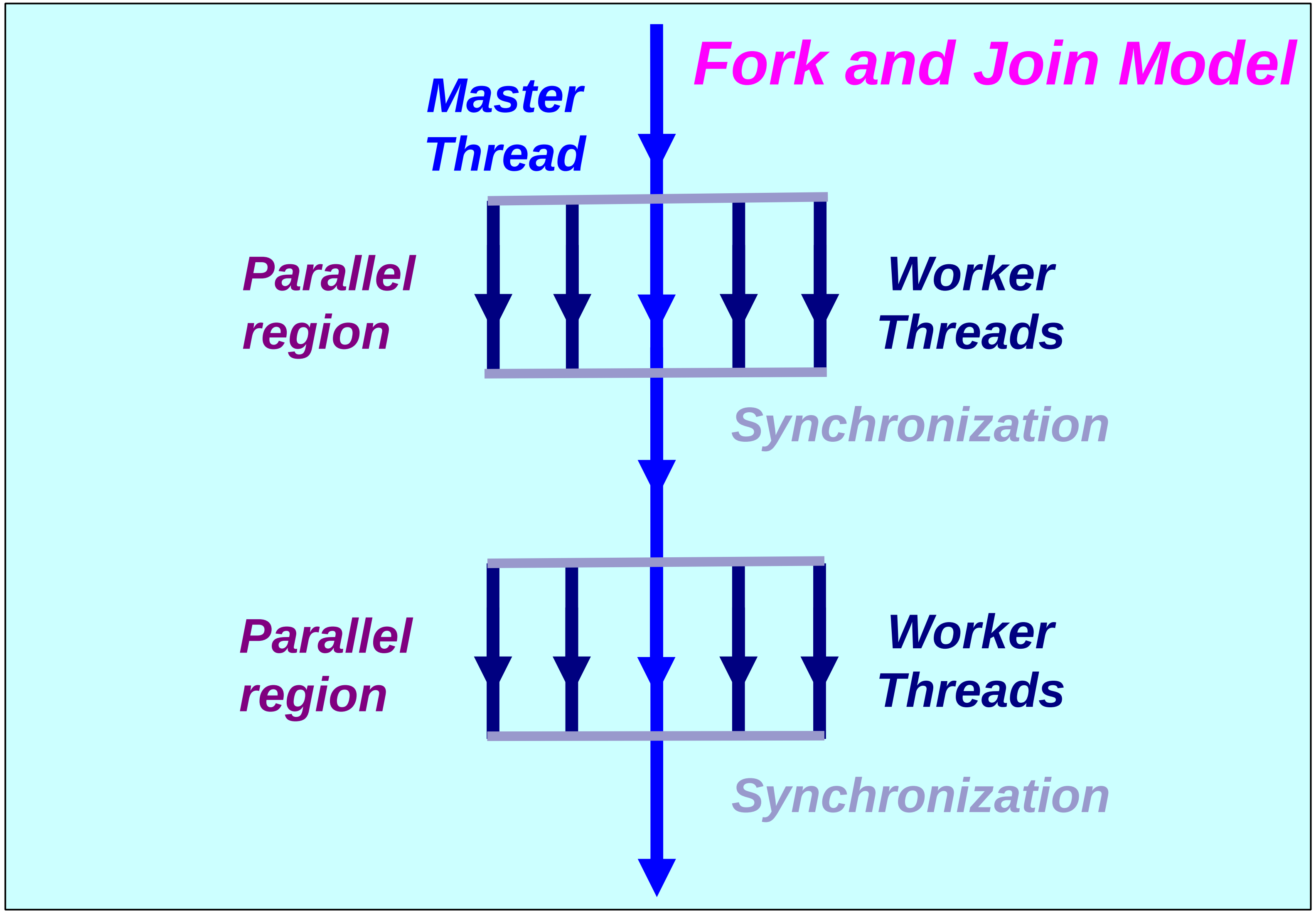
OpenMP Review

The OpenMP Execution Model



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

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

The Worksharing Constructs

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

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

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

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

The Single and Master Directives

- Single: only one thread in the team executes the code enclosed

```
#pragma omp single [private][firstprivate] \
                   [copyprivate][nowait]
{
    <code-block>
}
```

- Master: the master thread executes the code enclosed

```
#pragma omp master
{<code-block>}
```

There is no implied barrier on entry or exit !

The OpenMP Barrier

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

```
#pragma omp barrier
```

Tasking Motivation

Sudoko for Lazy Computer Scientists

- Lets solve Sudoku puzzles with brute multi-core force

	6						8	11			15	14			16
15	11				16	14				12			6		
13		9	12					3	16	14		15	11	10	
2		16		11		15	10	1							
	15	11	10			16	2	13	8	9	12				
12	13			4	1	5	6	2	3					11	10
5		6	1	12		9		15	11	10	7	16			3
	2				10		11	6		5			13		9
10	7	15	11	16				12	13						6
9						1			2		16	10			11
1		4	6	9	13			7		11		3	16		
16	14			7		10	15	4	6	1				13	8
11	10		15				16	9	12	13			1	5	4
		12		1	4	6		16				11	10		
		5		8	12	13		10			11	2			14
3	16			10			7			6				12	

- (1) Search an empty field
- (2) Try all numbers:
  - (2 a) Check Sudoku
    - If invalid: skip
    - If valid: Go to next field
- Wait for completion

Parallel Brute-force Sudoku

- This parallel algorithm finds all valid solutions

	6						8	11			15	14			16
15	11				16	14				12			6		
13		9	12					3	16	14		15	11	10	
2		16		11		15	10	1							
	15	11	10			16	2	13	8	9	12				
12	13			4	1	5	6	2	3					11	10
5		6	1	12		9		15	11	10	7	16			3
	2				10		11	6		5			13		9
10	7	15	11	16				12	13						6
9						1			2		16	10			11
1		4	6	9	13			7		11		3	16		
16	14			7		10	15	4	6	1				13	8
11	10		15				16	9	12	13			1	5	4
		12		1	4	6		16				11	10		
		5		8	12	13		10			11	2			14
3	16			10			7			6				12	

- (1) Search an empty field
- (2) Try all numbers:
  - (2 a) Check Sudoku
    - If invalid: skip
    - If valid: Go to next field
- Wait for completion

first call contained in a

```
#pragma omp parallel
#pragma omp single
```

such that one tasks starts the execution of the algorithm

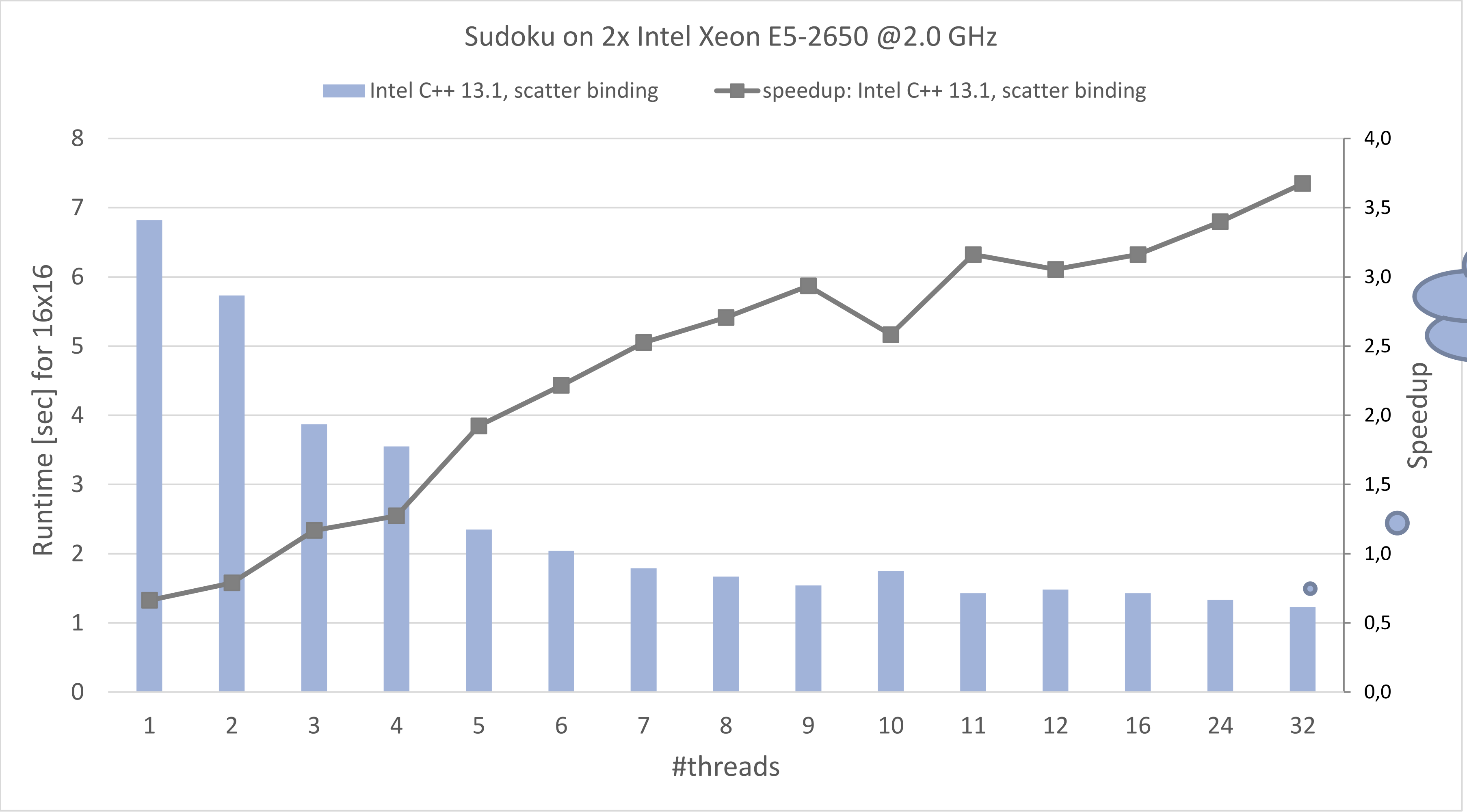
```
#pragma omp task
```

needs to work on a new copy of the Sudoku board

```
#pragma omp taskwait
```

wait for all child tasks

Performance Evaluation



Is this the best we can can do?

Tasking Overview

What is a task in OpenMP?

- Tasks are work units whose execution
  - → may be deferred or…
  - → … can be executed immediately
- Tasks are composed of
  - → **code** to execute, a **data** environment (initialized at creation time), internal **control** variables (ICVs)
- Tasks are created…

  … when reaching a parallel region → implicit tasks are created (per thread)

  … when encountering a task construct → explicit task is created

  … when encountering a taskloop construct → explicit tasks per chunk are created

  … when encountering a target construct → target task is created

Tasking execution model

- Supports unstructured parallelism
  → unbounded loops

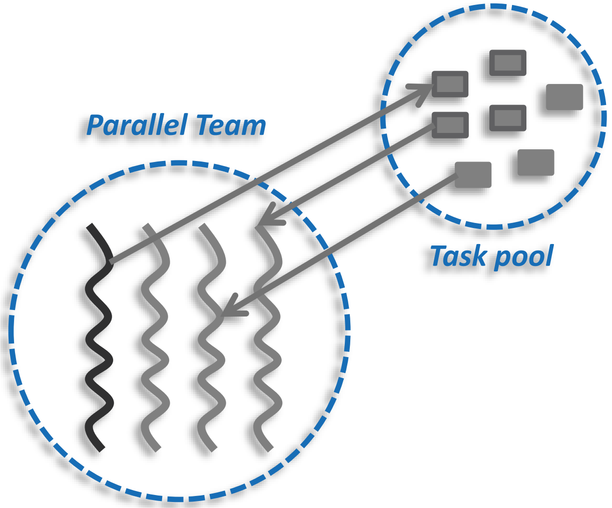
```
while ( <expr> ) {
    ...
}
```

  → recursive functions

```
void myfunc( <args> )
{
    ...; myfunc( <newargs> ); ...;
}
```

- Example (unstructured parallelism)

```
#pragma omp parallel
#pragma omp master
while (elem != NULL) {
   #pragma omp task
      compute(elem);
   elem = elem->next;
}
```



- Several scenarios are possible:
  → single creator, multiple creators, nested tasks (tasks & WS)
- All threads in the team are candidates to execute tasks

The task construct

- Deferring (or not) a unit of work (executable for any member of the team)

```
#pragma omp task [clause[[,] clause]...]
{structured-block}
```

```
!$omp task [clause[[,] clause]...]
…structured-block…
!$omp end task
```

- Where clause is one of:

Data Environment

- → private(list)
- → firstprivate(list)
- → shared(list)
- → default(shared | none)
- → in_reduction(r-id: list)

Miscellaneous

- → allocate([allocator:] list)
- → detach(event-handler)

Cutoff Strategies

- → if(scalar-expression)
- → mergeable
- → final(scalar-expression)

Synchronization

- → depend(dep-type: list)

Task Scheduling

- → untied
- → priority(priority-value)
- → affinity(list)

Task scheduling: tied vs untied tasks

- Tasks are tied by default (when no untied clause present)
  - → tied tasks are executed always by the same thread (not necessarily creator)
  - → tied tasks may run into performance problems
- Programmers may specify tasks to be untied (relax scheduling)

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

  - → can potentially switch to any thread (of the team)
  - → bad mix with thread based features: thread-id, threadprivate, critical regions...
  - → gives the runtime more flexibility to schedule tasks
  - → but most of OpenMP implementations doesn’t “honor” untied ☹

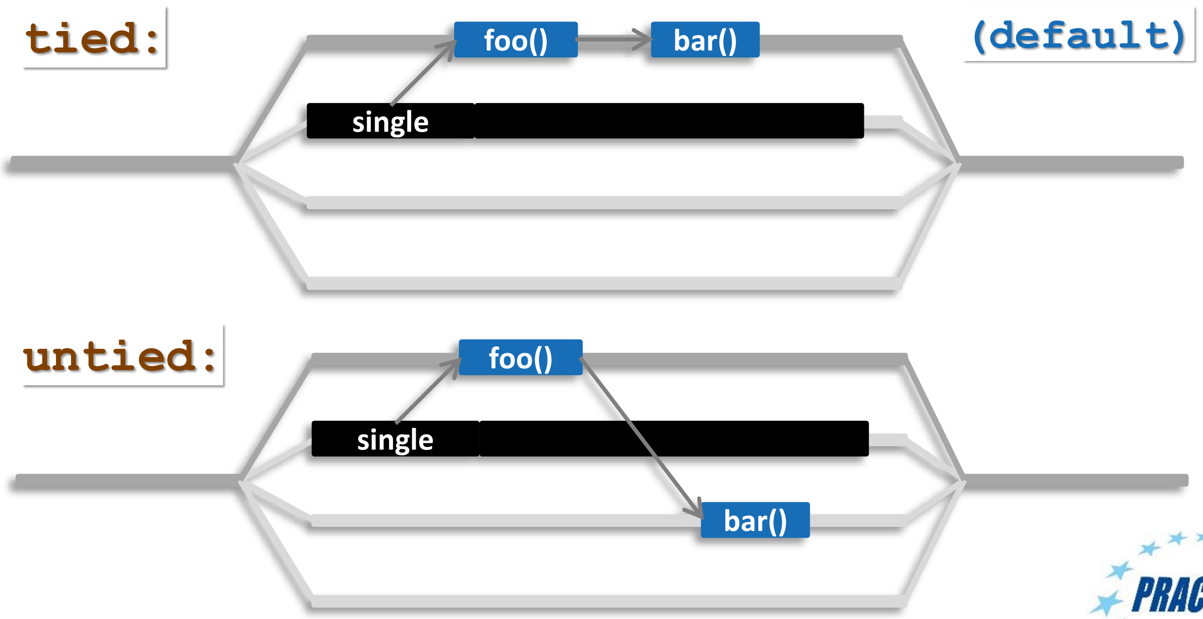
Task scheduling: taskyield directive

- Task scheduling points (and the taskyield directive)
  - → tasks can be suspended/resumed at TSPs → some additional constraints to avoid deadlock problems
  - → implicit scheduling points (creation, synchronization, ...)
  - → explicit scheduling point: the taskyield directive

```
#pragma omp taskyield
```

- Scheduling [tied/untied] tasks: example

```
#pragma omp parallel
#pragma omp single
{
   #pragma omp task untied
   {
      foo();
      #pragma omp taskyield
      bar()
   }
}
```



Task scheduling: programmer’s hints

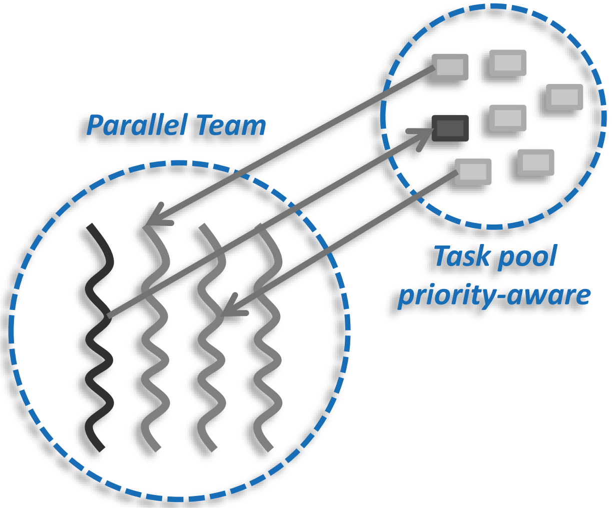
- Programmers may specify a priority value when creating a task

```
#pragma omp task priority(pvalue)
{structured-block}
```

→ pvalue: the higher → the best (will be scheduled earlier)

→ once a thread becomes idle, gets one of the highest priority tasks

```
#pragma omp parallel
#pragma omp single
{
 for ( i = 0; i < SIZE; i++) {
  #pragma omp task priority(1)
  { code_A; }
 }
 #pragma omp task priority(100)
 { code_B; }
 ...
}
```



Task synchronization: taskwait directive

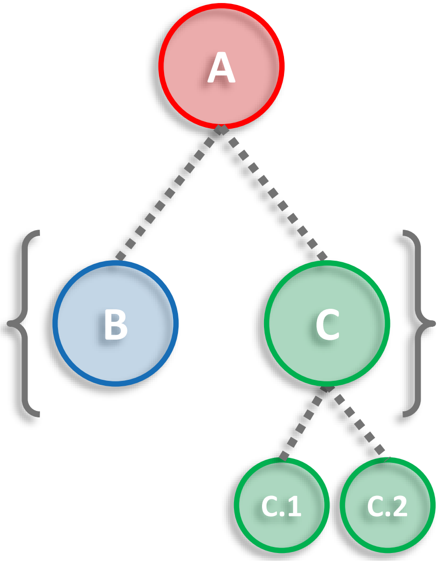
- The taskwait directive (shallow task synchronization)
  - → It is a stand-alone directive

```
#pragma omp taskwait
```

  - → wait on the completion of child tasks of the current task; just direct children, not all descendant tasks; includes an implicit task scheduling point (TSP)

```
#pragma omp parallel
#pragma omp single
{
   #pragma omp task                     : A
   {
      #pragma omp task            : B
      { … }
      #pragma omp task            : C
      { … #C.1; #C.2; …}
      #pragma omp taskwait
   }
} // implicit barrier will wait for C.x
```

wait for…



Task synchronization: barrier semantics

- OpenMP barrier (implicit or explicit)
  - → All tasks created by any thread of the current team are guaranteed to be completed at barrier exit

```
#pragma omp barrier
```

  - → And all other implicit barriers at parallel, sections, for, single, etc…

Task synchronization: taskgroup construct

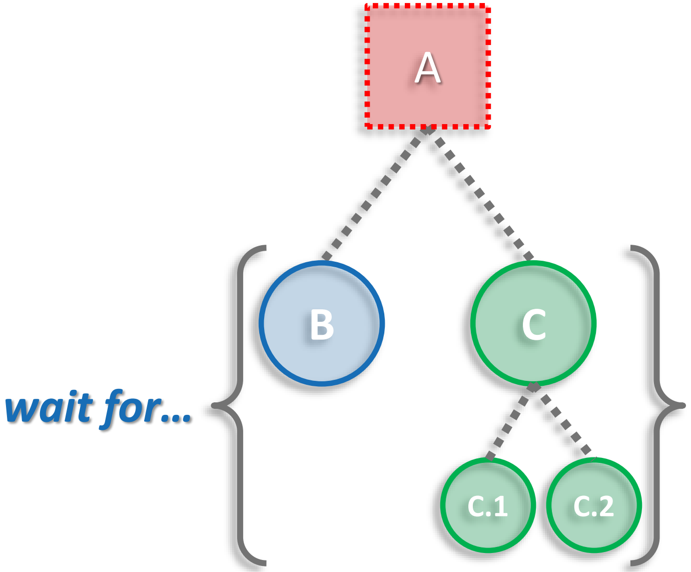
- The taskgroup construct (deep task synchronization)
  - → attached to a structured block; completion of all descendants of the current task; TSP at the end

```
#pragma omp taskgroup [clause[[,] clause]...]
{structured-block}
```

  - → where clause (could only be): reduction(reduction-identifier: list-items)

```
#pragma omp parallel
#pragma omp single
{
   #pragma omp taskgroup              : A
   {
      #pragma omp task                :B
      { … }
      #pragma omp task                :C
      { … #C.1; #C.2; …}

   } // end of taskgroup
}
```



Data Environment

Explicit data-sharing clauses

- Explicit data-sharing clauses (shared, private and firstprivate)

```
#pragma omp task shared(a)
{
  // Scope of a: shared
}
```

```
#pragma omp task private(b)
{
  // Scope of b: private
}
```

```
#pragma omp task firstprivate(c)
{
  // Scope of c: firstprivate
}
```

- If **default** clause present, what the clause says
  - → shared: data which is not explicitly included in any other data sharing clause will be **shared**
  - → none: compiler will issue an error if the attribute is not explicitly set by the programmer (very useful!!!)

```
#pragma omp task default(shared)
{
 // Scope of all the references, not explicitly
 // included in any other data sharing clause,
 // and with no pre-determined attribute: shared
}
```

```
#pragma omp task default(none)
{
 // Compiler will force to specify the scope for
 // every single variable referenced in the context
}
```

Hint: Use default(none) to be forced to think about every variable if you do not see clearly.

