Programming OpenMP

Christian Terboven

Michael Klemm

Agenda (in total 5 webinars)

- Webinar 1: OpenMP Introduction
- **Webinar 2: Tasking**
  - → Review of webinar 1 / homework assignments
  - → Tasking Motivation
  - → Task Model in OpenMP
  - → Scoping
  - → Taskloop
  - → Dependencies
  - → Cut-off strategies
  - → Homework assignments ☺
- Webinar 3: Optimization for NUMA and SIMD
- Webinar 4: Introduction to Offloading with OpenMP
- Webinar 5: Advanced Offloading Topics

Programming OpenMP

Review

Christian Terboven

Michael Klemm

RWTH AACHEN UNIVERSITY

OpenMP

Questions?

Solution of Homework Assignments

Example: sin-cos

```
double do_some_computation(int i) {
    double t = 0.0; int j;
    for (j = 0; j < i*i; j++) {
        t += sin((double)j) * cos((double)j);
    }
    return t;
}

int main(int argc, char* argv[]) {
    const int dimension = 500;
    int i;
    double result = 0.0;
    double t1 = omp_get_wtime();
    #pragma omp parallel for schedule(dynamic) reduction(+:result)
    for (i = 0; i < dimension; i++) {
        result += do_some_computation(i);
    }
    double t2 = omp_get_wtime();
    printf("Computation took %.3lf seconds.\n", t2 - t1);
    printf("Result is %.3lf.\n", result);
    return 0;
}
```

Example: matmul

```
void matmul_seq(double * C, double * A, double * B, size_t n) { ... }

void matmul_par(double * C, double * A, double * B, size_t n) {
#pragma omp parallel for shared(A,B,C) firstprivate(n) \
                         schedule(static) // collapse(2)
  for (size_t i = 0; i < n; ++i) {
    for (size_t k = 0; k < n; ++k) {
      for (size_t j = 0; j < n; ++j) {
        C[i * n + j] += A[i * n + k] * B[k * n + j];
      }
    }
  }
}

void init_mat(double * C, double * A, double * B, size_t n) { ... }

void dump_mat(double * mtx, size_t n) { ... }
double sum_mat(double * mtx, size_t n) { ... }

int main(int argc, char *argv[]) { ... }
```

Example: cholesky

```
void cholesky(int ts, int nt, double* Ah[nt][nt]) {
   for (int k = 0; k < nt; k++) {
      LAPACKE_dpotrf(LAPACK_COL_MAJOR, 'L', ts, Ah[k][k], ts);

      #pragma omp parallel for
      for (int i = k + 1; i < nt; i++) {
         cblas_dtrsm(CblasColMajor, CblasRight, CblasLower, CblasTrans,
                     CblasNonUnit, ts, ts, 1.0, Ah[k][k], ts, Ah[k][i], ts);
      }

      #pragma omp parallel for
      for (int i = k + 1; i < nt; i++) {
         for (int j = k + 1; j < i; j++) {
            cblas_dgemm(CblasColMajor, CblasNoTrans, CblasTrans, ts, ts, ts, -1.0,
            Ah[k][i], ts, Ah[k][j], ts, 1.0, Ah[j][i], ts);
         }
         cblas_dsyrk(CblasColMajor, CblasLower, CblasNoTrans, ts, ts, -1.0,
                     Ah[k][i], ts, 1.0, Ah[i][i], ts);
}     }  }
```

Blocked matrix w/ block size *ts*

Programming OpenMP

Tasking Introduction

Christian Terboven

Michael Klemm

RWTH AACHEN UNIVERSITY

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	

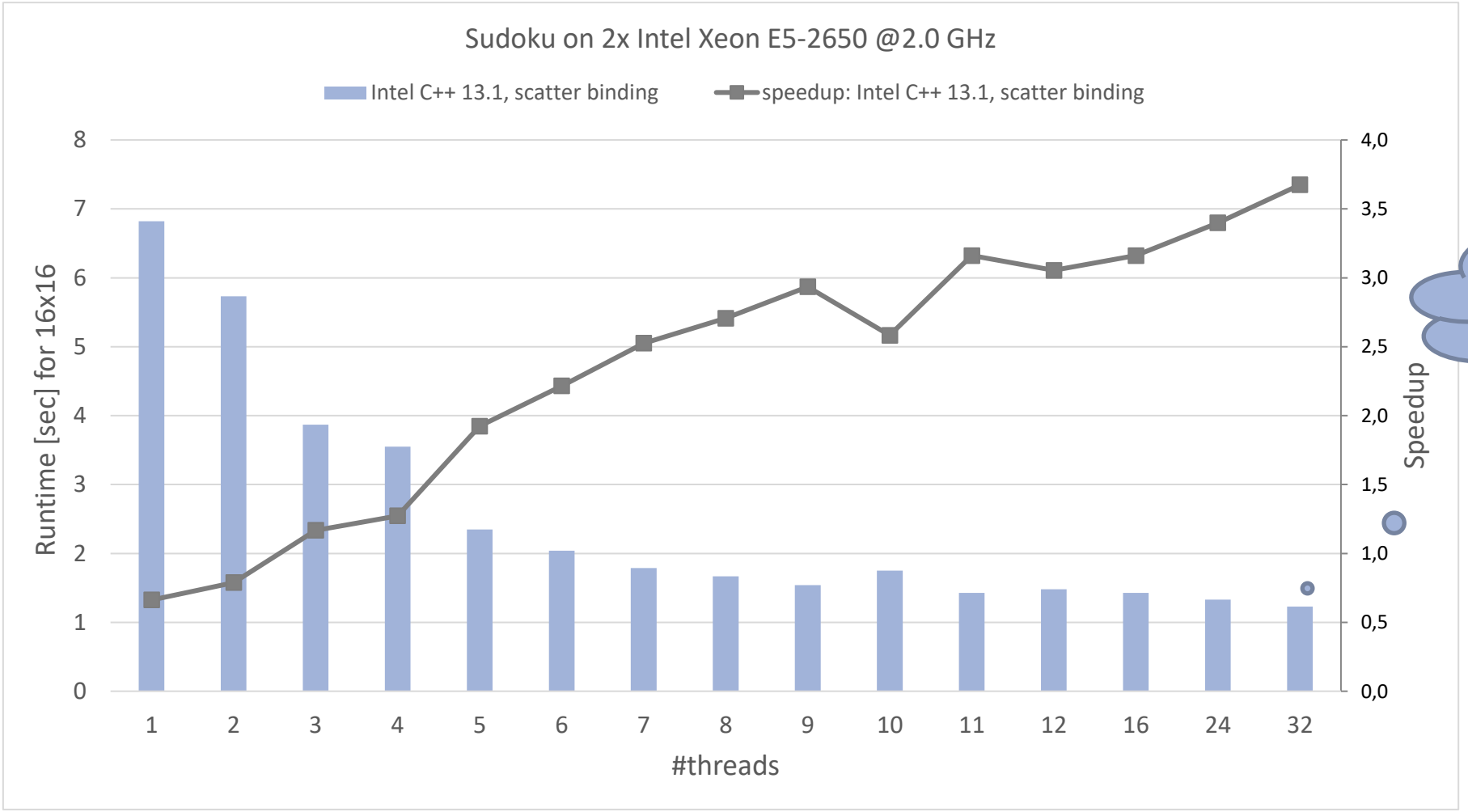
- (1) Search an empty field
- (2) Try all numbers:
  - (2 a) Check Sudoku
    - If invalid: skip
    - If valid: Go to next field
- Wait for completion