Pre-determined data-sharing attributes

- threadprivate variables are threadprivate **(1)**
- dynamic storage duration objects are shared (malloc, new,…) **(2)**
- static data members are shared **(3)**
- variables declared inside the construct
  - → static storage duration variables are shared **(4)**
  - → automatic storage duration variables are private **(5)**
- the loop iteration variable(s)…

5

```
#pragma omp task
{
   int x = MN;
   // Scope of x: private
}
```

4

```
#pragma omp task
{
   static int y;
   // Scope of y: shared
}
```

1

```
int A[SIZE];
#pragma omp threadprivate(A)

// ...
#pragma omp task
{
  // A: threadprivate
}
```

2

```
int *p;

p = malloc(sizeof(float)*SIZE);

#pragma omp task
{
   // *p: shared
}
```

3

```
void foo(void){
   static int s = MN;
}

#pragma omp task
{
   foo(); // s@foo(): shared
}
```

Implicit data-sharing attributes (in-practice)

- Implicit data-sharing rules for the task region
  - → the **shared** attribute is lexically inherited
  - → in any other case the variable is **firstprivate**

```
int a = 1;
void foo() {
   int b = 2, c = 3;
   #pragma omp parallel private(b)
   {
      int d = 4;
      #pragma omp task
      {
         int e = 5;
         // Scope of a:
         // Scope of b:
         // Scope of c:
         // Scope of d:
         // Scope of e:
      }
   }
}
```

- → Pre-determined rules (could not change)
- → Explicit data-sharing clauses (+ default)
- → Implicit data-sharing rules

- (in-practice) variable values within the task:
  - → value of a: 1
  - → value of b: x // undefined (undefined in parallel)
  - → value of c: 3
  - → value of d: 4
  - → value of e: 5

Task reductions (using taskgroup)

- Reduction operation
  - → perform some forms of recurrence calculations
  - → associative and commutative operators
- The (taskgroup) scoping reduction clause

```
#pragma omp taskgroup task_reduction(op: list)
{structured-block}
```

  - → Register a new reduction at [1]
  - → Computes the final result after [3]
- The (task) in_reduction clause [participating]

```
#pragma omp task in_reduction(op: list)
{structured-block}
```

  - → Task participates in a reduction operation [2]

```
int res = 0;
node_t* node = NULL;
...
#pragma omp parallel
{
  #pragma omp single
  {
    #pragma omp taskgroup task_reduction(+: res)
    { // [1]
      while (node) {
        #pragma omp task in_reduction(+: res) \
                    firstprivate(node)
        { // [2]
          res += node->value;
        }
        node = node->next;
      }
    } // [3]
  }
}
```

Task reductions (+ modifiers)

- Reduction modifiers
  - → Former reductions clauses have been extended
  - → task modifier allows to express task reductions
  - → Registering a new task reduction [1]
  - → Implicit tasks participate in the reduction [2]
  - → Compute final result after [4]
- The (task) in_reduction clause [participating]

```
#pragma omp task in_reduction(op: list)
{structured-block}
```

  - → Task participates in a reduction operation [3]

```
int res = 0;
node_t* node = NULL;
...
#pragma omp parallel reduction(task,+: res)
{ // [1][2]
  #pragma omp single
  {
    #pragma omp taskgroup
    {
      while (node) {
        #pragma omp task in_reduction(+: res) \
                   firstprivate(node)
        { // [3]
          res += node->value;
        }
        node = node->next;
      }
    }
  }
} // [4]
```

Tasking illustrated

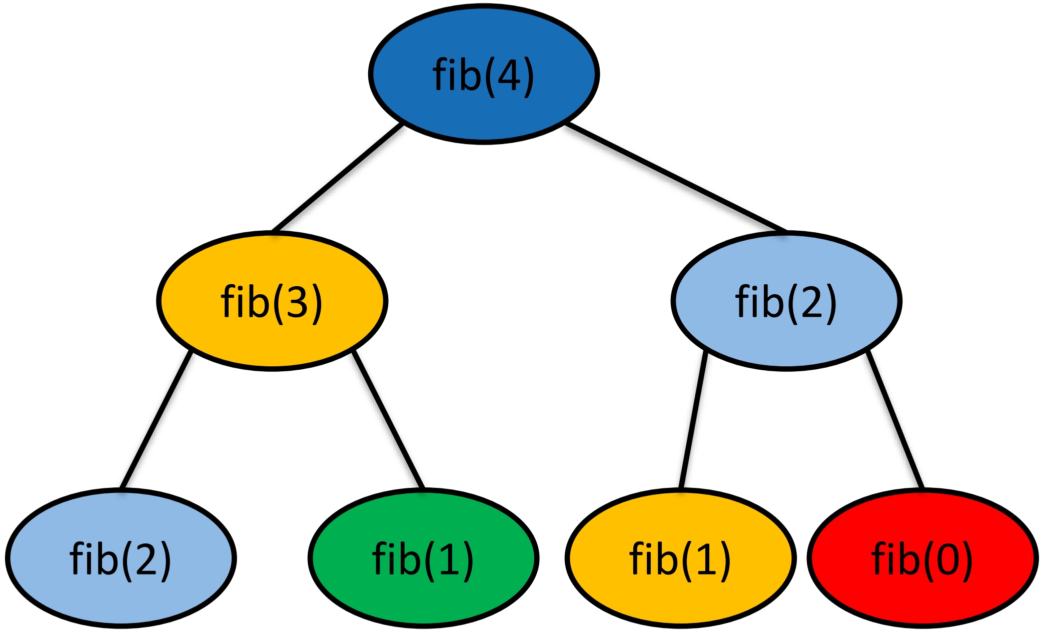
Fibonacci illustrated

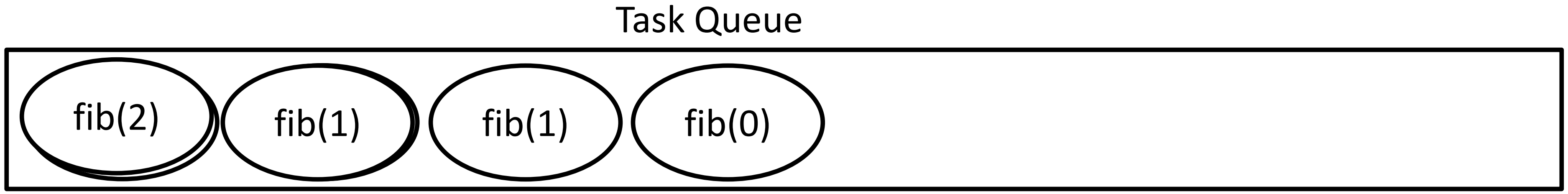
```
int main(int argc,
         char* argv[])
{
    [...]
    #pragma omp parallel
    {
        #pragma omp single
       {
           fib(input);
       }
    }
    [...]
}
```

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

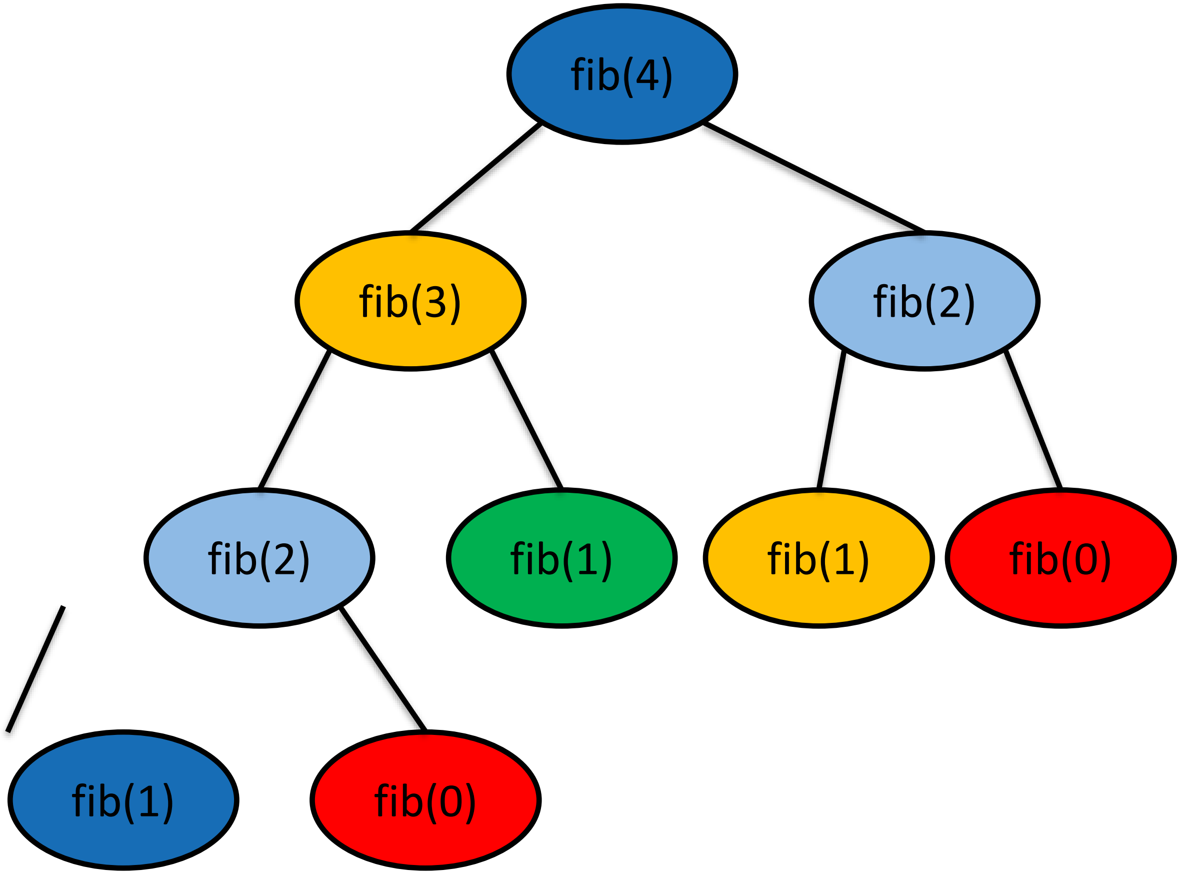
- Only one Task / Thread enters fib() from main(), it is responsible for creating the two initial work tasks
- Taskwait is required, as otherwise x and y would get lost

- T1 enters fib(4)
- T1 creates tasks for fib(3) and fib(2)
- T1 and T2 execute tasks from the queue
- T1 and T2 create 4 new tasks
- T1 - T4 execute tasks





- T1 enters fib(4)
- T1 creates tasks for fib(3) and fib(2)
- T1 and T2 execute tasks from the queue
- T1 and T2 create 4 new tasks
- T1 - T4 execute tasks
- …



The `taskloop` Construct

Traditional Worksharing

- Worksharing constructs do not compose well
- Pathological example: parallel dgemm in MKL

```
void example() {
#pragma omp parallel
    {
        compute_in_parallel(A);
        compute_in_parallel_too(B);
        // dgemm is either parallel or sequential,
        // but has no orphaned worksharing
        cblas_dgemm(CblasRowMajor, CblasNoTrans, CblasNoTrans,
                    m, n, k, alpha, A, k, B, n, beta, C, n);

}   }
```

- Writing such code either
  - → oversubscribes the system,
  - → yields bad performance due to OpenMP overheads, or
  - → needs a lot of glue code to use sequential dgemm only for sub-matrixes

Example: Sparse CG

```
for (iter = 0; iter < sc->maxIter; iter++) {
    precon(A, r, z);
    vectorDot(r, z, n, &rho);
    beta = rho / rho_old;
    xpay(z, beta, n, p);
    matvec(A, p, q);
    vectorDot(p, q, n, &dot_pq);
    alpha = rho / dot_pq;
    axpy(alpha, p, n, x);
    axpy(-alpha, q, n, r);
    sc->residual = sqrt(rho) * b
    if (sc->residual <= sc->tole
        break;
    rho_old = rho;
}
```

```
void matvec(Matrix *A, double *x, double *y) {
    // ...
#pragma omp parallel for \
            private(i,j,is,ie,j0,y0) \
            schedule(static)
for (i = 0; i < A->n; i++) {
        y0 = 0;
        is = A->ptr[i];
        ie = A->ptr[i + 1];
        for (j = is; j < ie; j++) {
            j0 = index[j];
            y0 += value[j] * x[j0];
        }
        y[i] = y0;
    }
    // ...
}
```

Tasking use case: saxpy (taskloop)

```
for ( i = 0; i<SIZE; i+=1) {
   A[i]=A[i]*B[i]*S;
}
```

```
for ( i = 0; i<SIZE; i+=TS) {
   UB = SIZE < (i+TS)?SIZE:i+TS;
   for ( ii=i; ii<UB; ii++) {
      A[ii]=A[ii]*B[ii]*S;
   }
}
```

```
#pragma omp parallel
#pragma omp single
for ( i = 0; i<SIZE; i+=TS) {
   UB = SIZE < (i+TS)?SIZE:i+TS;
   #pragma omp task private(ii) \
    firstprivate(i,UB) shared(S,A,B)
   for ( ii=i; ii<UB; ii++) {
      A[ii]=A[ii]*B[ii]*S;
   }
}
```

- Difficult to determine grain
  - → 1 single iteration → to fine
  - → whole loop → no parallelism
- Manually transform the code
  - → blocking techniques
- Improving programmability
  - → OpenMP taskloop

```
#pragma omp taskloop grainsize(TS)
for ( i = 0; i<SIZE; i+=1) {
   A[i]=A[i]*B[i]*S;
}
```

  - → Hiding the internal details
  - → Grain size ~ Tile size (TS) → but implementation decides exact grain size

The taskloop Construct

- Task generating construct: decompose a loop into chunks, create a task for each loop chunk

```
#pragma omp taskloop [clause[[,] clause]…]
{structured-for-loops}
```

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

- Where clause is one of:

Data Environment

→ shared(list)

→ private(list)

→ firstprivate(list)

→ lastprivate(list)

→ default(sh | *pr* | *fp* | none)

→ reduction(r-id: list)

→ in_reduction(r-id: list)

Chunks/Grain

→ grainsize(grain-size)

→ num_tasks(num-tasks)

Cutoff Strategies

→ if(scalar-expression)

→ final(scalar-expression)

→ mergeable

Scheduler (R/H)

→ untied

→ priority(priority-value)

Miscellaneous

→ collapse(n)

→ nogroup

→ allocate([allocator:] list)

Worksharing vs. taskloop constructs (1/2)

```fortran
subroutine worksharing
    integer :: x
    integer :: i
    integer, parameter :: T = 16
    integer, parameter :: N = 1024

    x = 0
!$omp parallel shared(x) num_threads(T)

!$omp do
    do i = 1,N
!$omp atomic
        x = x + 1
!$omp end atomic
    end do
!$omp end do

!$omp end parallel
    write (*,'(A,I0)') 'x = ', x
end subroutine
```

Result: x = 1024

```fortran
subroutine taskloop
    integer :: x
    integer :: i
    integer, parameter :: T = 16
    integer, parameter :: N = 1024

    x = 0
!$omp parallel shared(x) num_threads(T)

!$omp taskloop
    do i = 1,N
!$omp atomic
        x = x + 1
!$omp end atomic
    end do
!$omp end taskloop

!$omp end parallel
    write (*,'(A,I0)') 'x = ', x
end subroutine
```

Result: x = 16384

Worksharing vs. taskloop constructs (2/2)

```fortran
subroutine worksharing
    integer :: x
    integer :: i
    integer, parameter :: T = 16
    integer, parameter :: N = 1024

    x = 0
!$omp parallel shared(x) num_threads(T)

!$omp do
    do i = 1,N
!$omp atomic
        x = x + 1
!$omp end atomic
    end do
!$omp end do

!$omp end parallel
    write (*,'(A,I0)') 'x = ', x
end subroutine
```

Result: x = 1024

```fortran
subroutine taskloop
    integer :: x
    integer :: i
    integer, parameter :: T = 16
    integer, parameter :: N = 1024

    x = 0
!$omp parallel shared(x) num_threads(T)
!$omp single
!$omp taskloop
    do i = 1,N
!$omp atomic
        x = x + 1
!$omp end atomic
    end do
!$omp end taskloop
!$omp end single
!$omp end parallel
    write (*,'(A,I0)') 'x = ', x
end subroutine
```

Result: x = 1024

Taskloop decomposition approaches

- Clause: grainsize(grain-size)
  - → Chunks have at least grain-size iterations
  - → Chunks have maximum 2x grain-size iterations

```
int TS = 4 * 1024;
#pragma omp taskloop grainsize(TS)
for ( i = 0; i<SIZE; i+=1) {
   A[i]=A[i]*B[i]*S;
}
```

- Clause: num_tasks(num-tasks)
  - → Create num-tasks chunks
  - → Each chunk must have at least one iteration

```
int NT = 4 * omp_get_num_threads();
#pragma omp taskloop num_tasks(NT)
for ( i = 0; i<SIZE; i+=1) {
   A[i]=A[i]*B[i]*S;
}
```

- If none of previous clauses is present, the *number of chunks* and the *number of iterations per chunk* is implementation defined
- Additional considerations:
  - → The order of the creation of the loop tasks is unspecified
  - → Taskloop creates an implicit taskgroup region; **nogroup** → no implicit taskgroup region is created

Collapsing iteration spaces with taskloop

- The collapse clause in the taskloop construct

```
#pragma omp taskloop collapse(n)
{structured-for-loops}
```

  - → Number of loops associated with the taskloop construct (n)
  - → Loops are collapsed into one larger iteration space
  - → Then divided according to the **grainsize** and **num_tasks**
- Intervening code between any two associated loops
  - → at least once per iteration of the enclosing loop
  - → at most once per iteration of the innermost loop

```
#pragma omp taskloop collapse(2)
for ( i = 0; i<SX; i+=1) {
   for (  j= 0; i<SY; j+=1) {
      for ( k = 0; i<SZ; k+=1) {
         A[f(i,j,k)]=<expression>;
      }
   }
}
```

```
#pragma omp taskloop
for ( ij = 0; i<SX*SY; ij+=1) {
   for ( k = 0; i<SZ; k+=1) {
      i = index_for_i(ij);
      j = index_for_j(ij);
      A[f(i,j,k)]=<expression>;
   }
}
```

Task reductions (using taskloop)

- Clause: `reduction(r-id: list)`
  - → It defines the scope of a new reduction
  - → All created tasks participate in the reduction
  - → It cannot be used with the **`nogroup`** clause

```
double dotprod(int n, double *x, double *y) {
  double r = 0.0;
  #pragma omp taskloop reduction(+: r)
  for (i = 0; i < n; i++)
    r += x[i] * y[i];

  return r;
}
```

- Clause: `in_reduction(r-id: list)`
  - → Reuse an already defined reduction scope
  - → All created tasks participate in the reduction
  - → It can be used with the **`nogroup`*** clause, but it is user responsibility to guarantee result

```
double dotprod(int n, double *x, double *y) {
  double r = 0.0;
  #pragma omp taskgroup task_reduction(+: r)
  {
    #pragma omp taskloop in_reduction(+: r)*
    for (i = 0; i < n; i++)
      r += x[i] * y[i];
  }
  return r;
}
```

Composite construct: taskloop simd

- Task generating construct: decompose a loop into chunks, create a task for each loop chunk
- Each generated task will apply (internally) SIMD to each loop chunk

→ C/C++ syntax:

```
#pragma omp taskloop simd [clause[[,] clause]…]
{structured-for-loops}
```

→ Fortran syntax:

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

- Where clause is any of the clauses accepted by **taskloop** or **simd** directives

Improving Tasking Performance:
Task dependences

Motivation

- Task dependences as a way to define task-execution constraints

OpenMP 3.1

```
int x = 0;
#pragma omp parallel
#pragma omp single
{
🔵 #pragma omp task
   std::cout << x << std::endl;

   #pragma omp taskwait

🔴 #pragma omp task
   x++;
}
```

OpenMP 4.0

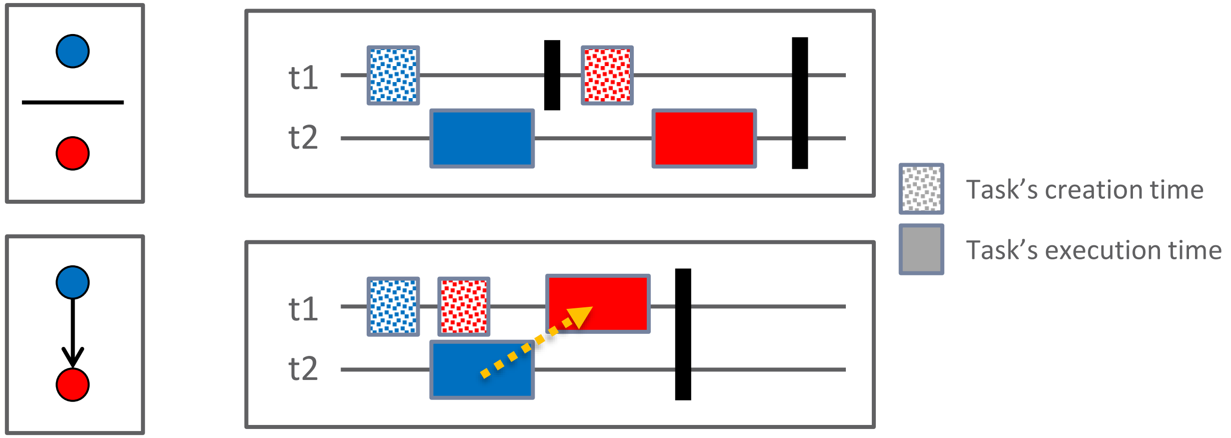
```
int x = 0;
#pragma omp parallel
#pragma omp single
{
🔵 #pragma omp task depend(in: x)
   std::cout << x << std::endl;



🔴 #pragma omp task depend(inout: x)
   x++;
}
```

OpenMP 3.1

OpenMP 4.0



Motivation

- Task dependences as a way to define task-execution constraints

OpenMP 3.1

```
int x = 0;
#pragma omp parallel
#pragma omp single
{
● #pragma omp task
  std::cout << x << std

  #pragma omp taskwait

● #pragma omp task
  x++;
}
```

OpenMP 4.0

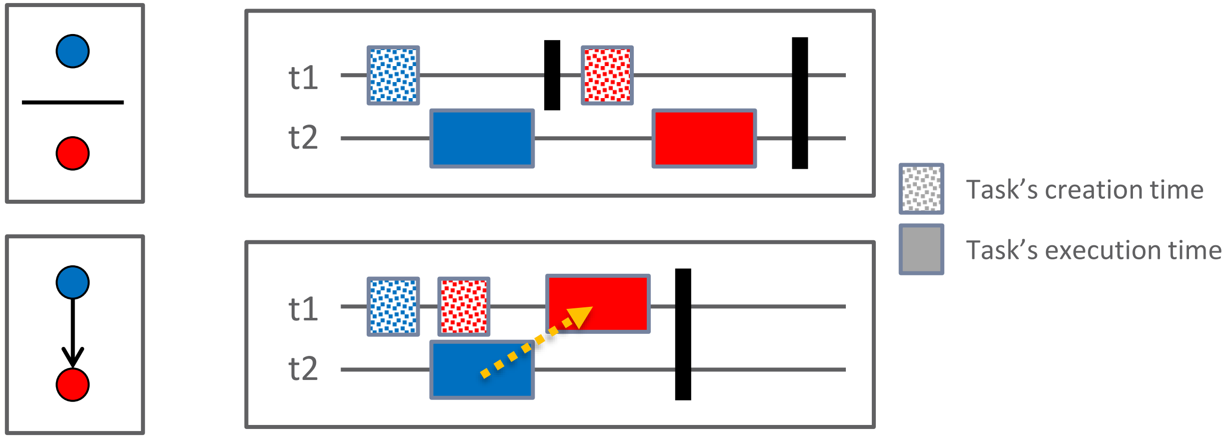
```
int x = 0;
#pragma omp parallel
#pragma omp single
{
● #pragma omp task depend(in: x)
                                    d::endl;

                                    end(inout: x)
  x++;
}
```

Task dependences can help us to remove “strong” synchronizations, increasing the look ahead and, frequently, the parallelism!!!!

OpenMP 3.1

OpenMP 4.0

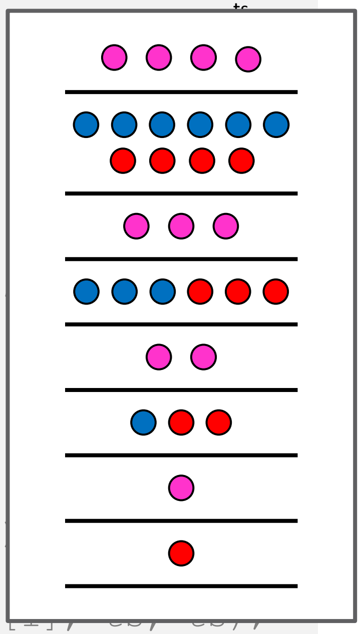


Motivation: Cholesky factorization

```
void cholesky(int ts, int nt, double* a[nt][nt]) {
  for (int k = 0; k < nt; k++) {
    // Diagonal Block factorization
    potrf(a[k][k], ts, ts);

    // Triangular systems
    for (int i = k + 1; i < nt; i++)
      #pragma omp task
    ● trsm(a[k][k], a[k][i], ts, ts)
    }
    #pragma omp taskwait

    // Update trailing matrix
    for (int i = k + 1; i < nt; i++)
      for (int j = k + 1; j < i; j++)
        #pragma omp task
      ● dgemm(a[k][i], a[k][j], a[j][i], ts, ts);
      }
      #pragma omp task
    ● syrk(a[k][i], a[i][i], ts, ts);
    }
    #pragma omp taskwait
  }
}
```

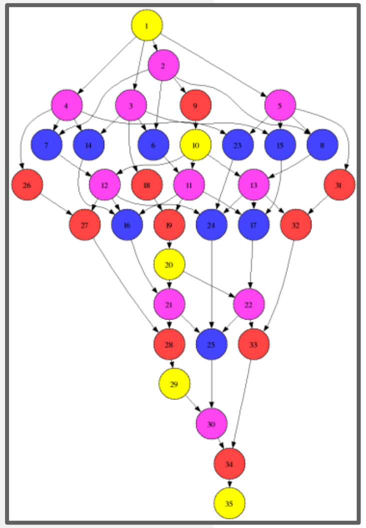


OpenMP 3.1

```
void cholesky(int ts, int nt, double* a[nt][nt]) {
  for (int k = 0; k < nt; k++) {
    // Diagonal Block factorization
    #pragma omp task depend(inout: a[k][k])
  ● potrf(a[k][k], ts, ts);

    // Triangular systems
    for (int i = k + 1; i < nt; i++) {
      #pragma omp task depend(in: a[k][k])
                  depend(inout: a[k][i])
    ● trsm(a[k][k], a[k][i], ts, ts);
    }

    // Update trailing matrix
    for (int i = k + 1; i < nt; i++) {
      for (int j = k + 1; j < i; j++) {
        #pragma omp task depend(inout: a[j][i])
                    depend(in: a[k][i], a[k][j])
      ● dgemm(a[k][i], a[k][j], a[j][i], ts, ts);
      }
      #pragma omp task depend(inout: a[i][i])
                   depend(in: a[k][i])
    ● syrk(a[k][i], a[i][i], ts, ts);
    }
  }
}
```



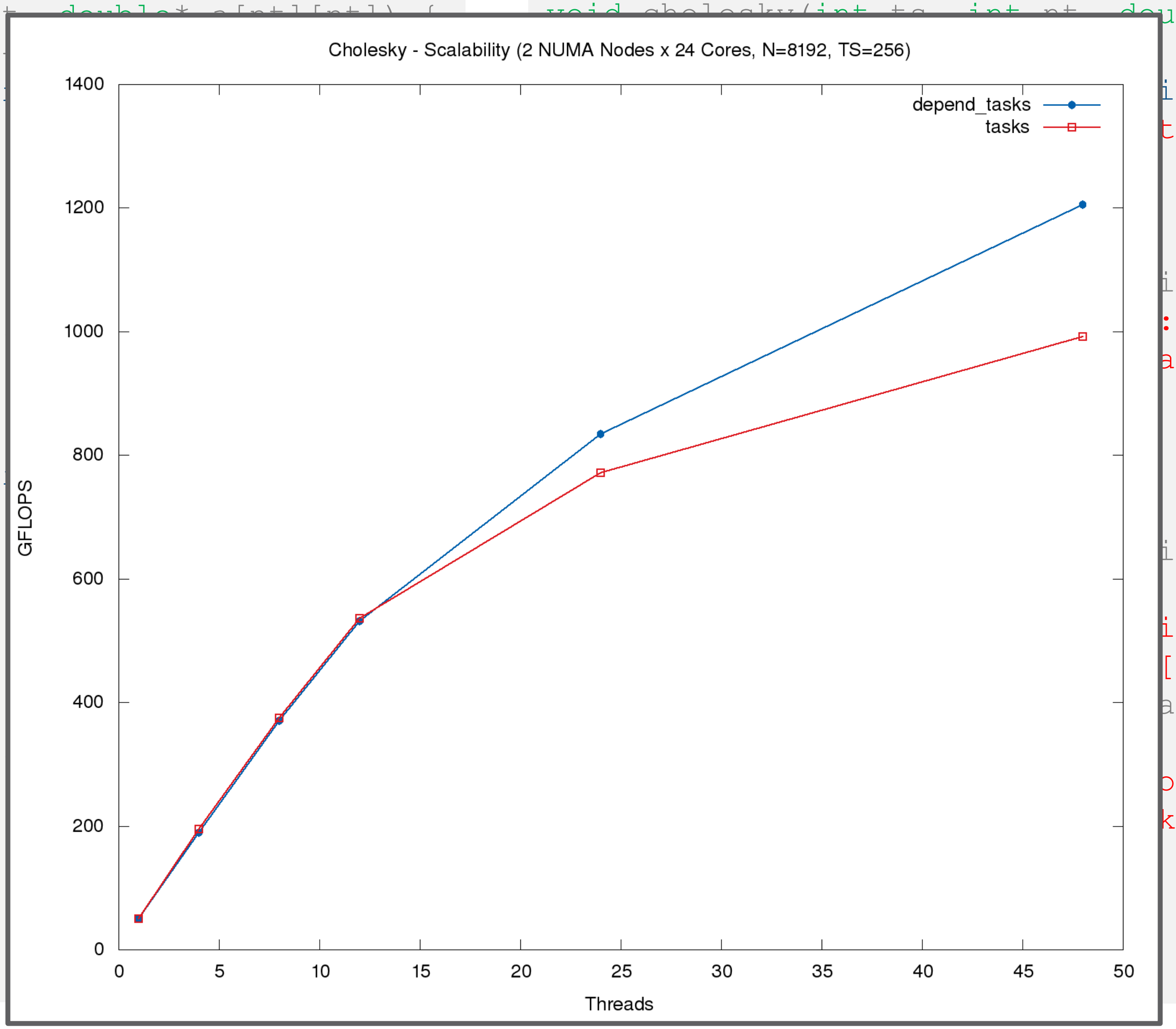
OpenMP 4.0

Motivation: Cholesky factorization

```
void cholesky(int ts, int nt, double* a[nt][nt]) {
  for (int k = 0; k < nt; k
    // Diagonal Block facto
    potrf(a[k][k], ts, ts);

    // Triangular systems
    for (int i = k + 1; i <
      #pragma omp task
   ●  trsm(a[k][k], a[k][i]
    }
    #pragma omp taskwait

    // Update trailing matr
    for (int i = k + 1; i <
      for (int j = k + 1; j
        #pragma omp task
     ●  dgemm(a[k][i], a[k]
      }
      #pragma omp task
    ● syrk(a[k][i], a[i][i]
    }
    #pragma omp taskwait
  }
}
```

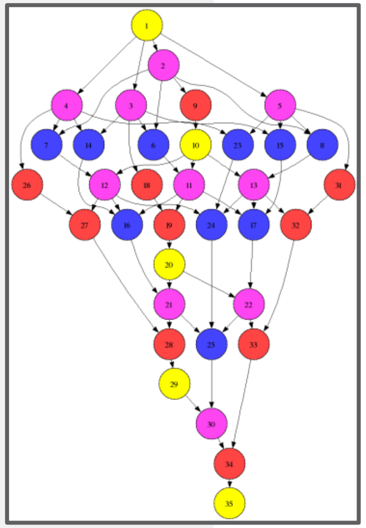


```
void cholesky(int ts, int nt, double* a[nt][nt]) {
                                    ion
                                    t: a[k][k])

                                    i++) {
                                    : a[k][k])
                                    a[k][i])
                                     ts);

                                    i++) {
                                     j++) {
                                    inout: a[j][i])
                                    [k][i], a[k][j])
                                    a[j][i], ts, ts);

                                    out: a[i][i])
                                    k][i])
                                     ts);
```



OpenMP 4.0

Using 2017 Intel compiler

What’s in the spec

What’s in the spec: a bit of history

OpenMP 4.0

- The `depend` clause was added to the `task` construct

OpenMP 4.5

- The `depend` clause was added to the target constructs
- Support to doacross loops

OpenMP 5.0

- `lvalue` expressions in the depend clause
- New dependency type: `mutexinoutset`
- Iterators were added to the `depend` clause
- The `depend` clause was added to the `taskwait` construct
- Dependable objects

What’s in the spec: syntax depend clause

```
depend([depend-modifier,] dependency-type: list-items)
```

where:

- → `depend-modifier` is used to define iterators
- → `dependency-type` may be: `in`, `out`, `inout`, `mutexinoutset` and `depobj`
- → A `list-item` may be:
  - C/C++: A `lvalue` expr or an array section `depend(in: x, v[i], *p, w[10:10])`
  - Fortran: A variable or an array section `depend(in: x, v(i), w(10:20))`

What's in the spec: sema `depend` clause (1)

- A task cannot be executed until all its predecessor tasks are completed

- If a task defines an `in` dependence over a list-item
  - → the task will depend on all previously generated sibling tasks that reference that list-item in an `out` or `inout` dependence

- If a task defines an `out`/`inout` dependence over list-item
  - → the task will depend on all previously generated sibling tasks that reference that list-item in an `in`, `out` or `inout` dependence

What’s in the spec: depend clause (1)

- A task cannot be executed until all its predecessor tasks are completed

- If a task defir
  - → the task will c ne of the list items in an out or in

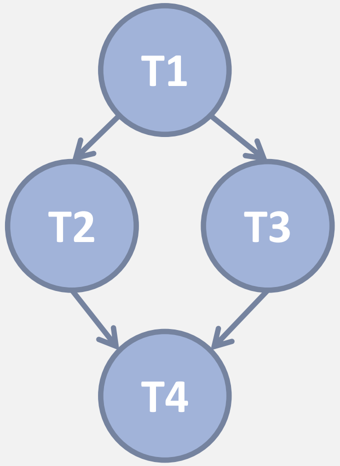
- If a task defir
  - → the task will c ne of the list items in an in, out c

```
int x = 0;
#pragma omp parallel
#pragma omp single
{
  #pragma omp task depend(inout: x) //T1
  { ... }

  #pragma omp task depend(in: x)    //T2
  { ... }

  #pragma omp task depend(in: x)    //T3
  { ... }

  #pragma omp task depend(inout: x) //T4
  { ... }
}
```



What’s in the spec: depend clause (2)

- New dependency type: `mutexinoutset`

```
int x = 0, y = 0, res = 0;
#pragma omp parallel
#pragma omp single
{
  #pragma omp task depend(out: res)  //T0
   res = 0;

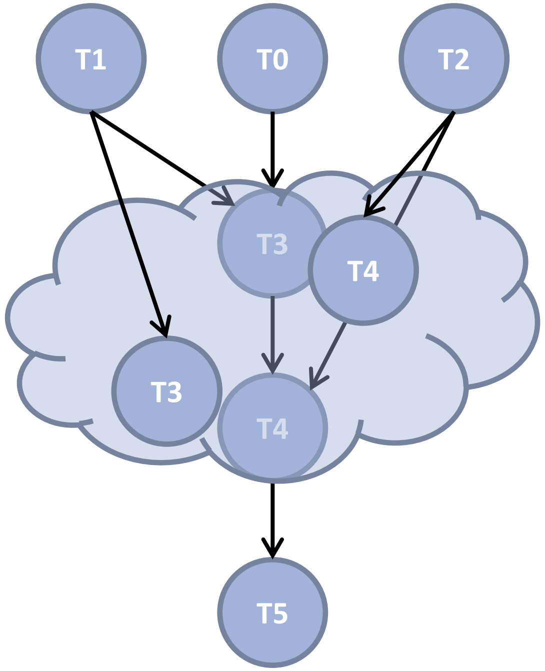
  #pragma omp task depend(out: x)  //T1
  long_computation(x);

  #pragma omp task depend(out: y)  //T2
  short_computation(y);

  #pragma omp task depend(in: x) depend(mutexinoutset: res)  //T3
  res += x;

  #pragma omp task depend(in: y) depend(mutexinoutset: res)  //T4
  res += y;

  #pragma omp task depend(in: res)  //T5
  std::cout << res << std::endl;
}
```



1. *inoutset property*: tasks with a `mutexinoutset` dependence create a cloud of tasks (an inout set) that synchronizes with previous & posterior tasks that dependent on the same list item

2. *mutex property*: Tasks inside the inout set can be executed in any order but with mutual exclusion

What’s in the spec: depend clause (4)

- Task dependences are defined among **sibling tasks**

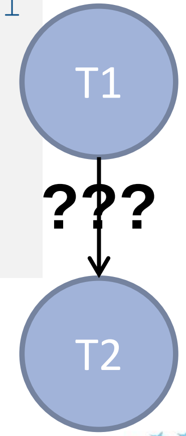
- List items used in the depend clauses […] must indicate **identical** or **disjoint storage**

```
//test1.cc
int x = 0;
#pragma omp parallel
#pragma omp single
{
  #pragma omp task depend(inout: x)    //T1
  {
    #pragma omp task depend(inout: x) //T1.1
    x++;

    #pragma omp taskwait
  }
  #pragma omp task depend(in: x) //T2
  std::cout << x << std::endl;
}
```

```
//test2.cc
int a[100] = {0};
#pragma omp parallel
#pragma omp single
{
  #pragma omp task depend(inout: a[50:99]) //T1
  compute(/* from */ &a[50], /*elems*/ 50);

  #pragma omp task depend(in: a)    //T2
  print(/* from */ a, /* elem */ 100);
}
```



What’s in the spec: depend clause (5)

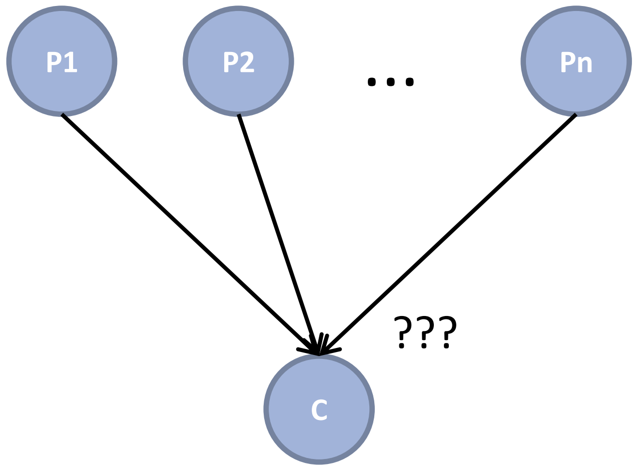
- Iterators + deps: a way to define a dynamic number of dependences

```
std::list<int> list = ...;
int n = list.size();

#pragma omp parallel
#pragma omp single
{
  for (int i = 0; i < n; ++i)
    #pragma omp task depend(out: list[i])     //Px
     compute_elem(list[i]);

  #pragma omp task depend(iterator(j=0:n), in : list[j]) //C
  print_elems(list);
}
```

It seems innocent but it’s not:
`depend(out: list.operator[](i))`



Equivalent to:
`depend(in: list[0], list[1], …, list[n-1])`

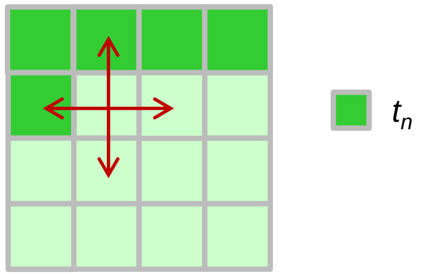
Use case

Use case: intro to Gauss-seidel

```
void serial_gauss_seidel(int tsteps, int size, int (*p)[size]) {
  for (int t = 0; t < tsteps; ++t) {
    for (int i = 1; i < size-1; ++i) {
      for (int j = 1; j < size-1; ++j) {
        p[i][j] = 0.25 * (p[i][j-1] + // left
                          p[i][j+1] + // right
                          p[i-1][j] + // top
                          p[i+1][j]); // bottom
      }
    }
  }
}
```

Access pattern analysis

For a specific t, i and j



Each cell depends on:

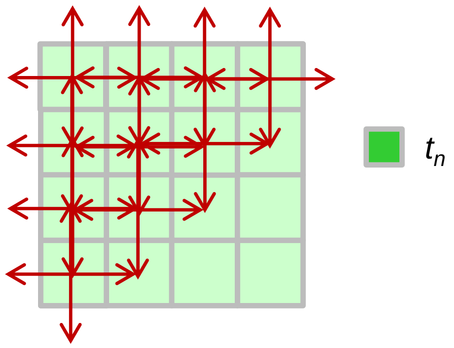
- two cells (north & west) that are computed in the current time step, and
- two cells (south & east) that were computed in the previous time step

Use case: Gauss-seidel (2)

```
void serial_gauss_seidel(int tsteps, int size, int (*p)[size]) {
  for (int t = 0; t < tsteps; ++t) {
    for (int i = 1; i < size-1; ++i) {
      for (int j = 1; j < size-1; ++j) {
        p[i][j] = 0.25 * (p[i][j-1] + // left
                          p[i][j+1] + // right
                          p[i-1][j] + // top
                          p[i+1][j]); // bottom
      }
    }
  }
}
```

1st parallelization strategy

For an specific t



We can exploit the wavefront to obtain parallelism!!

Use case : Gauss-seidel (3)

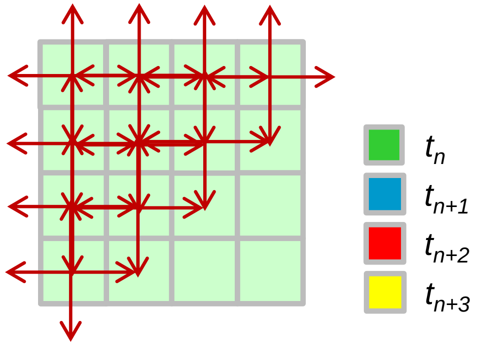
```
void gauss_seidel(int tsteps, int size, int TS, int (*p)[size]) {
  int NB = size / TS;
  #pragma omp parallel
  for (int t = 0; t < tsteps; ++t) {
    // First NB diagonals
    for (int diag = 0; diag < NB; ++diag) {
      #pragma omp for
      for (int d = 0; d <= diag; ++d) {
        int ii = d;
        int jj = diag - d;
        for (int i = 1+ii*TS; i < ((ii+1)*TS); ++i)
          for (int j = 1+jj*TS; i < ((jj+1)*TS); ++j)
             p[i][j] = 0.25 * (p[i][j-1] + p[i][j+1] +
                               p[i-1][j] + p[i+1][j]);
      }
    }
    // Lasts NB diagonals
    for (int diag = NB-1; diag >= 0; --diag) {
      // Similar code to the previous loop
    }
  }
}
```

Use case : Gauss-seidel (4)

```
void serial_gauss_seidel(int tsteps, int size, int (*p)[size]) {
  for (int t = 0; t < tsteps; ++t) {
    for (int i = 1; i < size-1; ++i) {
      for (int j = 1; j < size-1; ++j) {
        p[i][j] = 0.25 * (p[i][j-1] + // left
                          p[i][j+1] + // right
                          p[i-1][j] + // top
                          p[i+1][j]); // bottom
      }
    }
  }
}
```

2nd parallelization strategy

multiple time iterations



We can exploit the wavefront
of multiple time steps to obtain MORE
parallelism!!