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> ) {
   ...
}
```

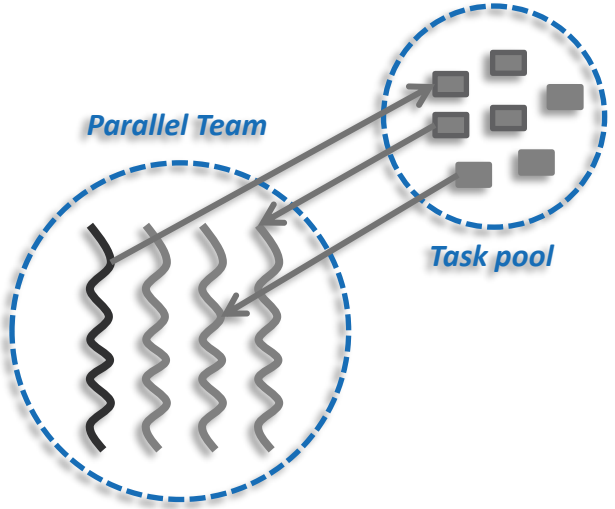
  - → recursive functions

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

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

- Example (unstructured parallelism)

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



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:

→ private(list) → firstprivate(list) → shared(list) → default(shared | none) → in_reduction(r-id: list)	Data Environment
→ allocate([allocator:] list) → detach(event-handler)	Miscellaneous
→ if(scalar-expression) → mergeable → final(scalar-expression)	Cutoff Strategies
→ depend(dep-type: list)	Synchronization
→ untied → priority(priority-value) → affinity(list)	Task Scheduling

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 ☹

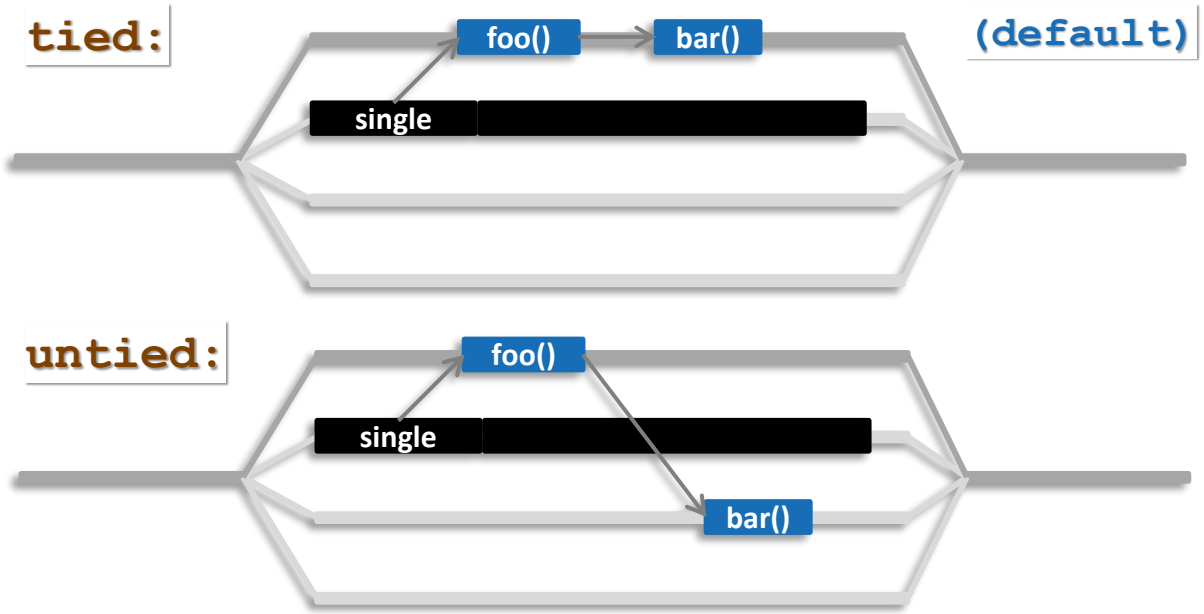
Task scheduling: taskyield directive

- 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()
   }
}
```



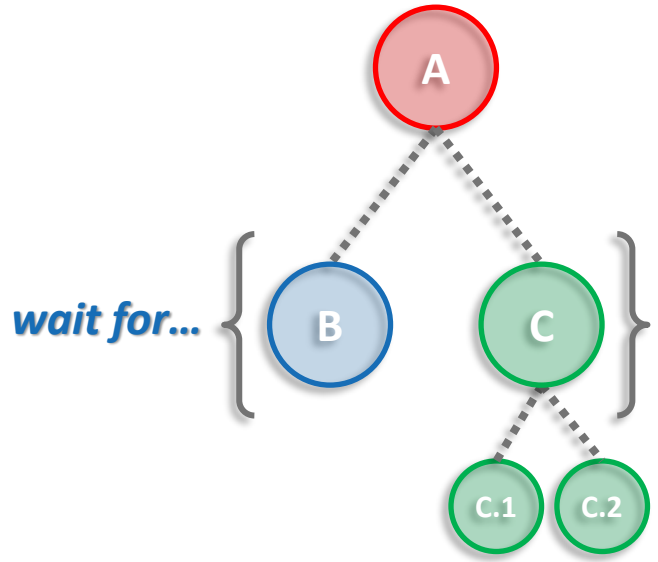
Task synchronization: taskwait directive