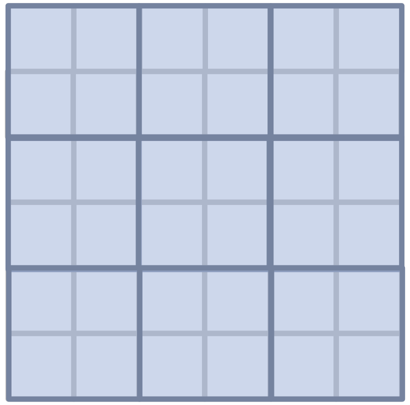
Use case : Gauss-seidel (5)

```
void gauss_seidel(int tsteps, int size, int TS, int (*p)[size]) {
  int NB = size / TS;

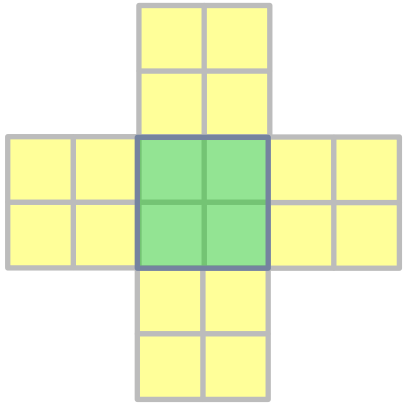
  #pragma omp parallel
  #pragma omp single
  for (int t = 0; t < tsteps; ++t)
    for (int ii=1; ii < size-1; ii+=TS)
      for (int jj=1; jj < size-1; jj+=TS) {
        #pragma omp task depend(inout: p[ii:TS][jj:TS])
            depend(in: p[ii-TS:TS][jj:TS], p[ii+TS:TS][jj:TS],
                        p[ii:TS][jj-TS:TS], p[ii:TS][jj+TS:TS])

        {
          for (int i=ii; i<(1+ii)*TS; ++i)
            for (int j=jj; j<(1+jj)*TS; ++j)
               p[i][j] = 0.25 * (p[i][j-1] + p[i][j+1] +
                                 p[i-1][j] + p[i+1][j]);
        }
      }
}
```

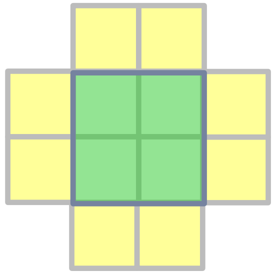
inner matrix region



Q: Why do the input dependences depend on the whole block rather than just a column/row?



vs



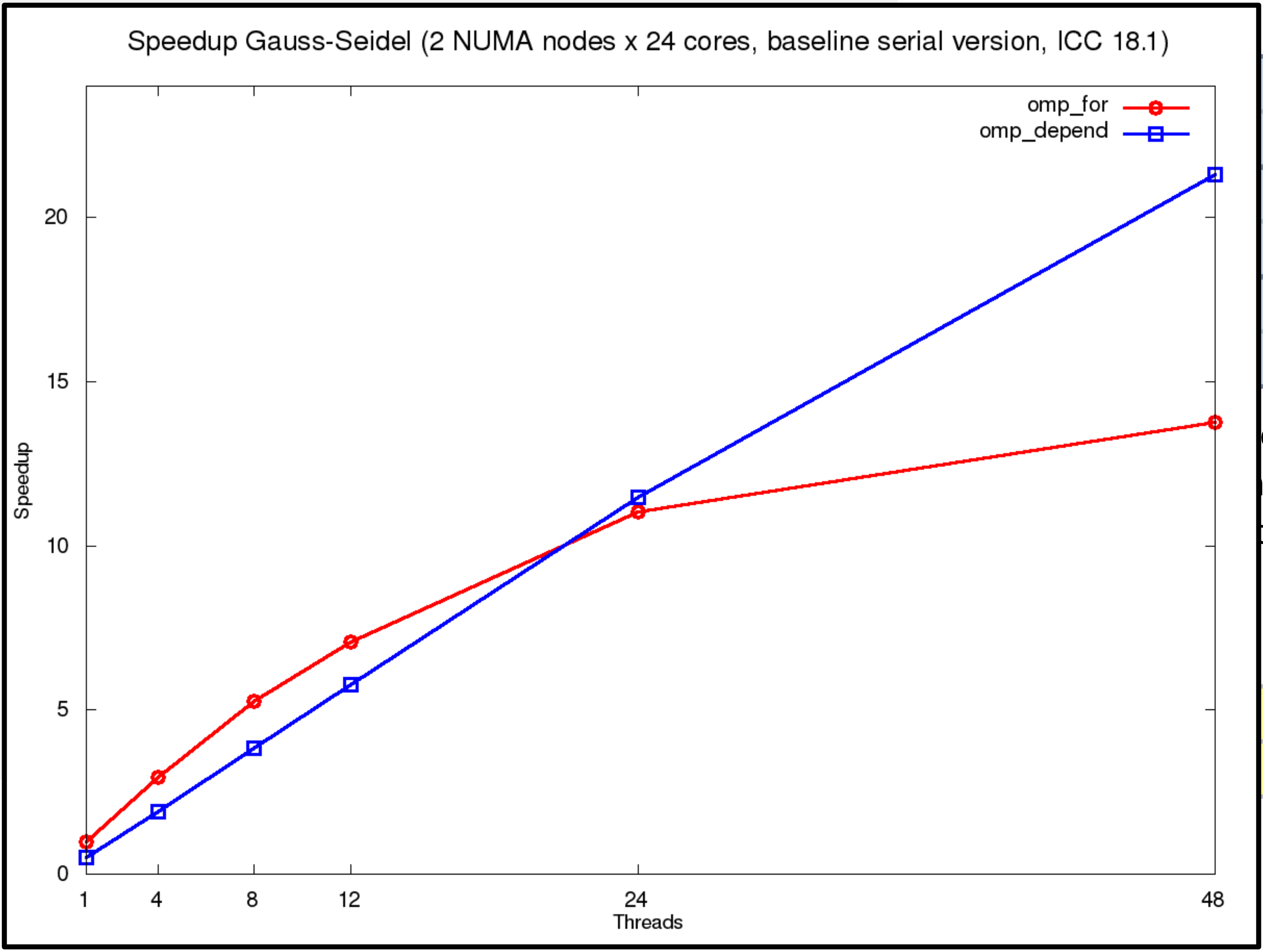
Use case : Gauss-seidel (5)

```
void gauss_seidel(i
  int NB = size / T

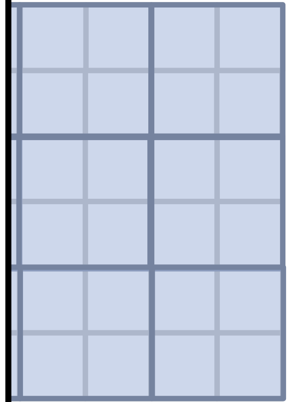
  #pragma omp paral
  #pragma omp singl
  for (int t = 0; t
    for (int ii=1;
      for (int jj=1
        #pragma omp
              depend(

        {
          for (int
            for (in
               p[i]

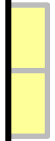
        }
      }
}
```



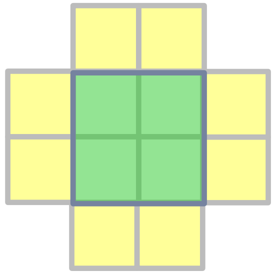
matrix region



e input dependences
e whole block rather
t a column/row?



vs



Improving Tasking Performance: Cutoff clauses and strategies

Example: Sudoku revisited

Parallel Brute-force Sudoku

- This parallel algorithm finds all valid solutions

	6						8	11			15	14			16
15	11				16	14				12			6		
13		9	12					3	16	14		15	11	10	
2		16		11		15	10	1							
	15	11	10			16	2	13	8	9	12				
12	13			4	1	5	6	2	3					11	10
5		6	1	12		9		15	11	10	7	16			3
	2				10		11	6		5			13		9
10	7	15	11	16				12	13						6
9						1			2		16	10			11
1		4	6	9	13			7		11		3	16		
16	14			7		10	15	4	6	1				13	8
11	10		15				16	9	12	13			1	5	4
		12		1	4	6		16				11	10		
		5		8	12	13		10			11	2			14
3	16			10			7			6				12	

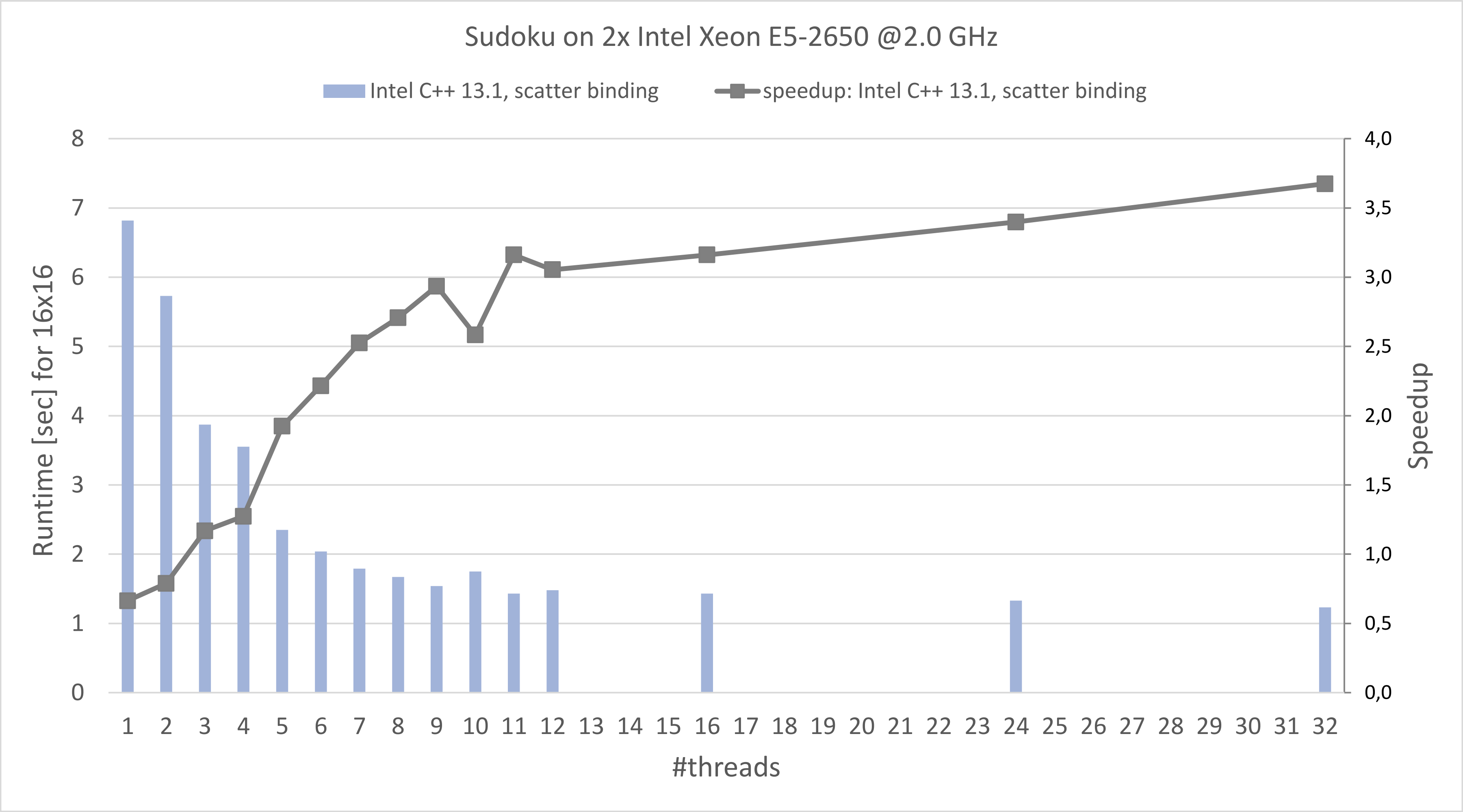
- (1) Search an empty field
- (2) Try all numbers:
  - (2 a) Check Sudoku
    - If invalid: skip
    - If valid: Go to next field
- Wait for completion

first call contained in a
`#pragma omp parallel`
`#pragma omp single`
such that one tasks starts the execution of the algorithm

`#pragma omp task`
needs to work on a new copy of the Sudoku board

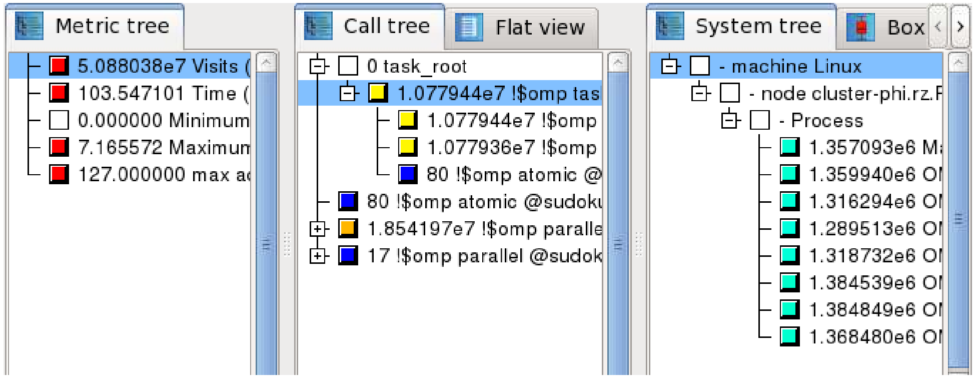
`#pragma omp taskwait`
wait for all child tasks

Performance Evaluation



Performance Analysis

Event-based profiling provides a good overview :



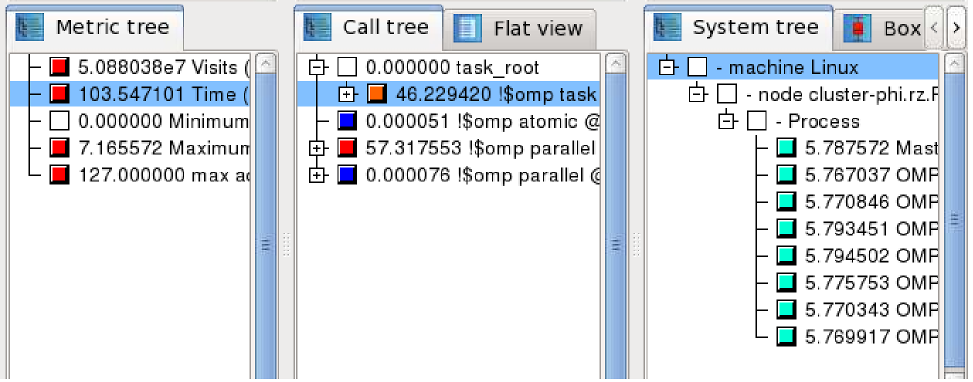
Metric tree | Call tree | Flat view | System tree | Box

5.088038e7 Visits (
103.547101 Time (
0.000000 Minimum
7.165572 Maximum
127.000000 max ac

0 task_root
1.077944e7 !$omp tas
1.077944e7 !$omp
1.077936e7 !$omp
80 !$omp atomic @
80 !$omp atomic @sudoku
1.854197e7 !$omp paralle
17 !$omp parallel @sudok

- machine Linux
- node cluster-phi.rz.R
- Process
1.357093e6 Ma
1.359940e6 OI
1.316294e6 OI
1.289513e6 OI
1.318732e6 OI
1.384539e6 OI
1.384849e6 OI
1.368480e6 OI

Every thread is executing ~1.3m tasks…



Metric tree | Call tree | Flat view | System tree | Box

5.088038e7 Visits (
103.547101 Time (
0.000000 Minimum
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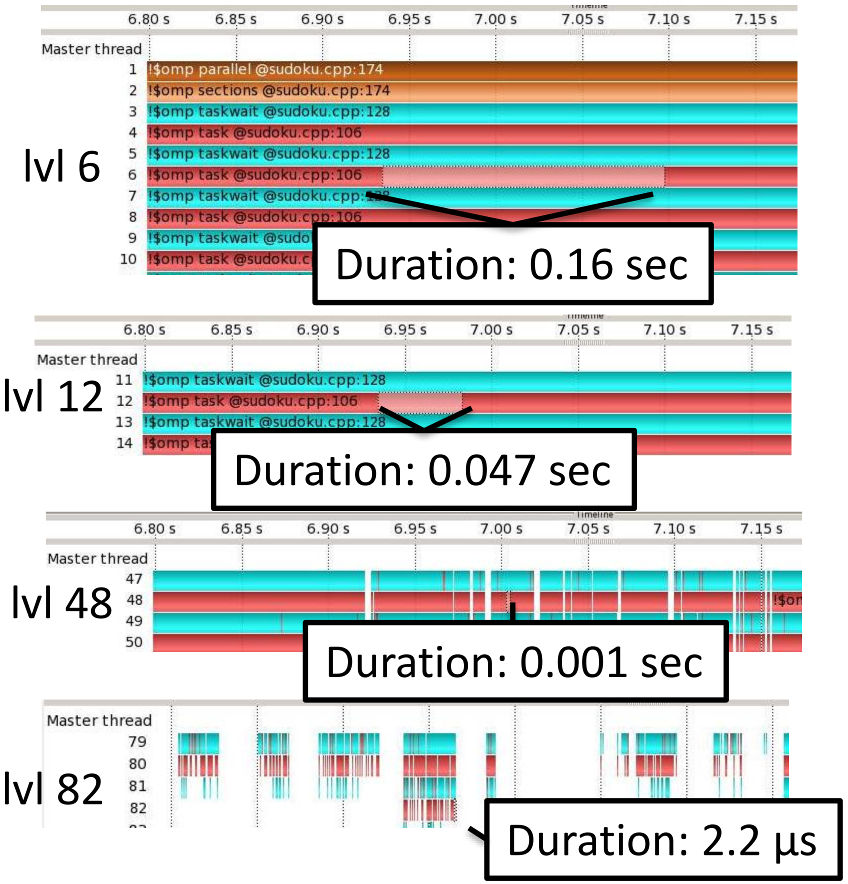
0.000000 task_root
46.229420 !$omp task
0.000051 !$omp atomic @
57.317553 !$omp parallel
0.000076 !$omp parallel @

- machine Linux
- node cluster-phi.rz.R
- Process
5.787572 Mast
5.767037 OMP
5.770846 OMP
5.793451 OMP
5.794502 OMP
5.775753 OMP
5.770343 OMP
5.769917 OMP

… in ~5.7 seconds.
=> average duration of a task is ~4.4 μs

Tracing provides more details:

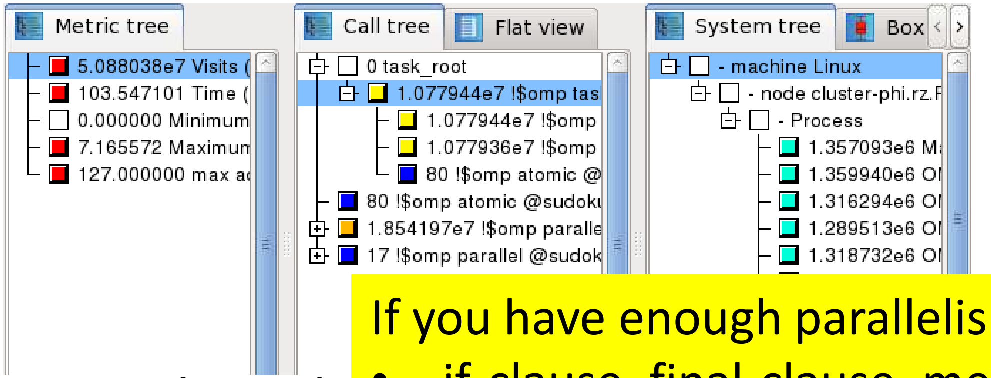


6.80 s
6.85 s
6.90 s
6.95 s
7.00 s
7.05 s
7.10 s
7.15 s
Master thread
lvl 6
1 !$omp parallel @sudoku.cpp:174
2 !$omp sections @sudoku.cpp:174
3 !$omp taskwait @sudoku.cpp:128
4 !$omp task @sudoku.cpp:106
5 !$omp taskwait @sudoku.cpp:128
6 !$omp task @sudoku.cpp:106
7 !$omp taskwait @sudoku.cpp:128
8 !$omp task @sudoku.cpp:106
9 !$omp taskwait @sudo
10 !$omp task @sudoku.c
Duration: 0.16 sec
lvl 12
11 !$omp taskwait @sudoku.cpp:128
12 !$omp task @sudoku.cpp:106
13 !$omp taskwait @sudoku.cpp:128
14 !$omp ta
Duration: 0.047 sec
lvl 48
47
48
49
50
Duration: 0.001 sec
lvl 82
79
80
81
82
Duration: 2.2 μs

Tasks get much smaller down the call-stack.

Performance Analysis

Event-based profiling provides a good overview :



Metric tree | Call tree | Flat view | System tree | Box

- 5.088038e7 Visits (
- 103.547101 Time (
- 0.000000 Minimum
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- 127.000000 max ac

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  1.077944e7 !$omp tas
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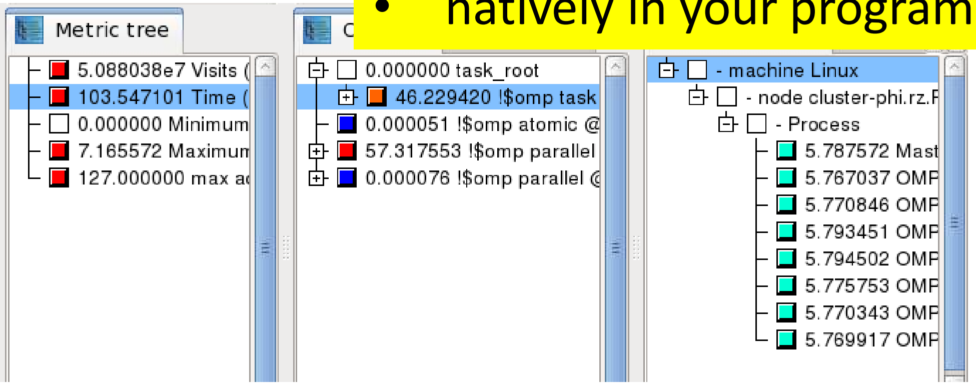
```

```
- machine Linux
  - node cluster-phi.rz.R
    - Process
      1.357093e6 Ma
      1.359940e6 OI
      1.316294e6 OI
      1.289513e6 OI
      1.318732e6 OI
```

Every thread i



Metric tree | C

- 5.088038e7 Visits (
- 103.547101 Time (
- 0.000000 Minimum
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```
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  46.229420 !$omp task
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  57.317553 !$omp parallel
  0.000076 !$omp parallel @
```

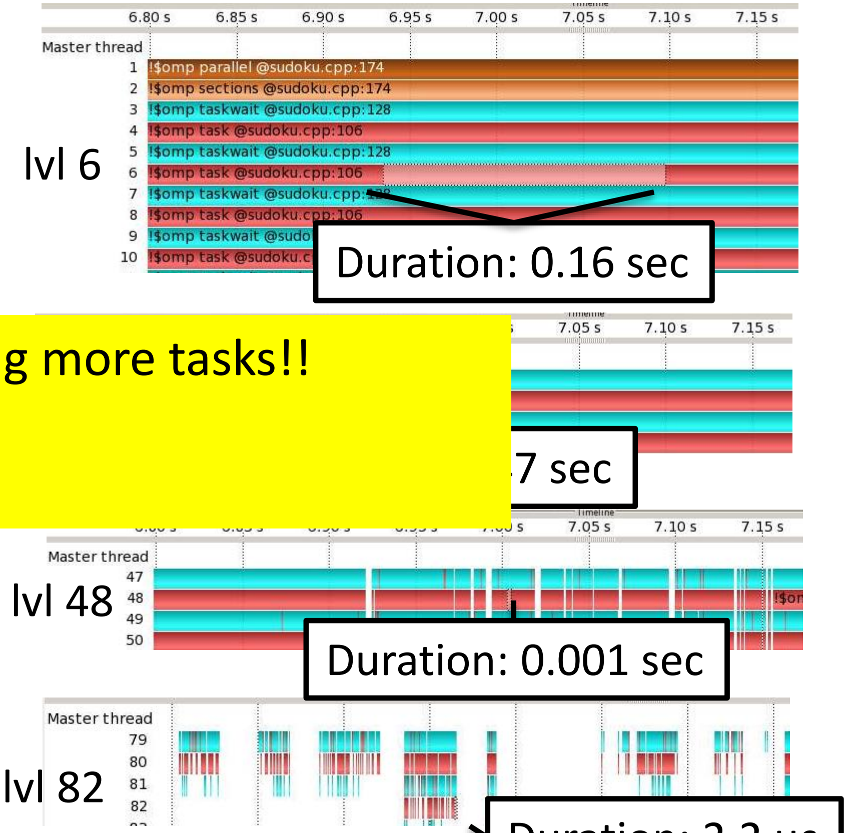
```
- machine Linux
  - node cluster-phi.rz.R
    - Process
      5.787572 Mast
      5.767037 OMP
      5.770846 OMP
      5.793451 OMP
      5.794502 OMP
      5.775753 OMP
      5.770343 OMP
      5.769917 OMP
```

… in ~5.7 seconds.
=> average duration of a task is ~4.4 µs

If you have enough parallelism, stop creating more tasks!!

- if-clause, final-clause, mergeable-clause
- natively in your program code

Tracing provides more details: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lvl 48
47
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49
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!$om
lvl 82
79
80
81
82

Duration: 0.16 sec

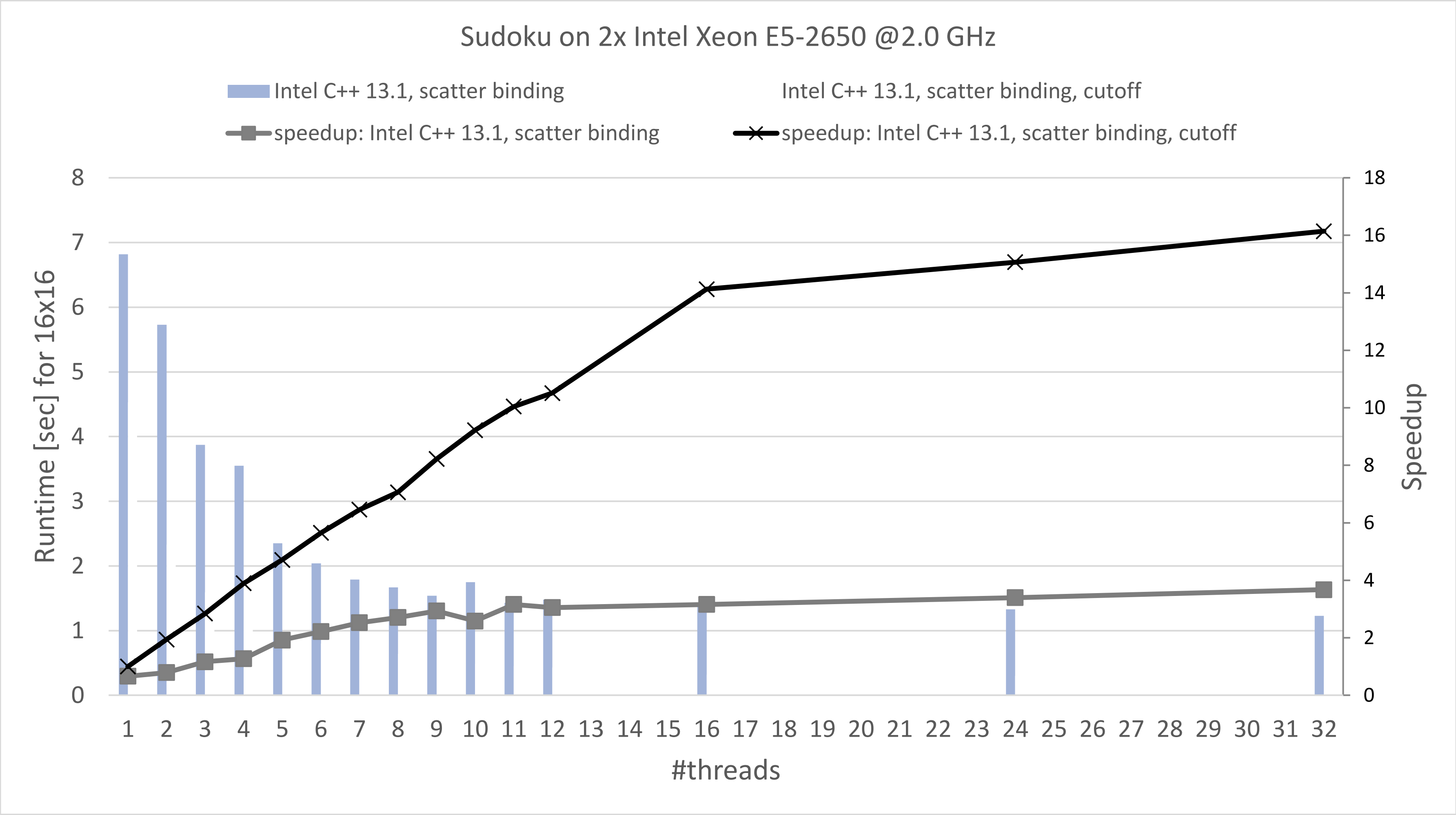
7 sec

Duration: 0.001 sec

Duration: 2.2 µs

Tasks get much smaller down the call-stack.

Performance Evaluation (with cutoff)



The `if` clause

- Rule of thumb: the `if(expression)` clause as a “switch off” mechanism
  - → Allows lightweight implementations of task creation and execution but it reduces the parallelism

- If the `expression` of the `if` clause evaluates to `false`
  - → the encountering task is suspended
  - → the new task is executed immediately (task dependences are respected!!)
  - → the encountering task resumes its execution once the new task is completed
  - → This is known as *undeferred task*

```
int foo(int x) {
  printf(“entering foo function\n”);
  int res = 0;
  #pragma omp task shared(res) if(false)
  {
        res += x;
  }
  printf(“leaving foo function\n”);
}
```

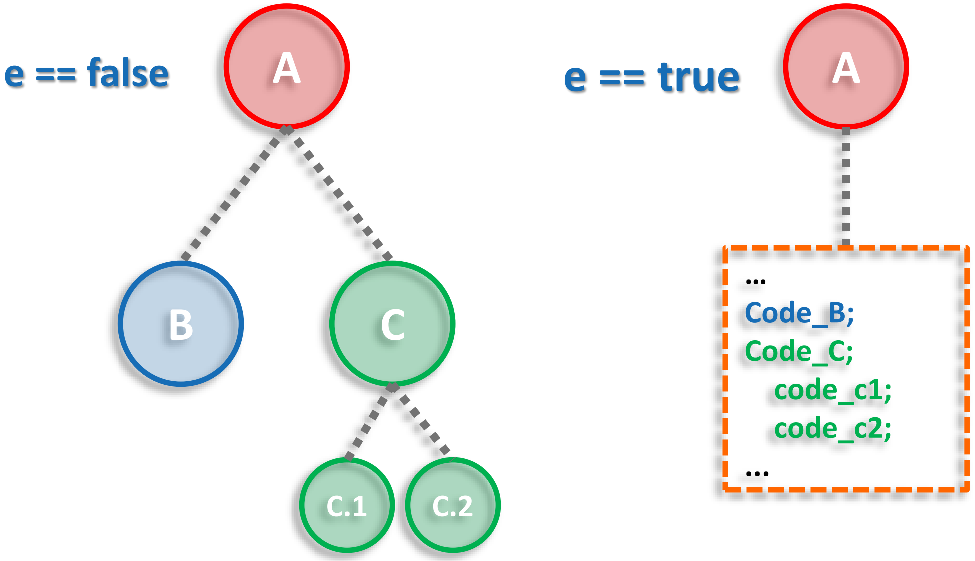
Really useful to debug tasking applications!

- Even if the `expression` is `false`, data-sharing clauses are honored

The `final` clause

- The `final(expression)` clause
  - → Nested tasks / recursive applications
  - → allows to avoid future task creation → reduces overhead but also reduces parallelism
- If the `expression` of the `final` clause evaluates to `true`
  - → The new task is created and executed normally but in its context all tasks will be executed immediately by the same thread (*included tasks*)

```
#pragma omp task final(e)
{
  #pragma omp task
  { … }
  #pragma omp task
  { … #C.1; #C.2 … }
  #pragma omp taskwait
}
```



- Data-sharing clauses are honored too!

The `mergeable` clause

- The `mergeable` clause
  - → Optimization: get rid of “data-sharing clauses are honored”
  - → This optimization can only be applied in *undeferred* or *included tasks*
- A Task that is annotated with the `mergeable` clause is called a *mergeable task*
  - → A task that may be a *merged task* if it is an *undeferred task* or an *included task*
- A *merged task* is:
  - → A task for which the data environment (inclusive of ICVs) may be the same as that of its generating task region
- A good implementation could execute a merged task without adding any OpenMP-related overhead

Unfortunately, there are no OpenMP commercial implementations taking advantage of `final` neither `mergeable` =(

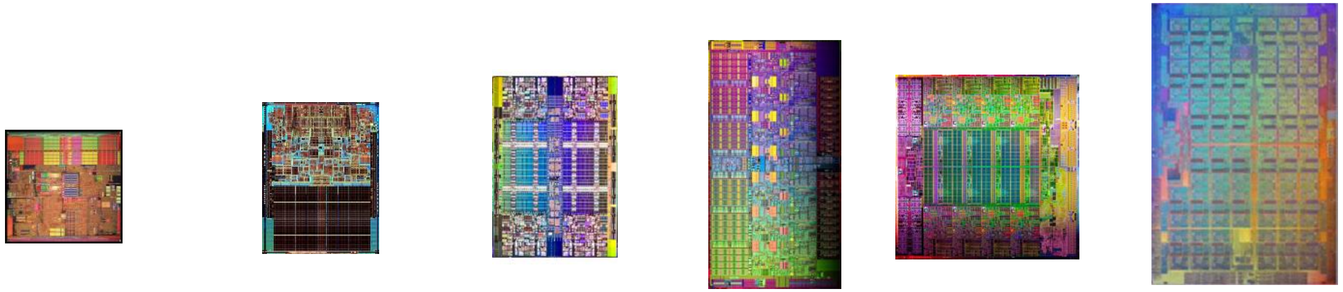
Programming OpenMP

Vectorization with OpenMP SIMD

Christian Terboven

Michael Klemm

Evolution of Intel Hardware



Images not intended to reflect actual die sizes

	64-bit Intel® Xeon® processor	Intel® Xeon® processor 5100 series	Intel® Xeon® processor 5500 series	Intel® Xeon® processor 5600 series	Intel® Xeon® processor E5-2600v3 series	Intel® Xeon® Scalable Processor
Frequency	3.6 GHz	3.0 GHz	3.2 GHz	3.3 GHz	2.3 GHz	2.5 GHz
Core(s)	1	2	4	6	18	28
Thread(s)	2	2	8	12	36	56
SIMD width	128 (2 clock)	128 (1 clock)	128 (1 clock)	128 (1 clock)	256 (1 clock)	512 (1 clock)

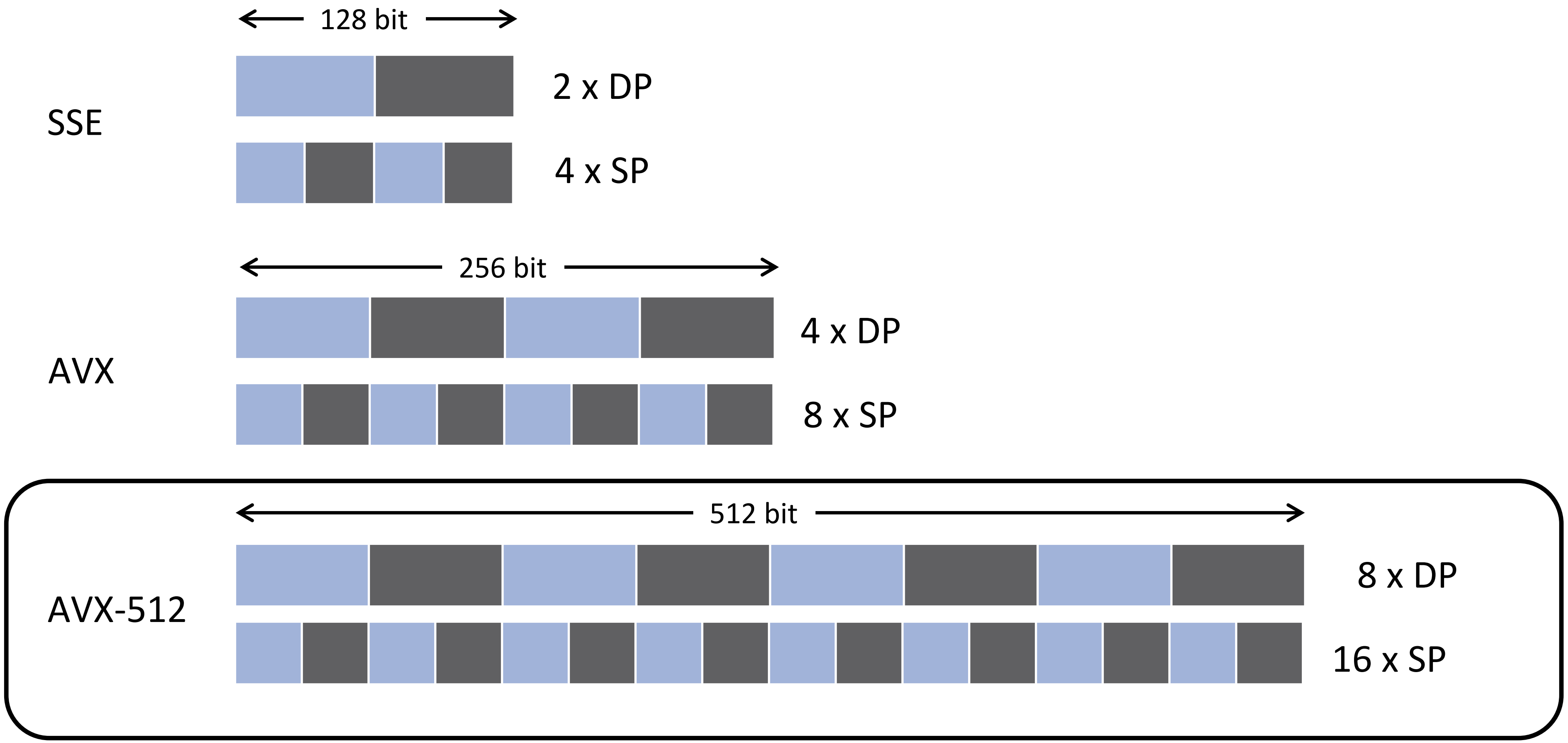
Levels of Parallelism

- OpenMP already supports several levels of parallelism in today’s hardware

Cluster	🟥	Group of computers communicating through fast interconnect
Coprocessors/Accelerators	🟩	Special compute devices attached to the local node through special interconnect
Node	🟩	Group of processors communicating through shared memory
Socket	🟩	Group of cores communicating through shared cache
Core	🟩	Group of functional units communicating through registers
Hyper-Threads	🟩	Group of thread contexts sharing functional units
Superscalar	🟨	Group of instructions sharing functional units
Pipeline	🟨	Sequence of instructions sharing functional units
Vector	🟩	Single instruction using multiple functional units

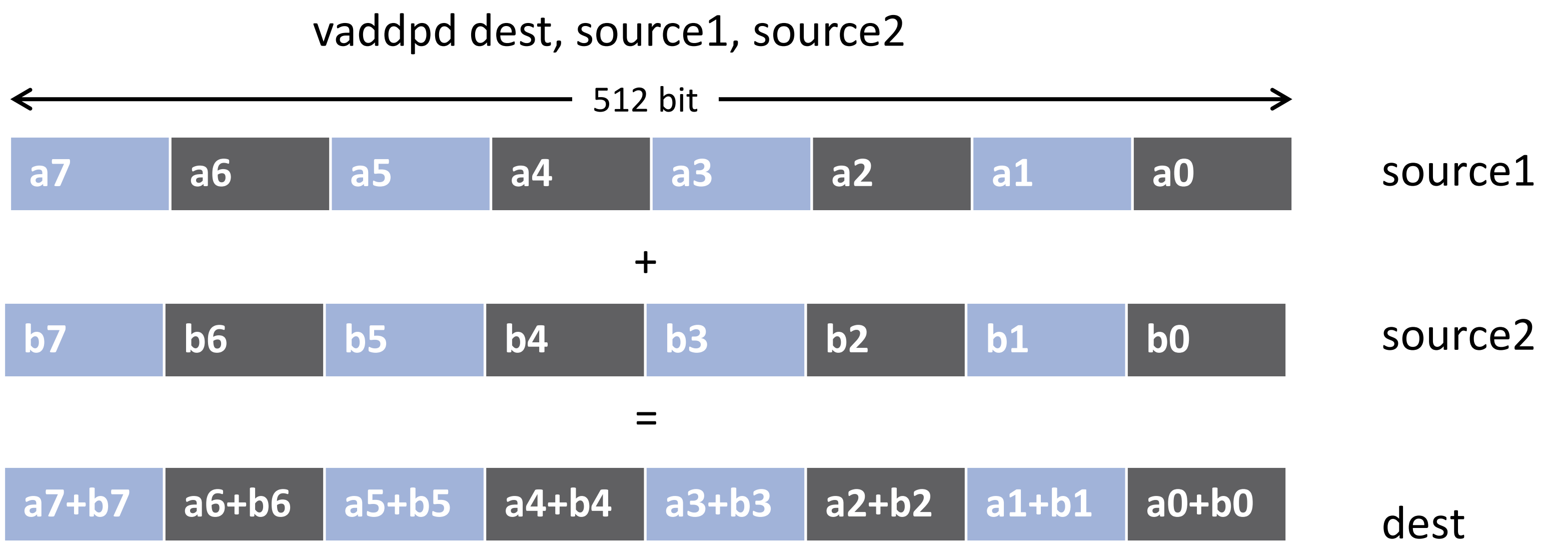
SIMD on Intel® Architecture

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



More Powerful SIMD Units

- SIMD instructions become more powerful
- One example is the Intel® Xeon Phi™ Coprocessor



vaddpd dest, source1, source2

512 bit

a7	a6	a5	a4	a3	a2	a1	a0	source1
				+				
b7	b6	b5	b4	b3	b2	b1	b0	source2
				=				
a7+b7	a6+b6	a5+b5	a4+b4	a3+b3	a2+b2	a1+b1	a0+b0	dest

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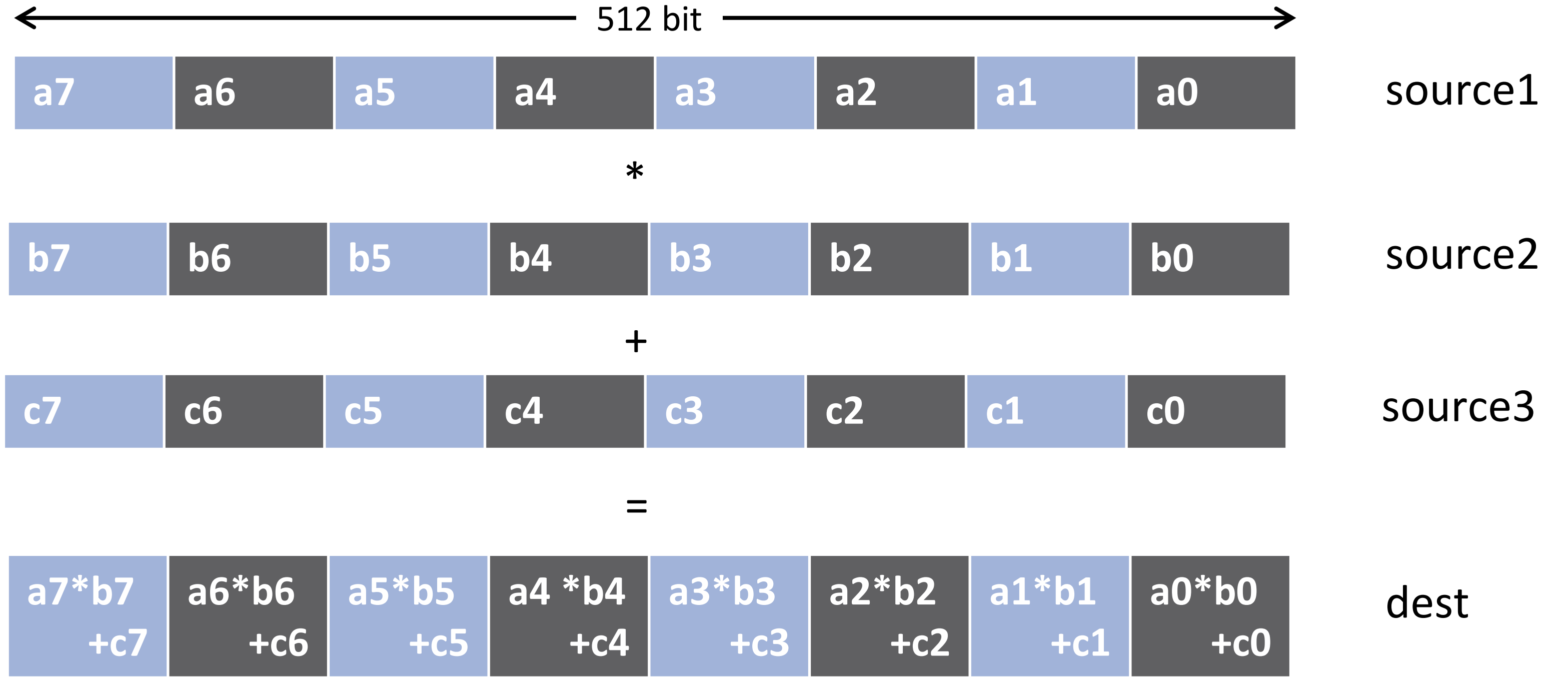
vfmadd213pd source1, source2, source3



512 bit

a7	a6	a5	a4	a3	a2	a1	a0	source1
*								
b7	b6	b5	b4	b3	b2	b1	b0	source2
+								
c7	c6	c5	c4	c3	c2	c1	c0	source3
=								
a7*b7 +c7	a6*b6 +c6	a5*b5 +c5	a4 *b4 +c4	a3*b3 +c3	a2*b2 +c2	a1*b1 +c1	a0*b0 +c0	dest

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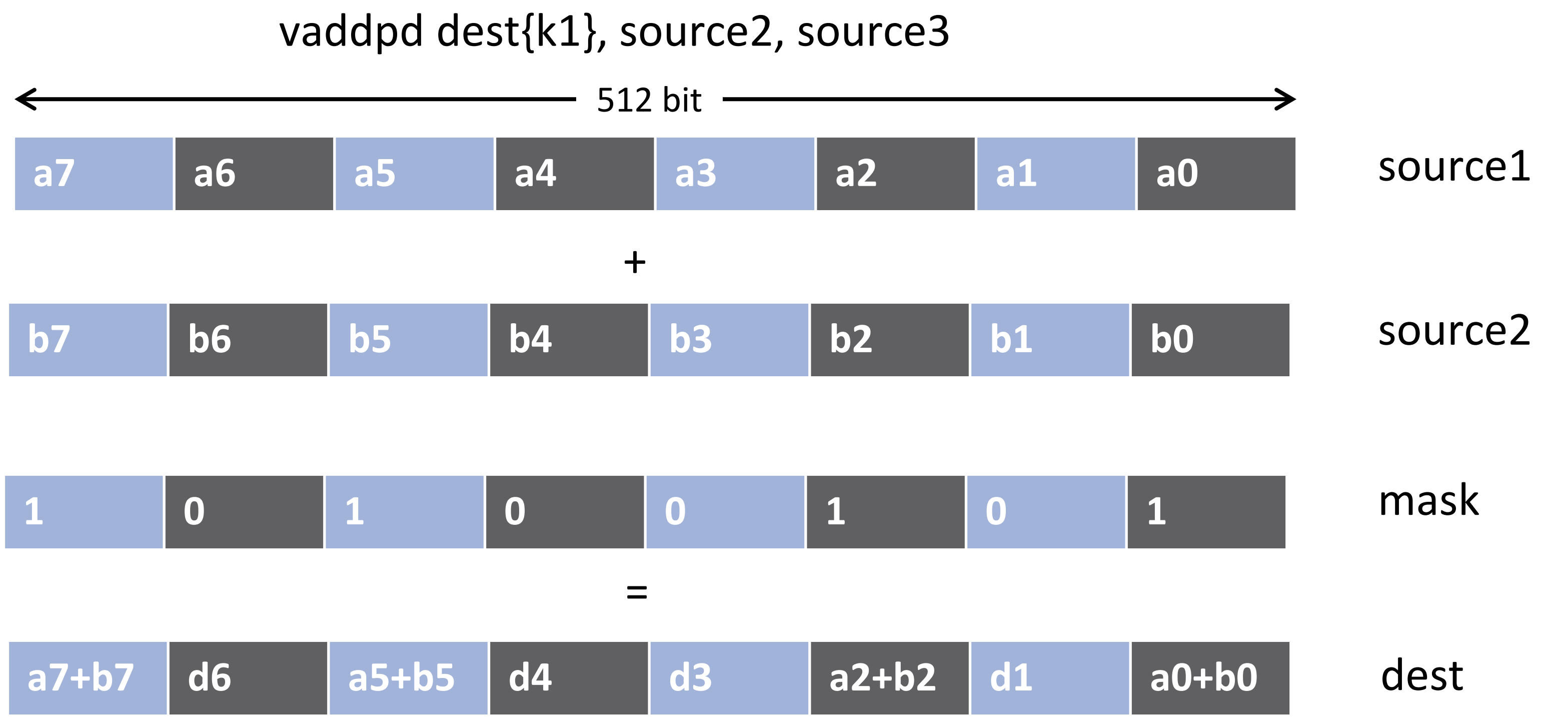