- 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
```



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

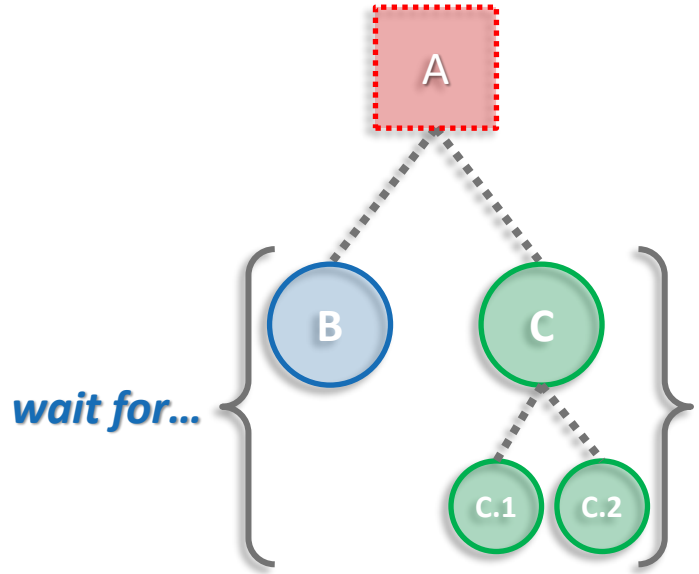
- The taskgroup construct (deep task synchronization)

  → 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)…

```
#pragma omp task
{
   int x = MN;
   // Scope of x: private
}
```
5

```
#pragma omp task
{
   static int y;
   // Scope of y: shared
}
```
4

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

// ...
#pragma omp task
{
  // A: threadprivate
}
```
1

```
int *p;

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

#pragma omp task
{
   // *p: shared
}
```
2

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

#pragma omp task
{
   foo(); // s@foo(): shared
}
```
3

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

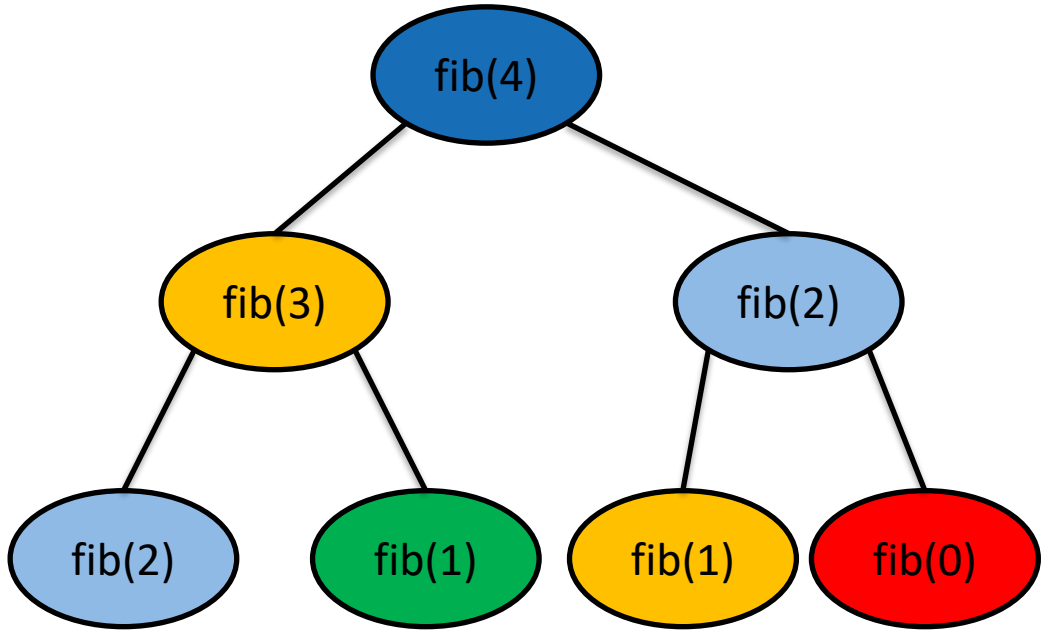
Fibonacci illustrated

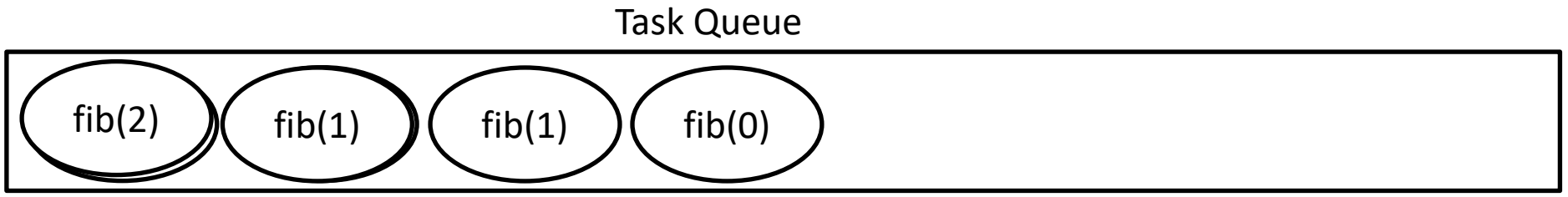
```
 1  int main(int argc,
 2           char* argv[])
 3  {
 4      [...]
 5      #pragma omp parallel
 6      {
 7          #pragma omp single
 8         {
 9             fib(input);
10         }
11      }
12      [...]
13 }
```