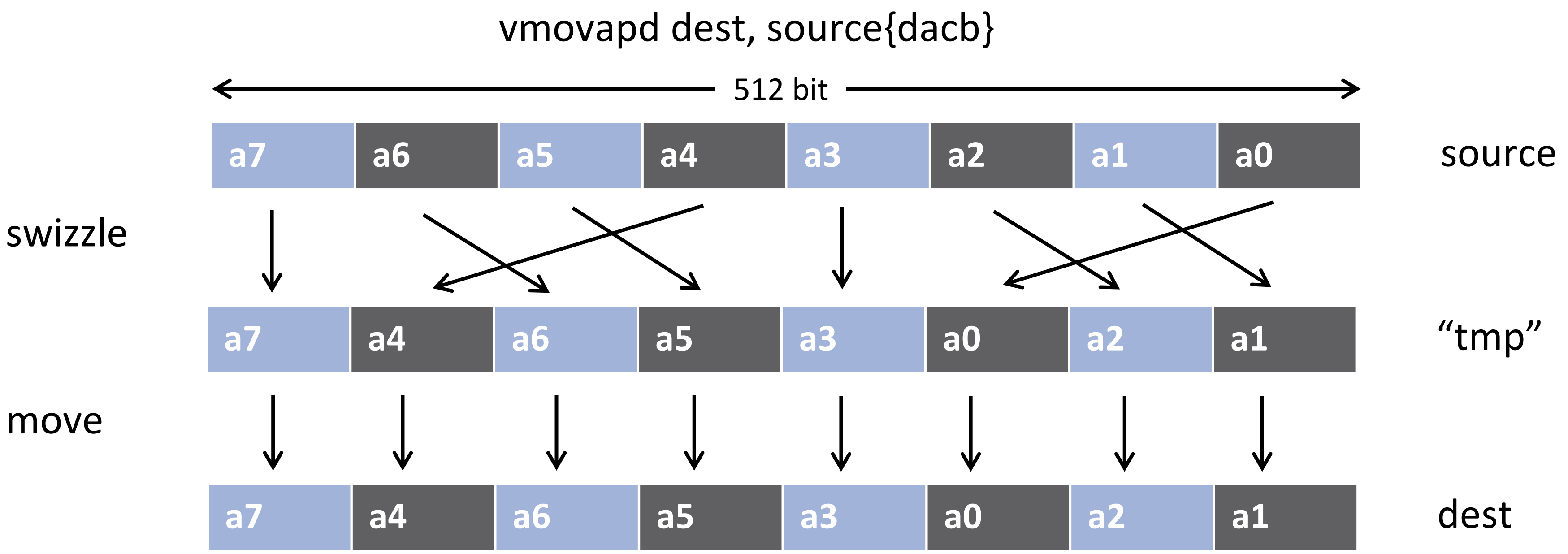
vaddpd dest{k1}, source2, source3

512 bit

a7	a6	a5	a4	a3	a2	a1	a0	source1
+								
b7	b6	b5	b4	b3	b2	b1	b0	source2
1	0	1	0	0	1	0	1	mask
=								
a7+b7	d6	a5+b5	d4	d3	a2+b2	d1	a0+b0	dest

More Powerful SIMD Units

- SIMD instructions become more powerful
- One example is the Intel® Xeon Phi™ Coprocessor



vmovapd dest, source{dacb}

512 bit

a7	a6	a5	a4	a3	a2	a1	a0	source
a7	a4	a6	a5	a3	a0	a2	a1	“tmp”
a7	a4	a6	a5	a3	a0	a2	a1	dest

Auto-vectorization

- Compilers offer auto-vectorization as an optimization pass
  - →Usually part of the general loop optimization passes
  - →Code analysis detects code properties that inhibit SIMD vectorization ?
  - →Heuristics determine if SIMD execution might be beneficial
  - →If all goes well, the compiler will generate SIMD instructions

- Example: Intel® Composer XE
  - →-vec (automatically enabled with –O2)
  - →-qopt-report

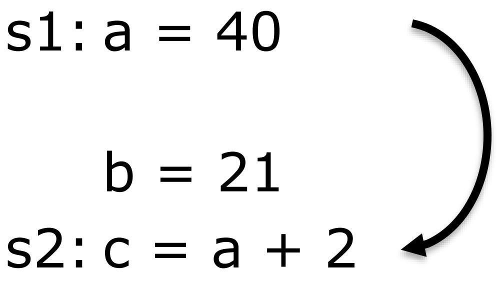
Why Auto-vectorizers Fail

- 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

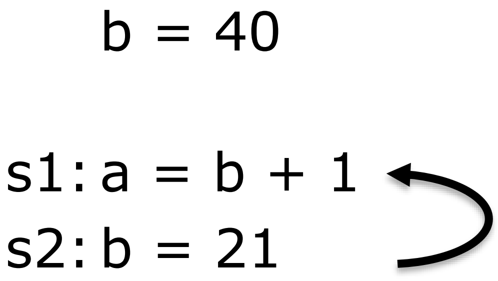
FLOW



```
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];
     }
}
```

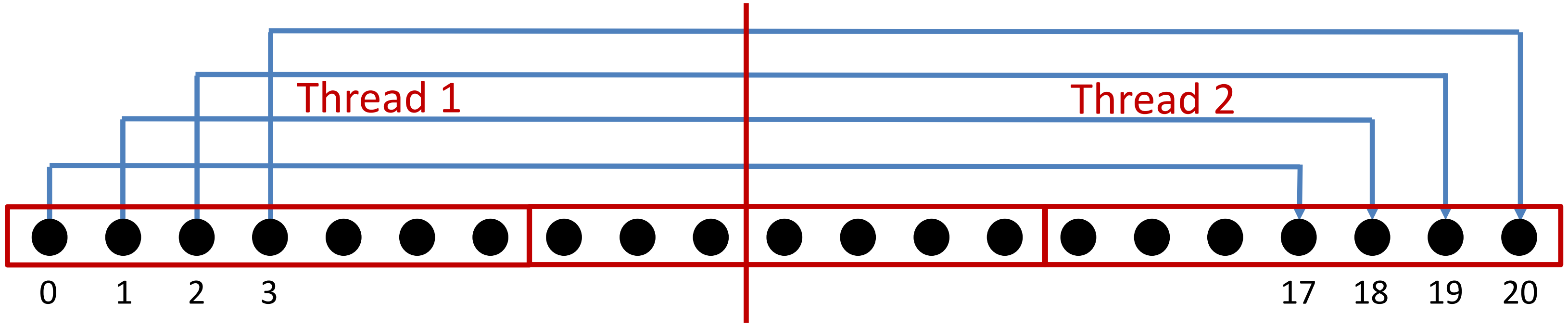
Loop-carried dependency for a[i] and a[i+17]; distance is 17.

- 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?

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];
}   }
```



→ Parallelization: no
(except for very specific loop schedules)

→ Vectorization: yes
(iff vector length is shorter than any distance of any dependency)

Example: Loop not Countable

- “Loop not Countable” plus “Assumed Dependencies”

```
typedef struct {
    float* data;
    size_t size;
} vec_t;

void vec_eltwise_product(vec_t* a, vec_t* b, vec_t* c) {
    size_t i;
    for (i = 0; i < a->size; i++) {
        c->data[i] = a->data[i] * b->data[i];
    }
}
```

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()`)

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

You need to trust your compiler to do the “right” thing.

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++)

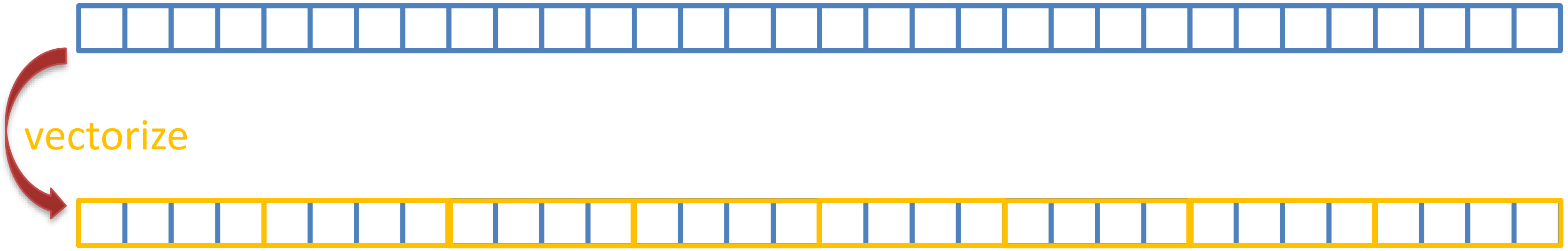
```
#pragma omp simd [clause[[,] clause],…]
for-loops
```

- Syntax (Fortran)

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

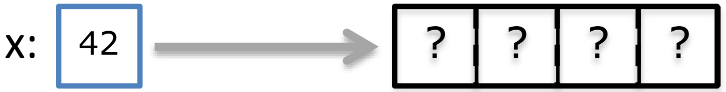
Example

```
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

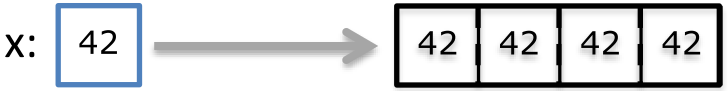
- `private(`*`var-list`*`):`
  Uninitialized vectors for variables in *var-list*



x: 42

? ? ? ?

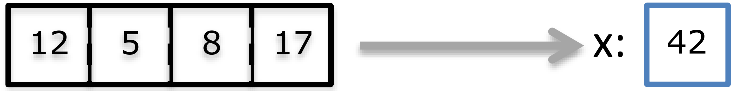
- `firstprivate(`*`var-list`*`):`
  Initialized vectors for variables in *var-list*



x: 42

42 42 42 42

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



12 5 8 17

x: 42

SIMD Loop Clauses

- `safelen (`*`length`*`)`
  - → Maximum number of iterations that can run concurrently without breaking a dependence
  - → In practice, maximum vector length
- `linear (`*`list`*`[:`*`linear-step`*`])`
  - → The variable’s value is in relationship with the iteration number
    - → $x_i = x_{orig} + i * \text{linear-step}$
- `aligned (`*`list`*`[:`*`alignment`*`])`
  - → Specifies that the list items have a given alignment
  - → Default is alignment for the architecture
- `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++)

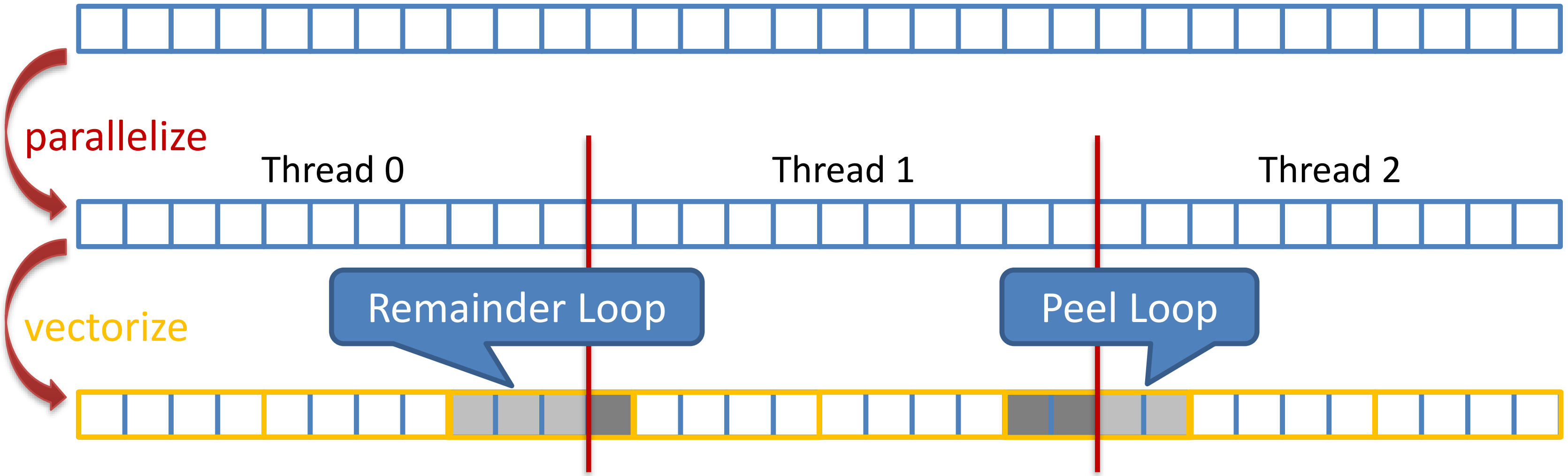
```
#pragma omp for simd [clause[[,] clause],…]
for-loops
```

- Syntax (Fortran)

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

Example

```
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;
}
```



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;
}
```

- 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

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

- 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
  - →Likely better performance

SIMD Function Vectorization

```
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

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

```
_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
- `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

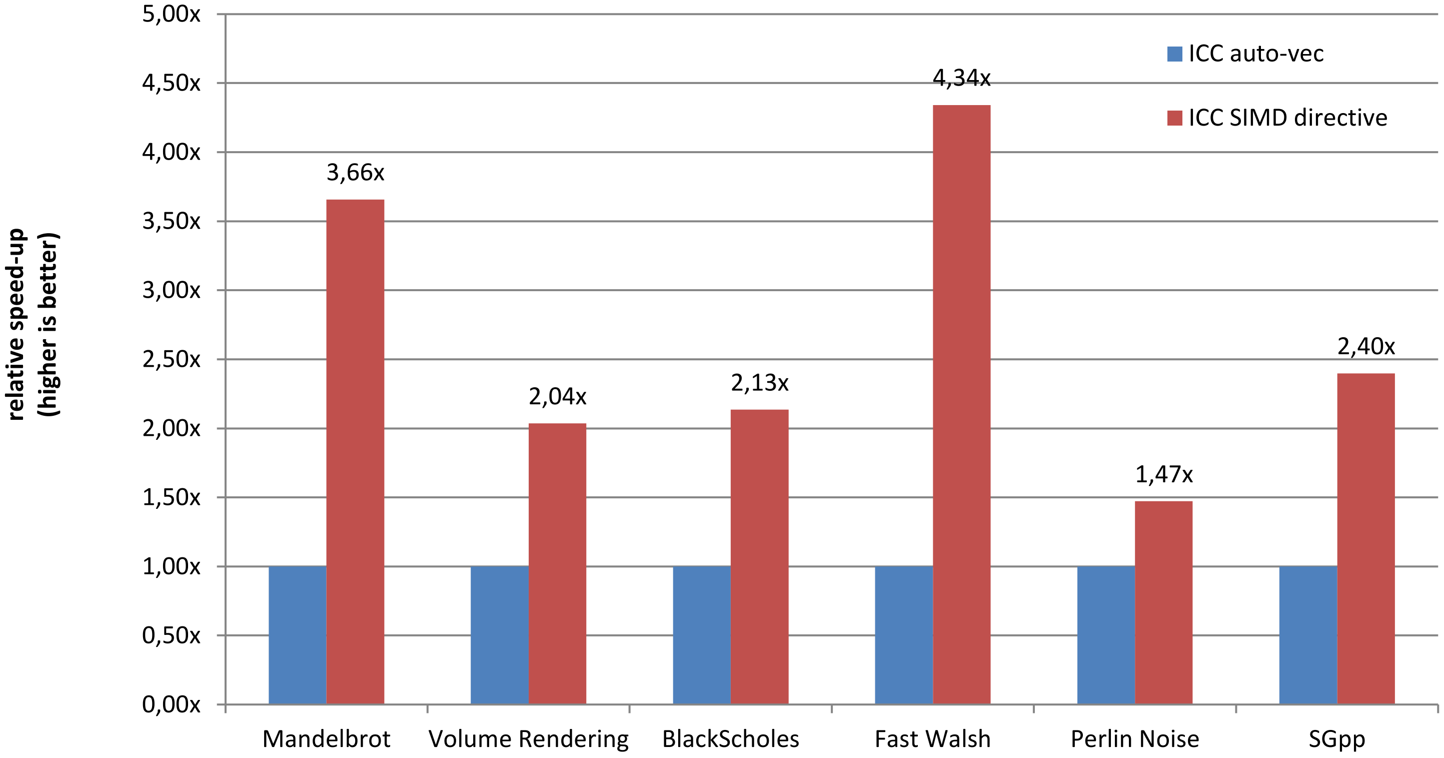
```
#pragma omp declare simd inbranch
float do_stuff(float x) {
    /* do something */
    return x * 2.0;
}

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

```
vec8 do_stuff_v(vec8 x, mask m) {
    /* do something */
    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

Memory Access in OpenMP

Christian Terboven

Michael Klemm

Example: Loop Parallelization

- Assume the following: you have learned that *load imbalances* can severely impact performance and a *dynamic* loop schedule may prevent this:
  - →What is the issue with the following code:

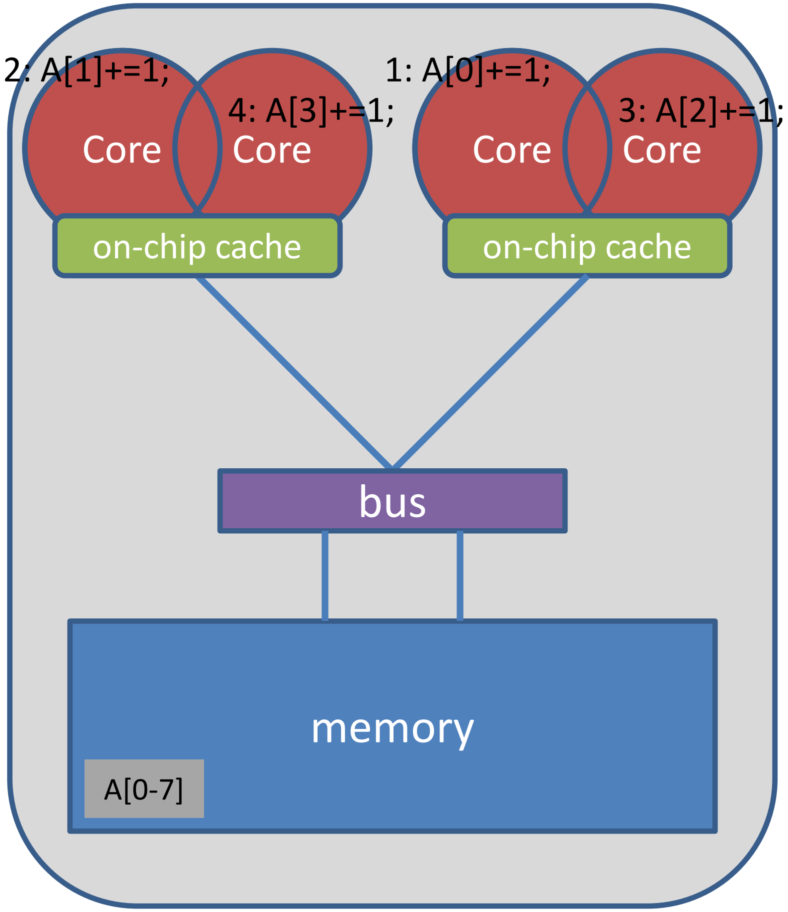
```
double* A;
A = (double*) malloc(N * sizeof(double));
/* assume some initialization of A */

#pragma omp parallel for schedule(dynamic, 1)
for (int i = 0; i < N; i++) {
   A[i] += 1.0;
}
```

  - →How is A accessed? Does that affect performance?

False Sharing

- **False Sharing: Parallel accesses to the same cache line may have a significant performance impact!**



Caches are organized in lines of typically 64 bytes: integer array a[0-4] fits into one cache line.

Whenever one element of a cache line is updated, the whole cache line is Invalidated.

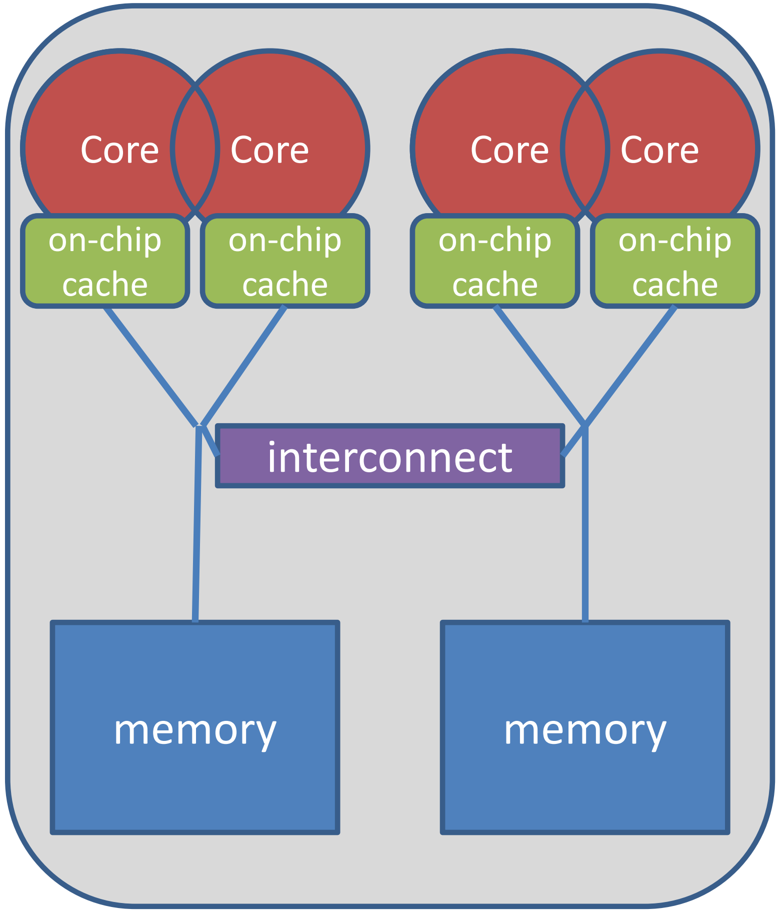
Local copies of a cache line have to be re-loaded from the main memory and the computation may have to be repeated.

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;
}
```