```
14  int fib(int n)   {
15      if (n < 2) return n;
16      int x, y;
17      #pragma omp task shared(x)
18      {
19          x = fib(n - 1);
20      }
21      #pragma omp task shared(y)
22      {
23          y = fib(n - 2);
24      }
25      #pragma omp taskwait
26          return x+y;
27 }
```

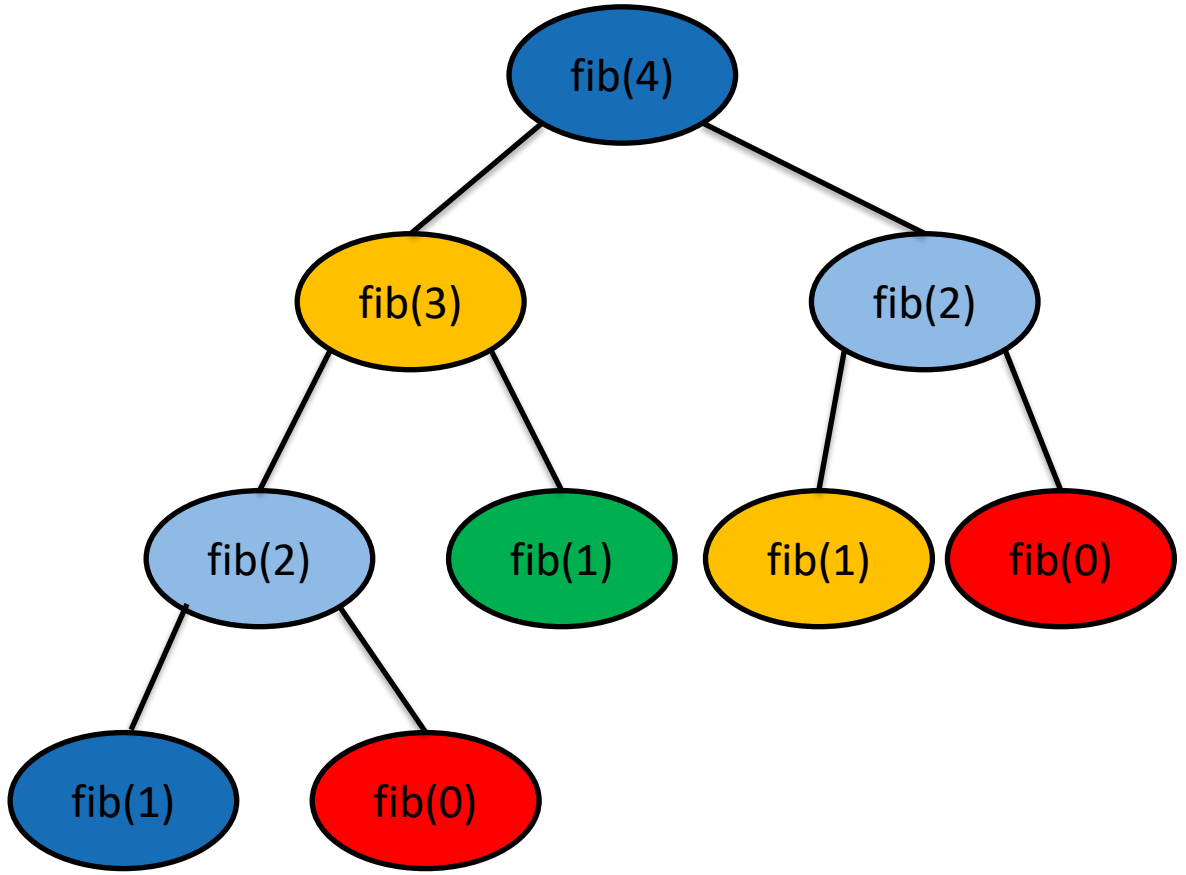
- Only one Task / Thread enters fib() from main(), it is responsible for creating the two initial work tasks
- Taskwait is required, as otherwise x and y would get lost

- 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
- …



Programming OpenMP

Tasking: taskloop and dependencies

Christian Terboven

Michael Klemm

RWTH AACHEN UNIVERSITY

OpenMP

The `taskloop` Construct

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)

```
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

```
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)

```
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

```
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

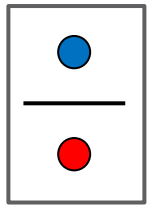
- Task dependences as a way to define task-execution constraints

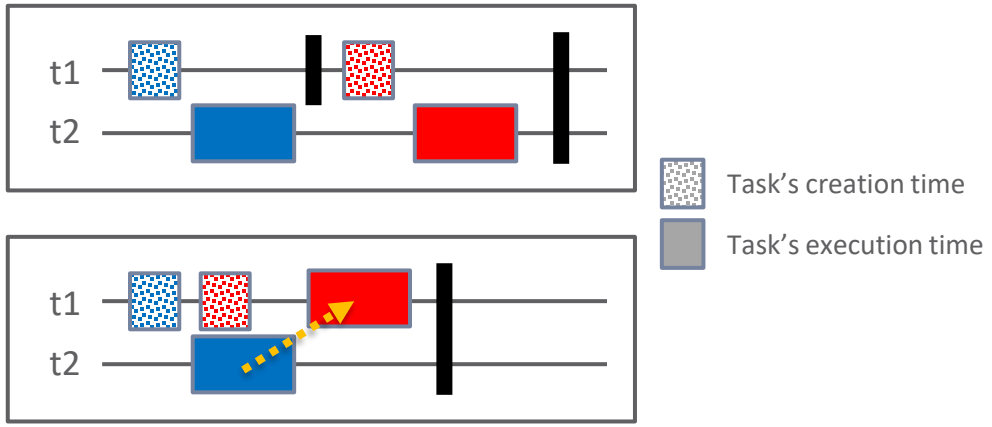
OpenMP 3.1

```
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++;
}
```





Motivation

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

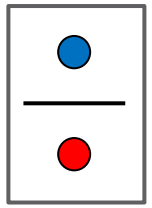
OpenMP 3.1

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

  #pragma omp taskwait

  #pragma omp task
  x++;
}
```

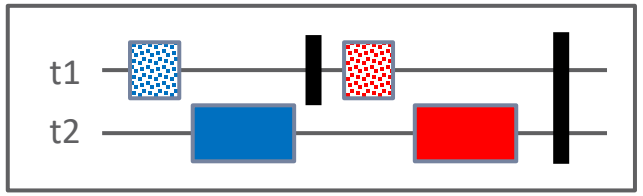
OpenMP 4.0

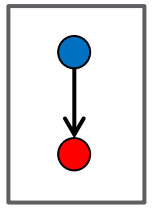
```
int x = 0;
#pragma omp parallel
#pragma omp single
{
  #pragma omp task depend(in: x)
                                d::endl;

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

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

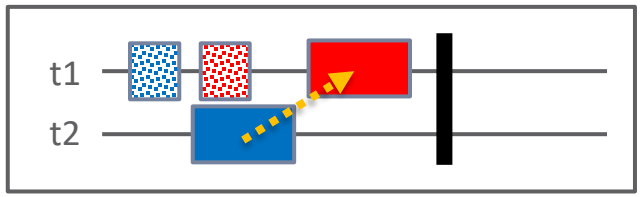


OpenMP 3.1





OpenMP 4.0

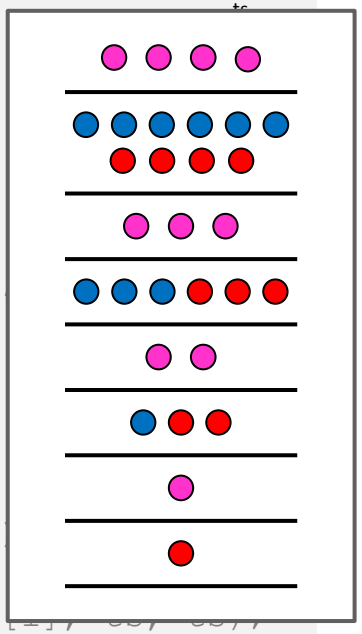


Task's creation time

Task's execution time

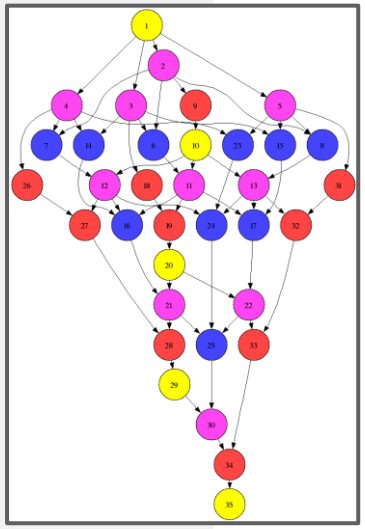
Motivation: Cholesky factorization

```
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],
        }
        #pragma omp task
      syrk(a[k][i], a[i][i], ts, ts);
      }
    #pragma omp taskwait
  }
}
```



OpenMP 3.1

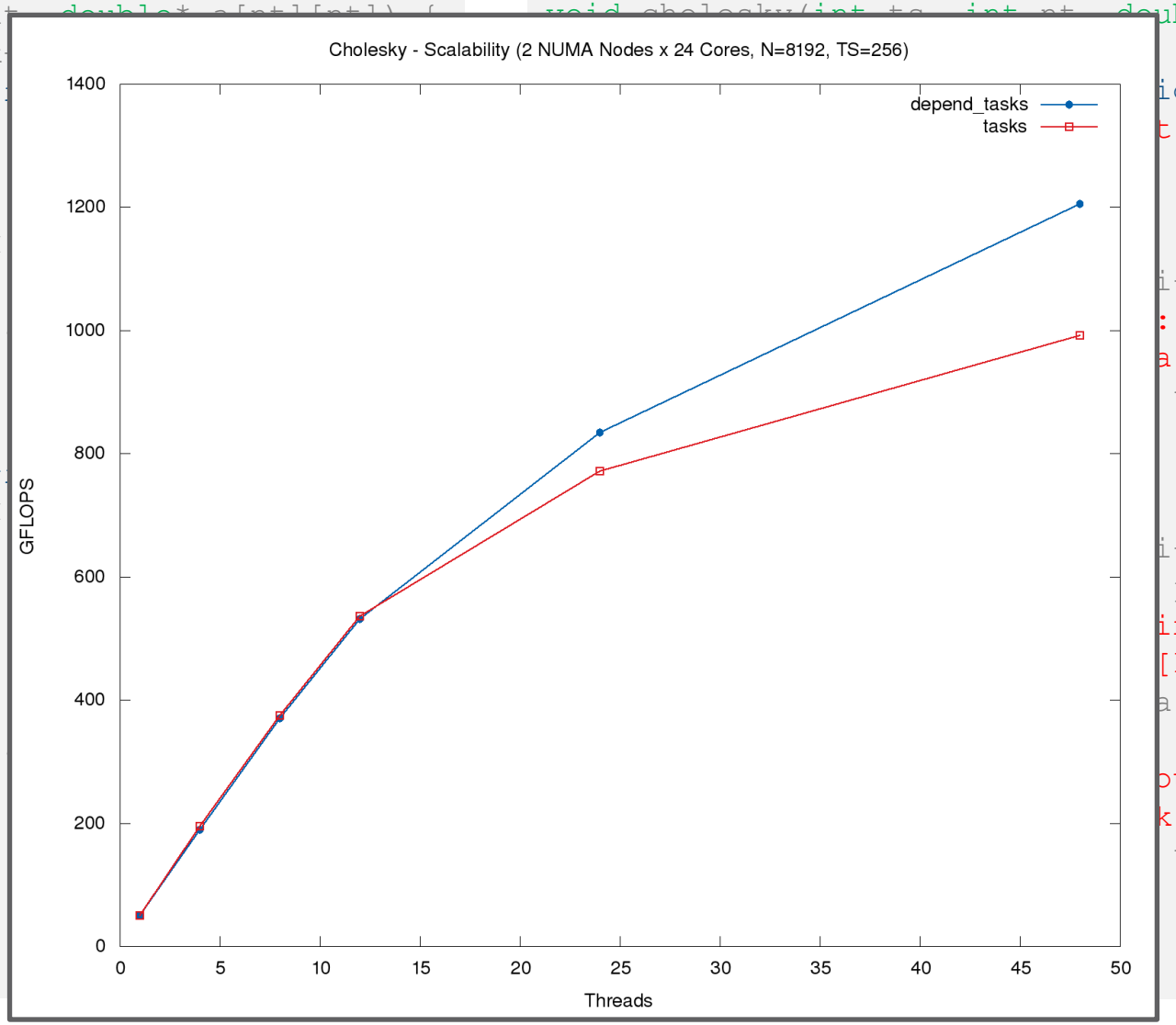
```
void cholesky(int ts, int nt, double* a[nt][nt]) {
  for (int k = 0; k < nt; k++) {
    // Diagonal Block factorization
    #pragma omp task depend(inout: a[k][k])
    potrf(a[k][k], ts, ts);

    // 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);
      }
    }
}
```

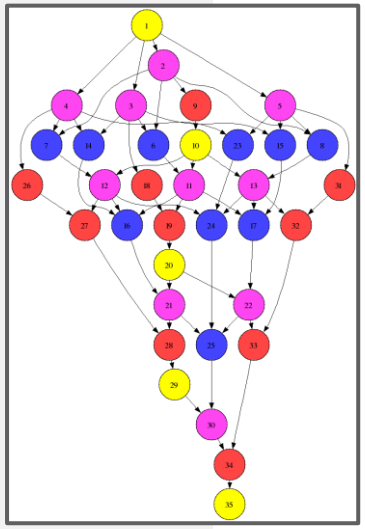


OpenMP 4.0

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
  }
}
```