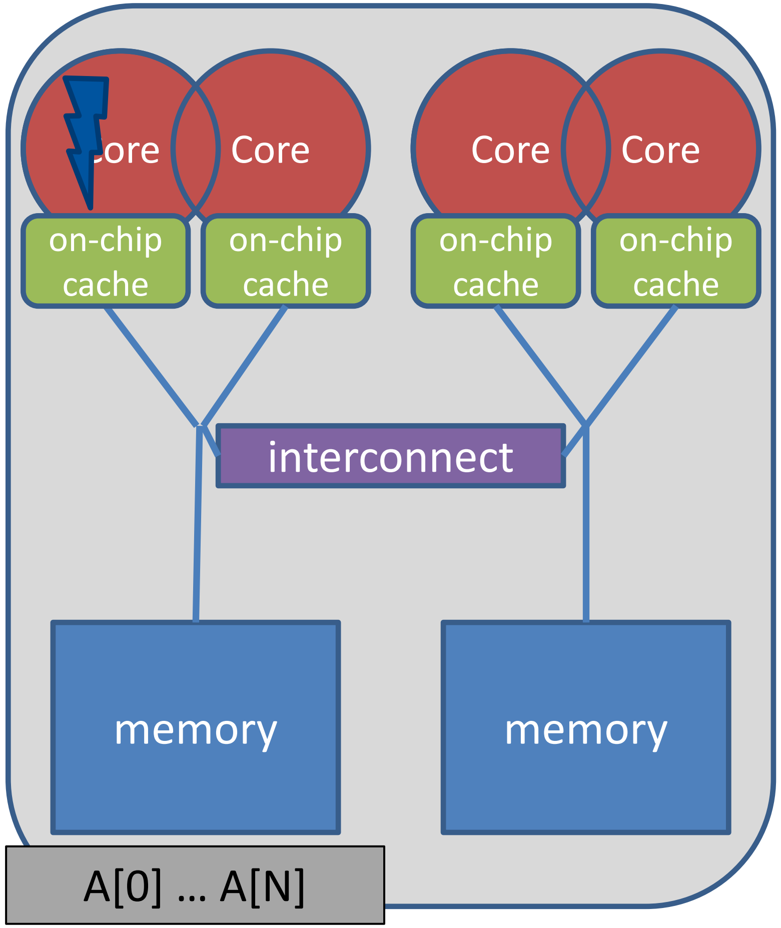
Non-uniform Memory

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

```
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)

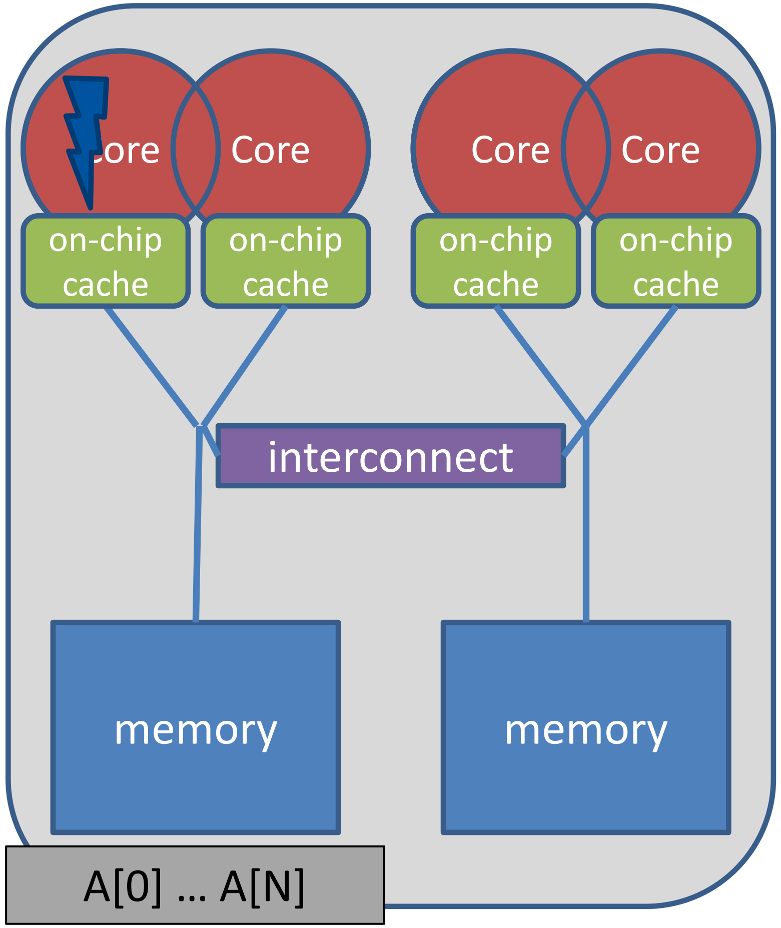
Non-uniform Memory

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

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



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



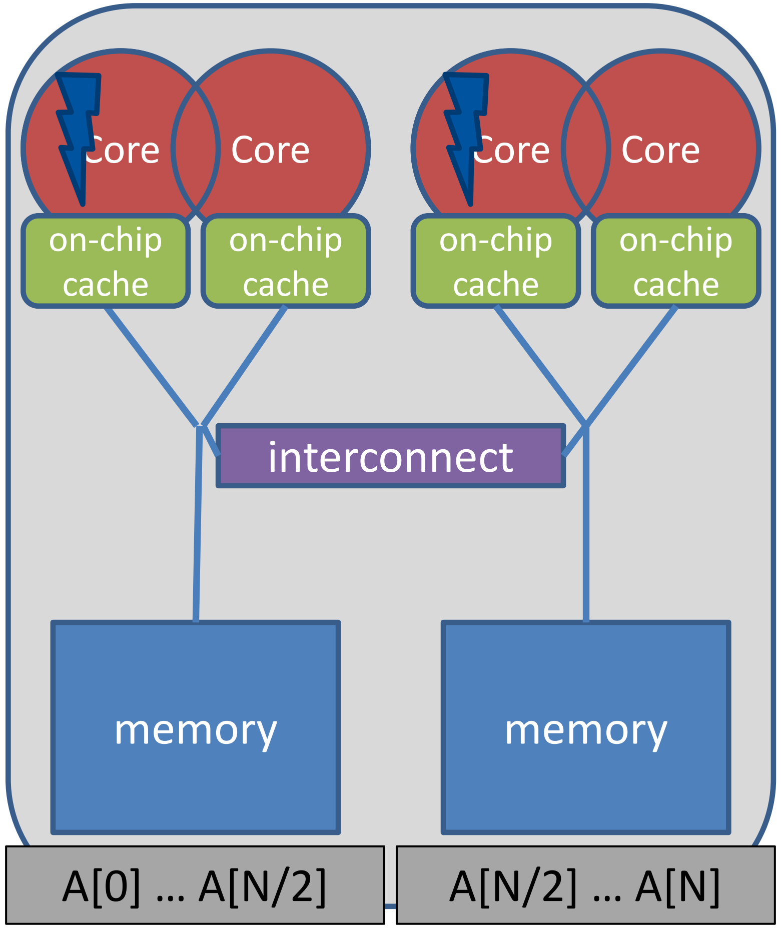
First Touch Memory Placement

- **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;
}
```

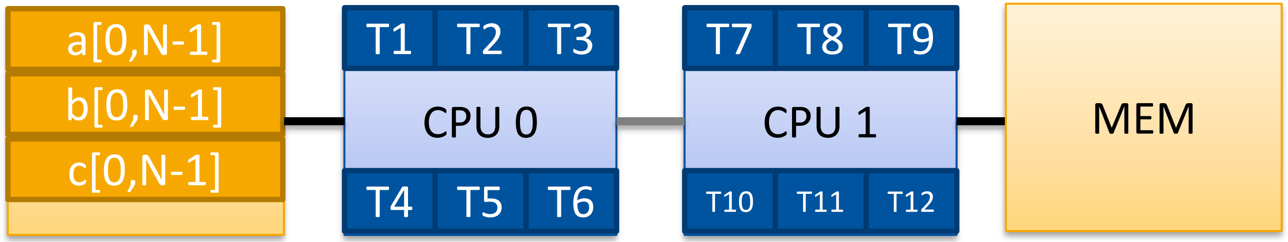


Serial vs. Parallel Initialization

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

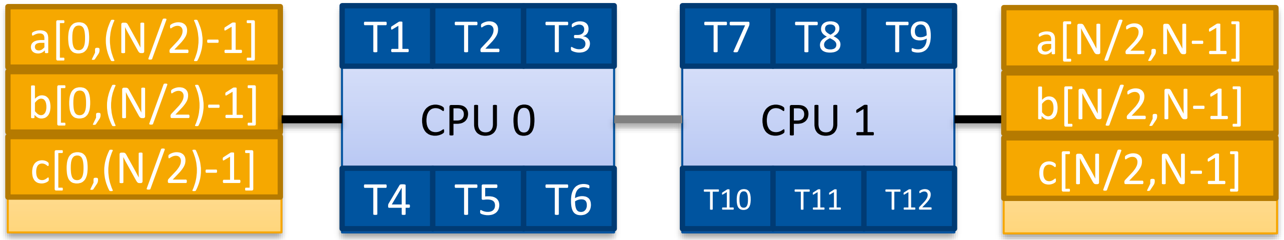
	copy	scale	add	triad
ser_init	18.8 GB/s	18.5 GB/s	18.1 GB/s	18.2 GB/s
par_init	41.3 GB/s	39.3 GB/s	40.3 GB/s	40.4 GB/s

ser_init:



a[0,N-1]
b[0,N-1]
c[0,N-1]
T1 T2 T3
CPU 0
T4 T5 T6
T7 T8 T9
CPU 1
T10 T11 T12
MEM

par_init:



a[0,(N/2)-1]
b[0,(N/2)-1]
c[0,(N/2)-1]
T1 T2 T3
CPU 0
T4 T5 T6
T7 T8 T9
CPU 1
T10 T11 T12
a[N/2,N-1]
b[N/2,N-1]
c[N/2,N-1]

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

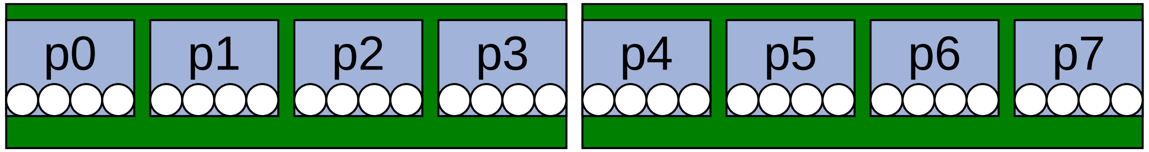
- Selecting the „right“ binding strategy depends not only on the topology, but also on application characteristics.
  - →Putting threads far apart, i.e., on different sockets
    - →May improve aggregated memory bandwidth available to application
    - →May improve the combined cache size available to 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 master thread
  - → MASTER: collocate OpenMP thread with master thread
- Goals
  - → user has a way to specify where to execute OpenMP threads
  - → locality between OpenMP threads / less false sharing / memory bandwidth

Places

- Assume the following machine:



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

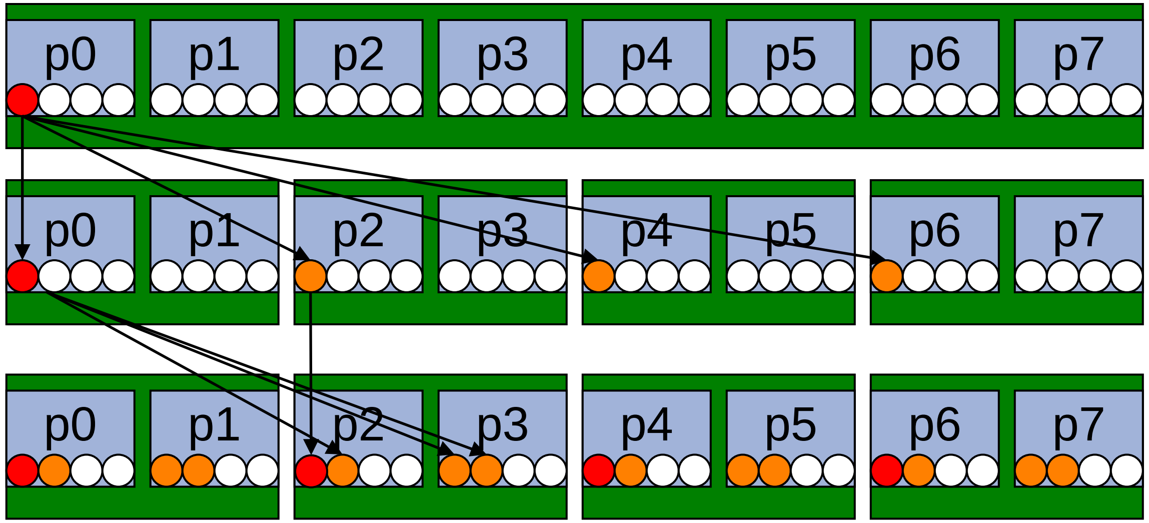
- Abstract names for OMP_PLACES:
  - → threads: Each place corresponds to a single hardware thread on the target machine.
  - → cores: Each place corresponds to a single core (having one or more hardware threads) on the target machine.
  - → sockets: Each place corresponds to a single socket (consisting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

Places + Binding Policies (2/2)

- Example‘s Objective:
  - → separate cores for outer loop and near cores for inner loop
- Outer Parallel Region: proc_bind(spread) num_threads(4)
  Inner Parallel Region: proc_bind(close) num_threads(4)
  - → spread creates partition, compact binds threads within respective partition

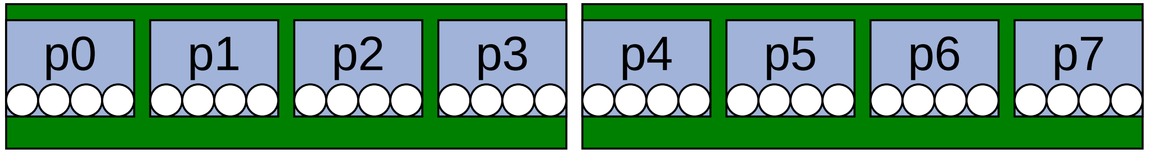
```
OMP_PLACES=(0,1,2,3), (4,5,6,7), ... = (0-3):8:4   = cores
#pragma omp parallel proc_bind(spread) num_threads(4)
#pragma omp parallel proc_bind(close) num_threads(4)
```

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



More Examples (1/3)

- Assume the following machine:



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

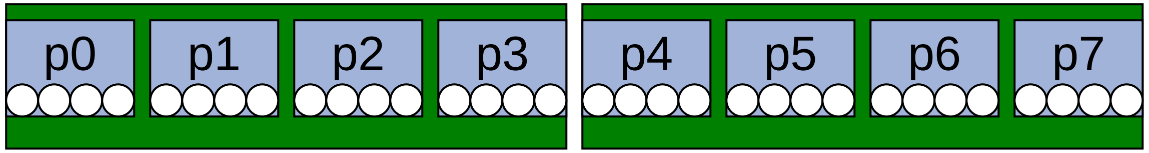
- Parallel Region with two threads, one per socket

  → `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 (1/2)

- 1: Query information about binding and a single place of all places with ids 0 … `omp_get_num_places()`:
- `omp_proc_bind_t omp_get_proc_bind()`: returns the thread affinity policy (omp_proc_bind_false, true, master, …)
- `int omp_get_num_places()`: returns the number of places
- `int omp_get_place_num_procs(int place_num)`: returns the number of processors in the given place
- `void omp_get_place_proc_ids(int place_num, int* ids)`: returns the ids of the processors in the given place

Places API (2/2)

- 2: Query information about the place partition:
- `int omp_get_place_num()`: returns the place number of the place to which the current thread is bound
- `int omp_get_partition_num_places()`: returns the number of places in the current partition
- `void omp_get_partition_place_nums(int* pns)`: returns the list of place numbers corresponding to the places in the current partition

Places API: Example

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

```
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:

```
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` env var or corresponding routine
  - → Formatted affinity information can be printed with `omp_display_affinity(const char* format)`

Affinity format specification

t	omp_get_team_num()
T	omp_get_num_teams()
L	omp_get_level()
n	omp_get_thread_num()
N	omp_get_num_threads()

a	omp_get_ancestor_thread_num() at level-1
H	hostname
P	process identifier
i	native thread identifier
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
```

A first summary

- Everything under control?
- In principle Yes, but only if
  - →threads can be bound explicitly,
  - →data can be placed well by first-touch, or can be migrated,
  - →you focus on a specific platform (= OS + arch) → no portability
- What if the data access pattern changes over time?
- What if you use more than one level of parallelism?

NUMA Strategies: Overview

- First Touch: Modern operating systems (i.e., Linux >= 2.4) decide for a physical location of a memory page during the first page fault, when the page is first „touched“, and put it close to the CPU causing the page fault.

- Explicit Migration: Selected regions of memory (pages) are moved from one NUMA node to another via explicit OS syscall.

- Next Touch: Binding of pages to NUMA nodes is removed and pages are migrated to the location of the next „touch“. Well-supported in Solaris, expensive to implement in Linux.

- Automatic Migration: No support for this in current operating systems.

User 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
    - → Windows: `VirtualAllocExNuma()` (limited functionality)
  - → By explicit migration of memory pages
    - → Linux: `move_pages()`
    - → Windows: no option

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

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

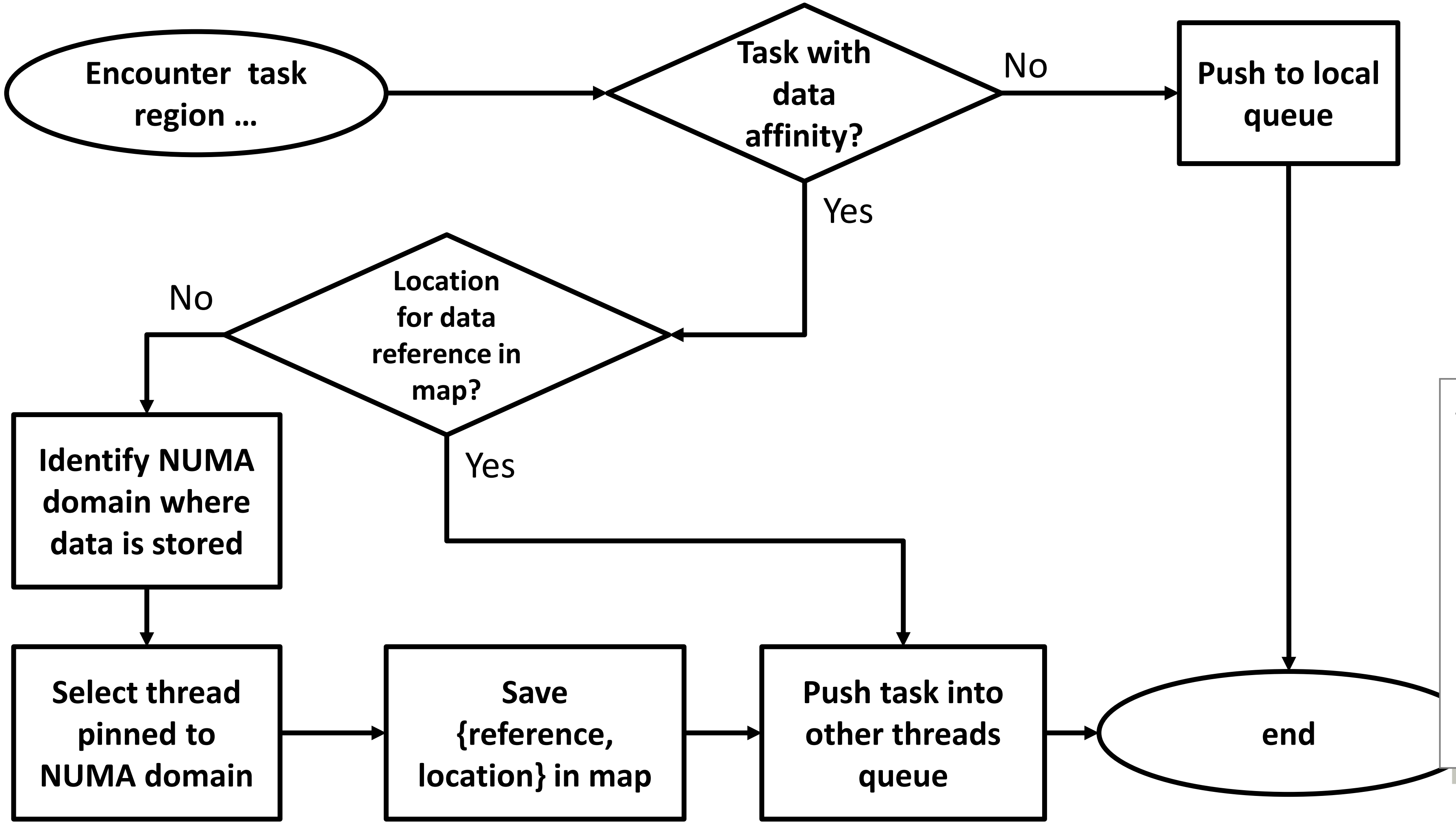
- Excerpt from task-parallel STREAM