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

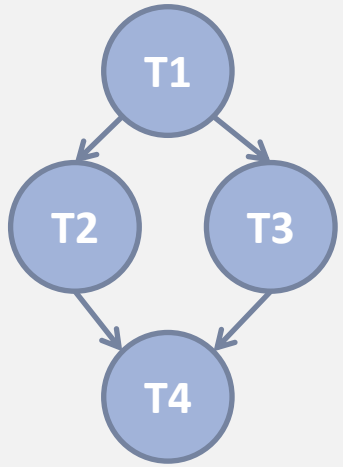
What's in the spec: depend clause (1)

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

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

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

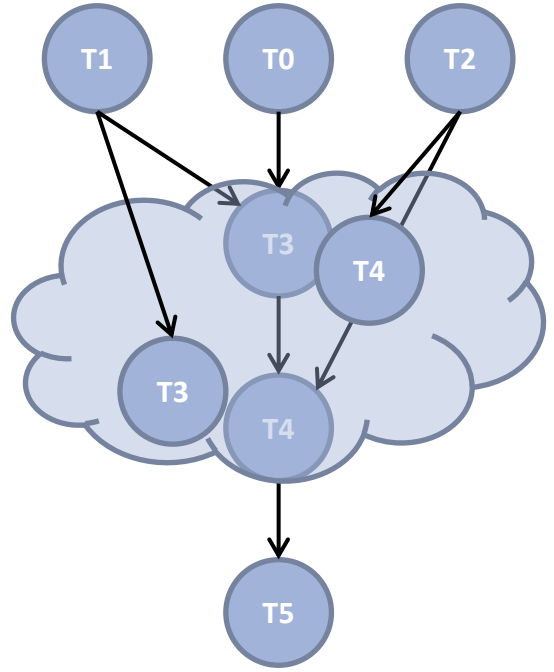
```
int x = 0;
#pragma omp parallel
#pragma omp single
{
  #pragma omp task depend(inout: x) //T1
  { ... }

  #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

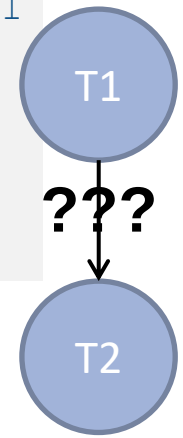
What's in the spec: depend clause (4)

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

```
//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;
}
```

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

```
//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);
}
```

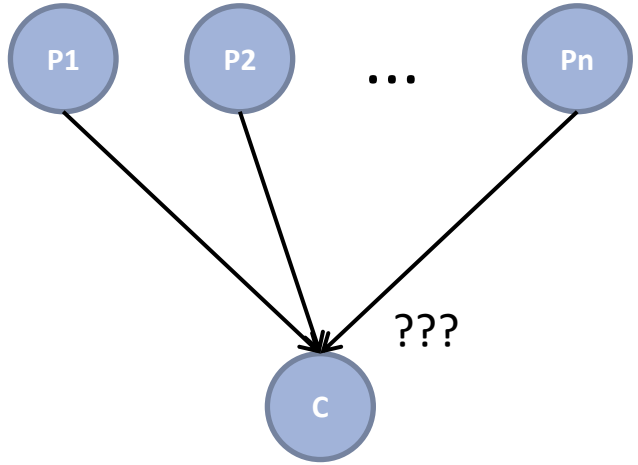


What's in the spec: depend clause (5)

- 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])`

Philosophy

Philosophy: data-flow model

- Task dependences are orthogonal to data-sharings
  - → **Dependences** as a way to define **a task-execution constraints**
  - → Data-sharings as **how the data is captured** to be used inside the task

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

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

OK, but it always prints ‘0’ :(

```
// test2.cc
int x = 0;
#pragma omp parallel
#pragma omp single
{
  #pragma omp task depend(inout: x) //T1
  x++;

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

We have a data-race!!

Philosophy: data-flow model (2)

- Properly combining dependences and data-sharings allow us to define a **task data-flow model**
  - → Data that is read in the task → input dependence
  - → Data that is written in the task → output dependence
- A task data-flow model
  - → Enhances the **composability**
  - → **Eases the parallelization** of new regions of your code

Philosophy: data-flow model (3)

```
//test1_v1.cc
int x = 0, y = 0;
#pragma omp parallel
#pragma omp single
{
  #pragma omp task depend(inout: x) //T1
  {
    x++;
    y++;    // !!!
  }
  #pragma omp task depend(in: x)    //T2
  std::cout << x << std::endl;

  #pragma omp taskwait
  std::cout << y << std::endl;
}
```

```
//test1_v2.cc
//test1_v3.cc
//test1_v4.cc
int x = 0, y = 0;
#pragma omp parallel
#pragma omp single
{
  #pragma omp task depend(inout: x, y) //T1
  {
    x++;
    y++;
  }
  #pragma omp task depend(in: x)       //T2
  std::cout << x << std::endl;

  #pragma omp task depend(in: y)       //T3
  std::cout << y << std::endl;
}
```

If all tasks are **properly annotated**,
we only have to worry about the
dependendences & data-sharings of the new task!!!

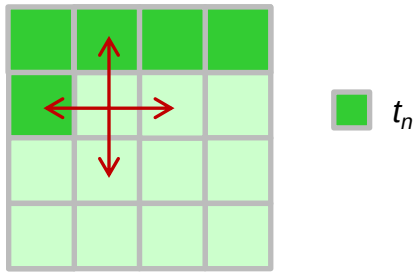
Use case

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

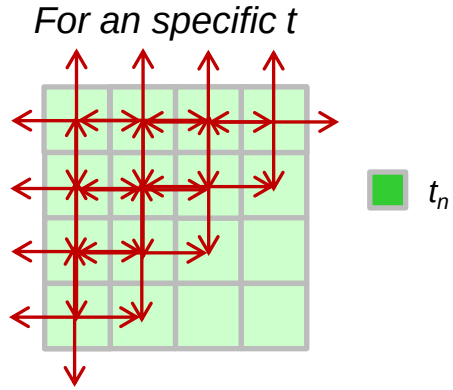


Each cell depends on:
- two cells (north & west) that are computed in the current time step, and
- two cells (south & east) that were computed in the previous time step

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



We can exploit the wavefront to obtain parallelism!!

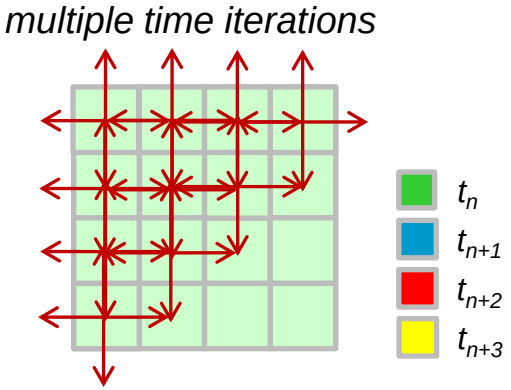
Use case : Gauss-seidel (3)

```
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

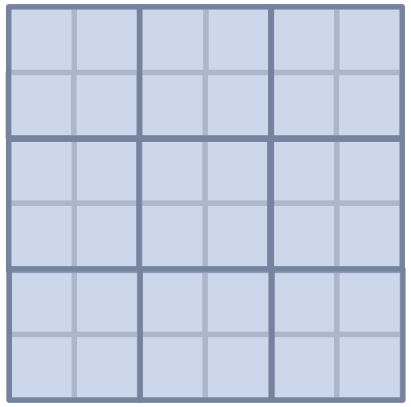


We can exploit the wavefront of multiple time steps to obtain MORE parallelism!!

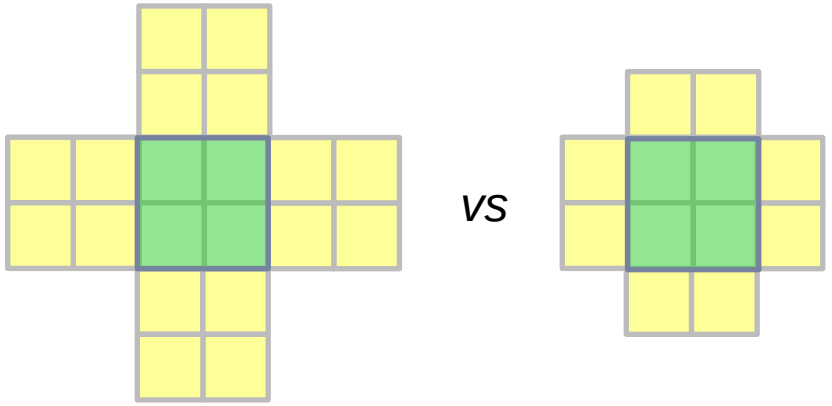
Use case : Gauss-seidel (5)

```
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])
        {
          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

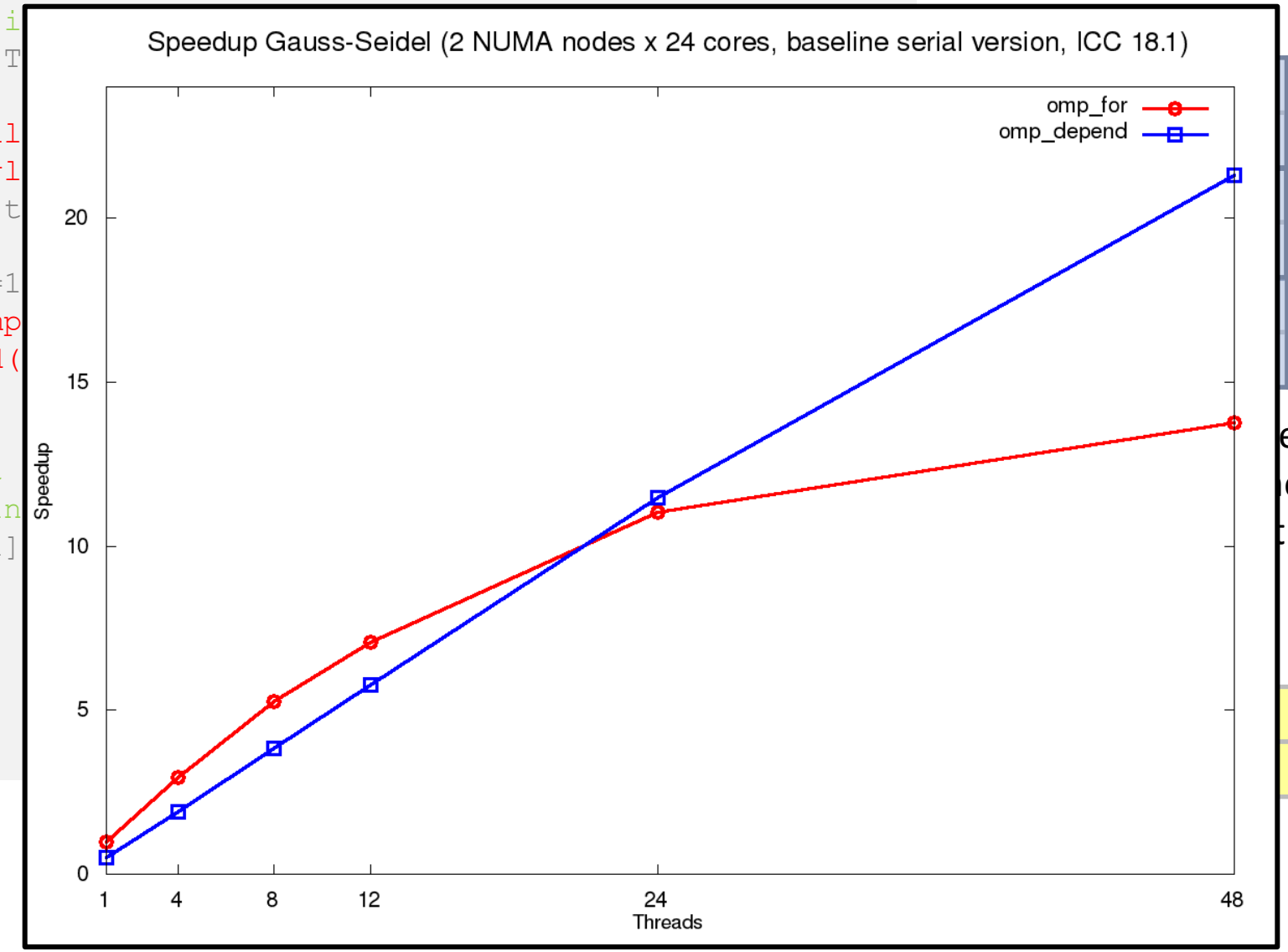


Q: Why do the input dependences depend on the whole block rather than just a column/row?