```
#pragma omp task \
    shared(a, b, c, scalar) \
    firstprivate(tmp_idx_start, tmp_idx_end) \
    affinity( a[tmp_idx_start] )
{
   int i;
   for(i = tmp_idx_start; i <= tmp_idx_end; i++)
       a[i] = b[i] + scalar * c[i];
}
```

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

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

Selected LLVM implementation details



Encounter task region …

Task with data affinity?

No

Push to local queue

Yes

Location for data reference in map?

No

Identify NUMA domain where data is stored

Yes

Select thread pinned to NUMA domain

Save {reference, location} in map

Push task into other threads queue

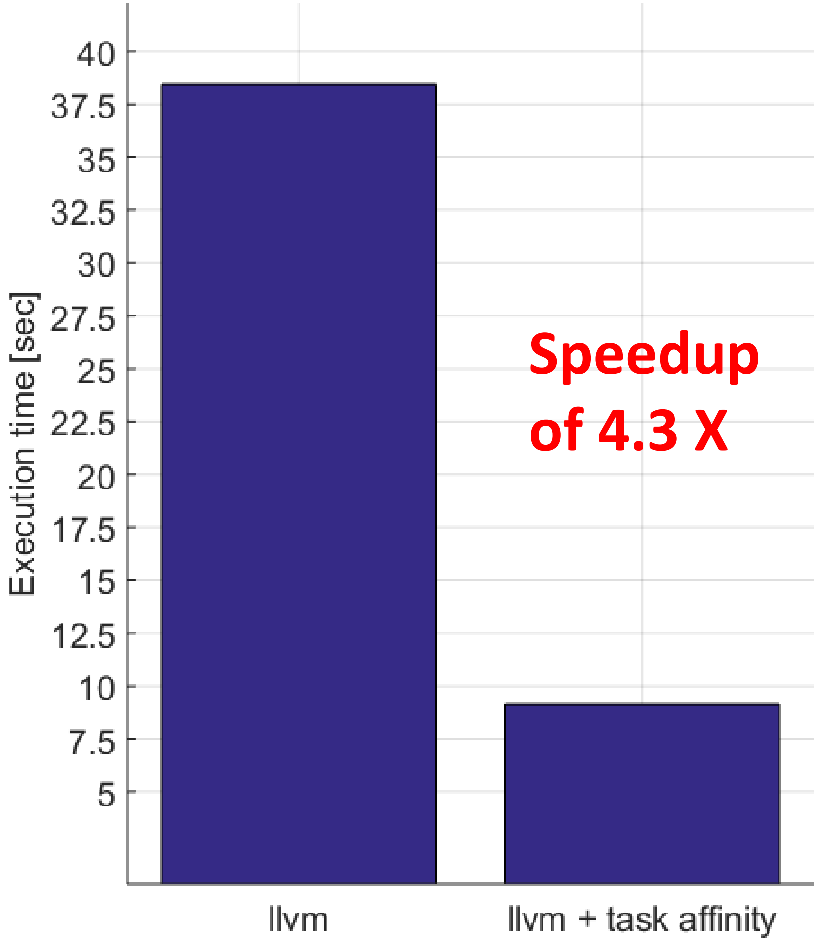
end

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

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.

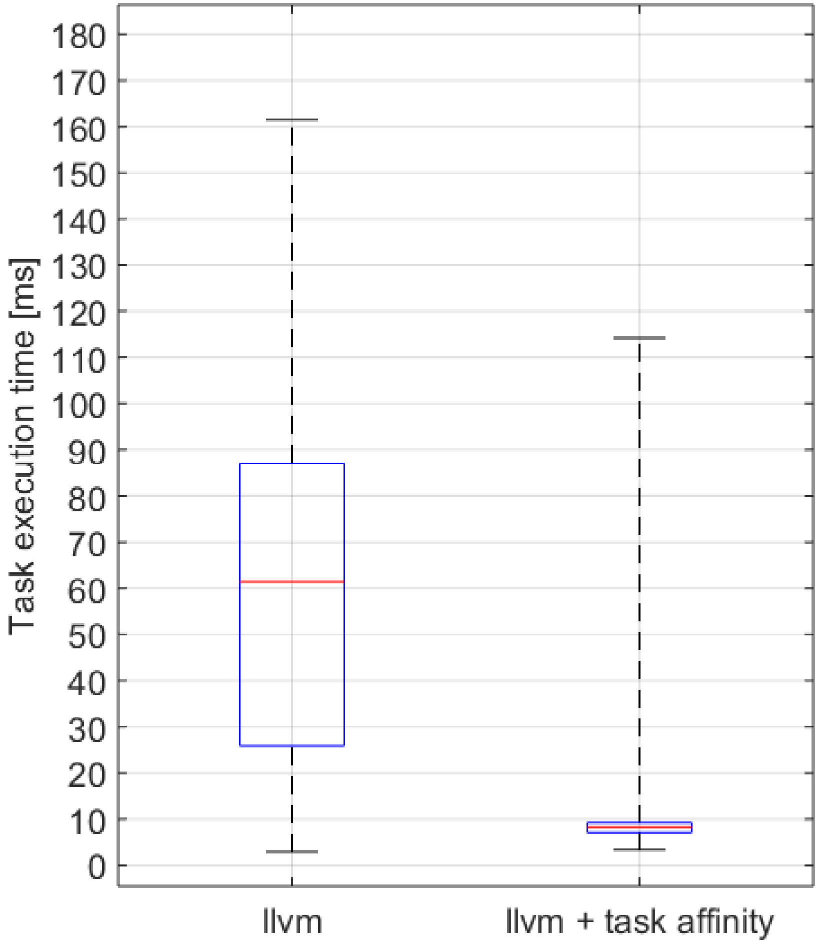
Evaluation

Program runtime
Median of 10 runs



Speedup of 4.3 X

Distribution of single task execution times



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

Summary

- Requirement for this feature: thread affinity enabled

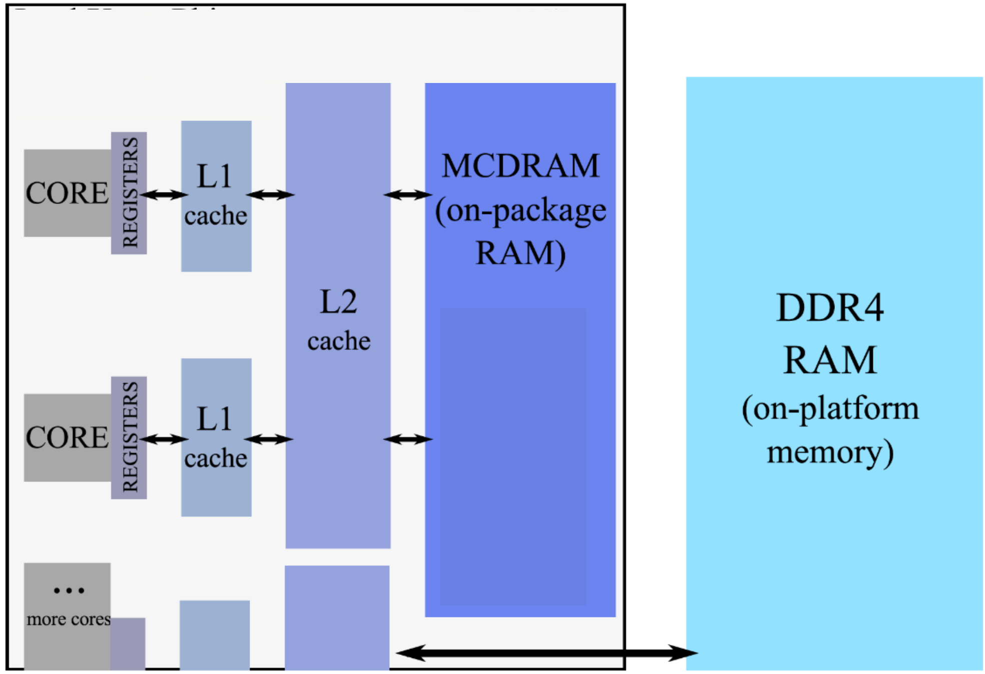
- The `affinity` clause helps, if
  - →tasks access data heavily
  - →single task creator scenario, or task not created with data affinity
  - →high load imbalance among the tasks

- Different from thread binding: task stealing is absolutely allowed

Managing Memory Spaces

Different kinds of memory

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



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

→Exact selection of memory space is implementation-def.

→Pre-defined allocators available to work with these

Programming OpenMP

Cancellation

Christian Terboven

Michael Klemm

OpenMP 3.1 Parallel Abort

- Once started, parallel execution cannot be aborted in OpenMP 3.1
  - → Code regions must always run to completion
  - → (or not start at all)

- Cancellation in OpenMP 4.0 provides a best-effort approach to terminate OpenMP regions
  - → Best-effort: not guaranteed to trigger termination immediately
  - → Triggered “as soon as” possible

Cancellation Constructs

- Two constructs:
  - → Activate cancellation:

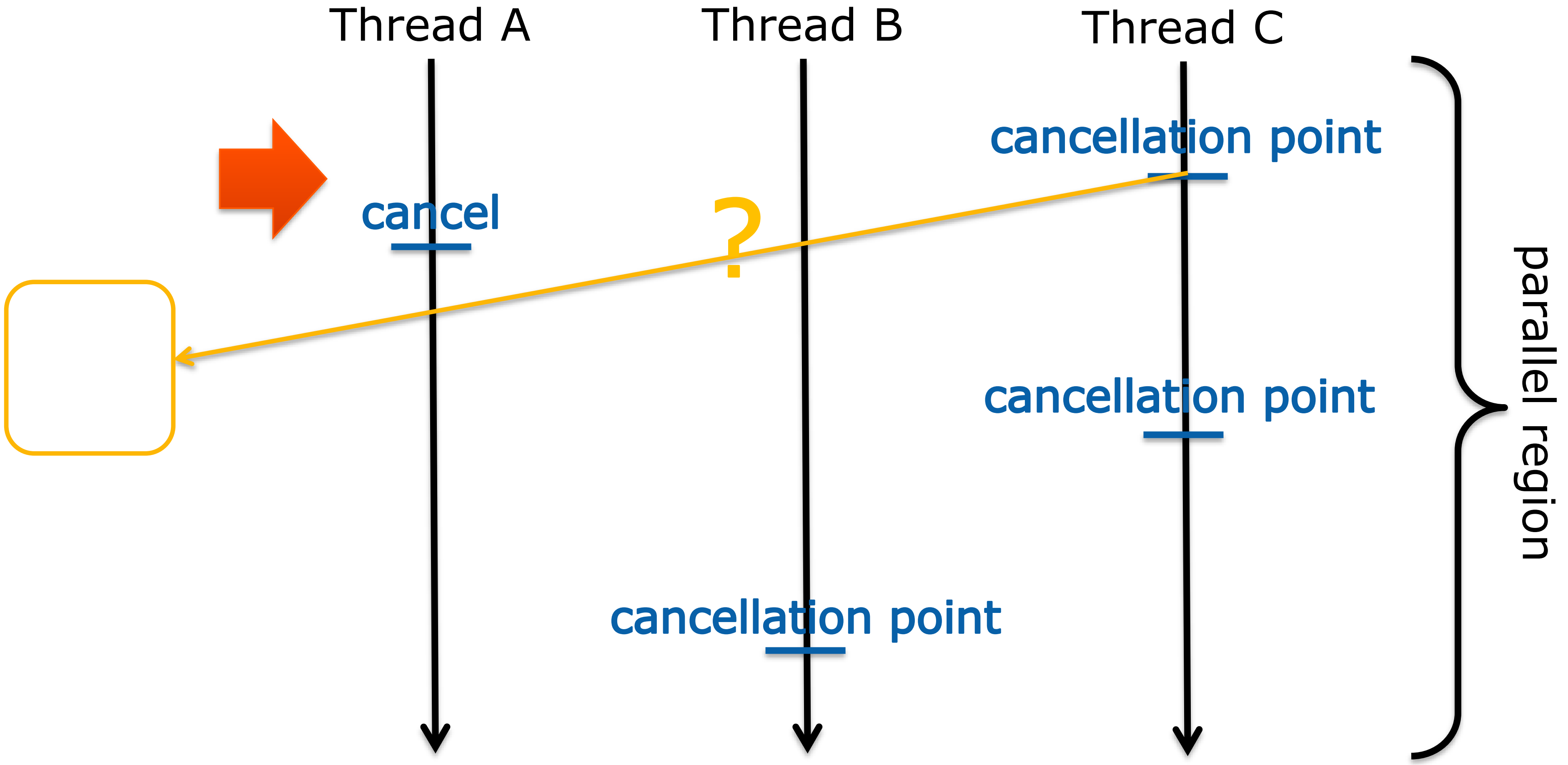
    C/C++: `#pragma omp cancel`

    Fortran: `!$omp cancel`
  - → Check for cancellation:

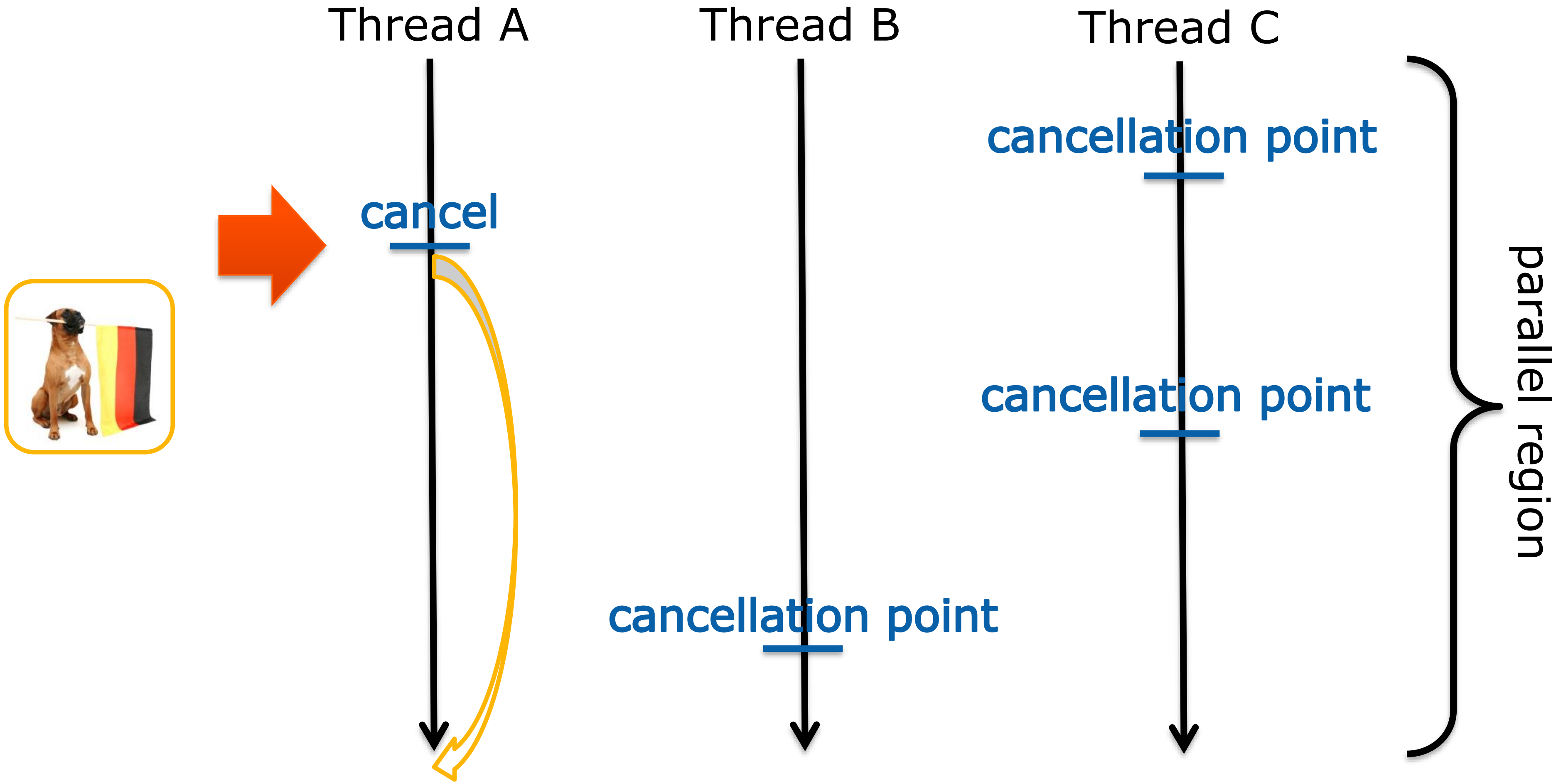
    C/C++: `#pragma omp cancellation point`

    Fortran: `!$omp cancellation point`
- Check for cancellation only a certain points
  - → Avoid unnecessary overheads
  - → Programmers need to reason about cancellation
  - → Cleanup code needs to be added manually

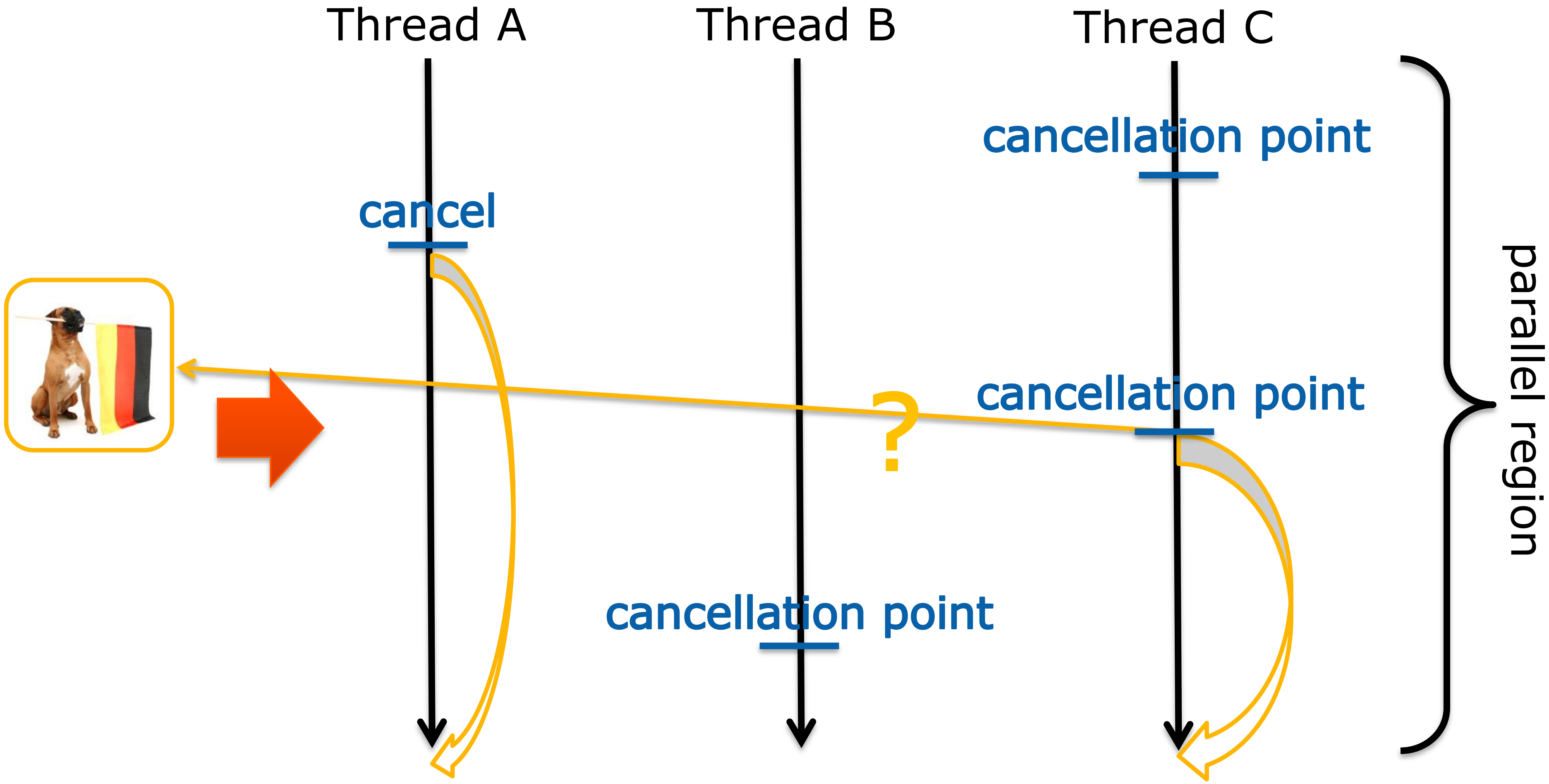
Cancellation Semantics



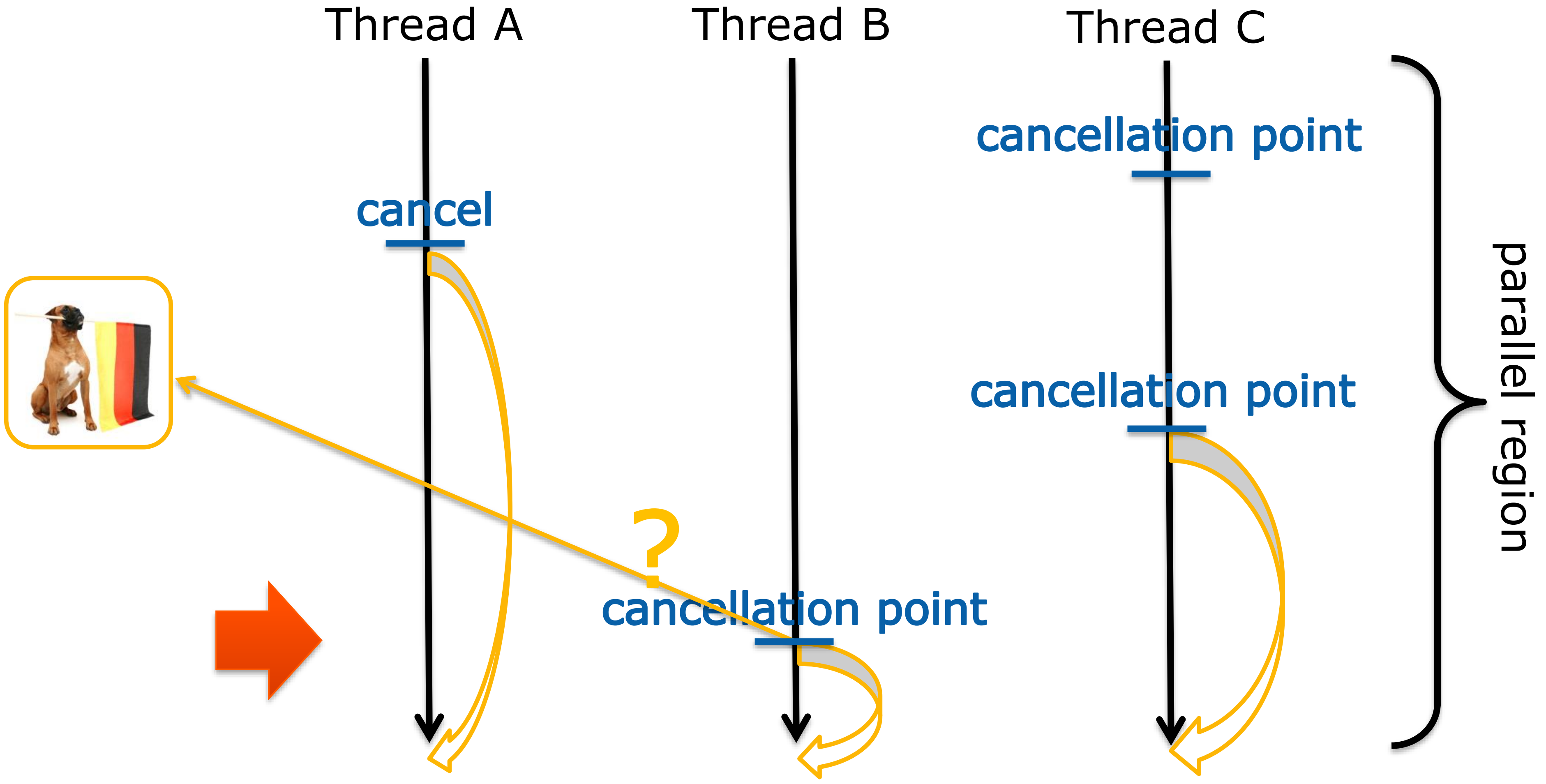
Cancellation Semantics



Cancellation Semantics



Cancellation Semantics



Thread A

Thread B

Thread C

cancel

cancellation point

cancellation point

cancellation point

?

parallel region

cancel Construct

- Syntax:

```
#pragma omp cancel construct-type-clause [ [, ]if-clause]
!$omp cancel construct-type-clause [ [, ]if-clause]
```

- Clauses:

```
parallel
sections
for   (C/C++)
do    (Fortran)
taskgroup
if (scalar-expression)
```

- Semantics
  - → Requests cancellation of the inner-most OpenMP region of the type specified in *construct-type-clause*
  - → Lets the encountering thread/task proceed to the end of the canceled region

cancellation point Construct

- Syntax:

```
#pragma omp cancellation point construct-type-clause
!$omp cancellation point construct-type-clause
```

- Clauses:

`parallel`

`sections`

`for` (C/C++)

`do` (Fortran)

`taskgroup`

- Semantics
  - → Introduces a user-defined cancellation point
  - → Pre-defined cancellation points:
    - → implicit/explicit barriers regions
    - → cancel regions

Cancellation of OpenMP Tasks

- Cancellation only acts on tasks grouped by the `taskgroup` construct
  - → The encountering tasks jumps to the end of its task region
  - → Any executing task will run to completion (or until they reach a `cancellation point` region)
  - → Any task that has not yet begun execution may be discarded (and is considered completed)

- Tasks cancellation also occurs, if a parallel region is canceled.
  - → But not if cancellation affects a worksharing construct.

Task Cancellation Example

```
binary_tree_t* search_tree_parallel(binary_tree_t* tree, int value) {
  binary_tree_t* found = NULL;
#pragma omp parallel shared(found,tree,value)
  {
#pragma omp master
    {
#pragma omp taskgroup
      {
        found = search_tree(tree, value);
      }
    }
  }
  return found;
}
```

Task Cancellation Example

```
binary_tree_t* search_tree(
     binary_tree_t* tree, int value,
     int level) {
  binary_tree_t* found = NULL;
  if (tree) {
    if (tree->value == value) {
      found = tree;
    }
    else {
#pragma omp task shared(found)
      {
        binary_tree_t* found_left;
        found_left =
          search_tree(tree->left, value);
        if (found_left) {
#pragma omp atomic write
          found = found_left;
#pragma omp cancel taskgroup
        }
      }
```

```
#pragma omp task shared(found)
      {
        binary_tree_t* found_right;
        found_right =
          search_tree(tree->right, value);
        if (found_right) {
#pragma omp atomic write
          found = found_right;
#pragma omp cancel taskgroup
        }
      }
#pragma omp taskwait
    }
  }
  return found;
}
```