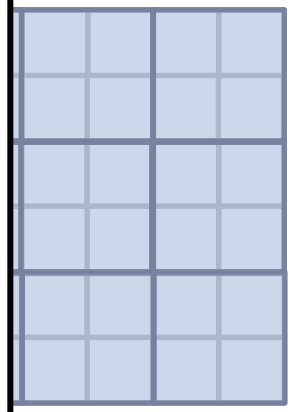


Use case : Gauss-seidel (5)

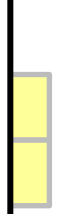
```
void gauss_seidel(i
  int NB = size / T

  #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]

        }
      }
}
```



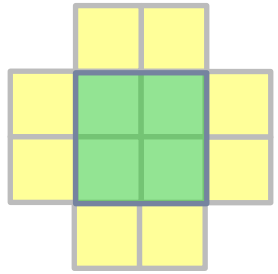
matrix region



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



vs



OpenMP 5.0: (even) more advanced features

Advanced features: deps on `taskwait`

- Adding dependences to the `taskwait` construct
  - → Using a `taskwait` construct to explicitly wait for some predecessor tasks
    - → Syntactic sugar!

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

  #pragma omp task depend(in: y)    //T2
  std::cout << y << std::endl;

  #pragma omp taskwait depend(in: x)

  std::cout << x << std::endl;
}
```

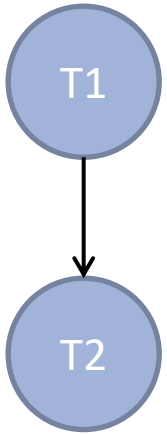
Advanced features: dependable objects (1)

- Offer a way to manually handle dependences
  - → Useful for complex task dependences
  - → It allows a more efficient allocation of task dependences
  - → New `omp_depend_t` opaque type
  - → 3 new constructs to manage dependable objects
    - → `#pragma omp depobj(obj) depend(dep-type: list)`
    - → `#pragma omp depobj(obj) update(dep-type)`
    - → `#pragma omp depobj(obj) destroy`

Advanced features: dependable objects (2)

- Offer a way to manually handle dependences

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

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




```
int x = 0;
#pragma omp parallel
#pragma omp single
{
  omp_depend_t obj;
  #pragma omp depobj(obj) depend(inout: x)

  #pragma omp task depend(depobj: obj)     //T1
  x++;

  #pragma omp depobj(obj) update(in)

  #pragma omp task depend(depobj: obj)     //T2
  std::cout << x << std::endl;

  #pragma omp depobj(obj) destroy
}
```

Programming OpenMP

Cut-off strategies

Christian Terboven

Michael Klemm

RWTH AACHEN UNIVERSITY

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	

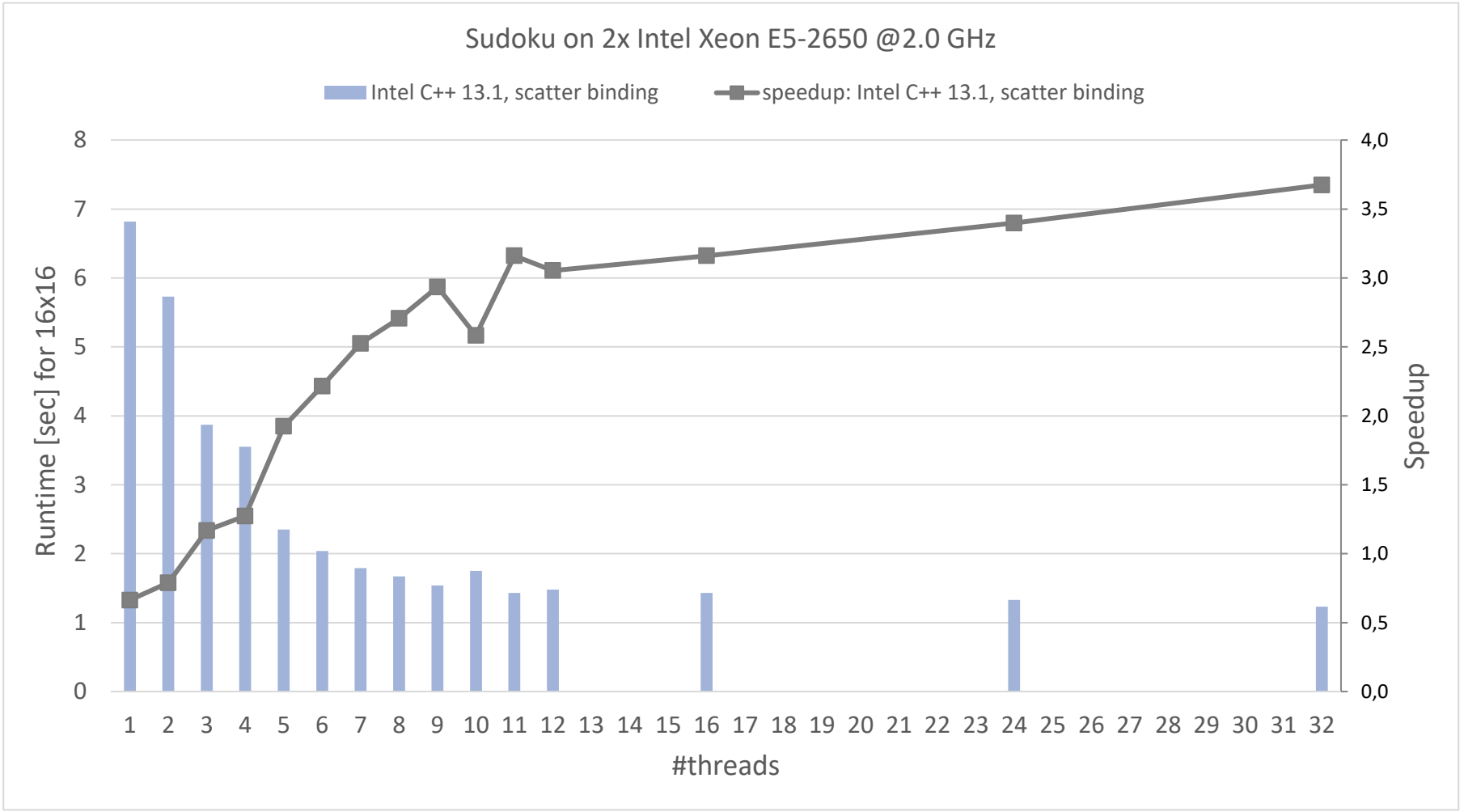
- (1) Search an empty field
- (2) Try all numbers:
  - (2 a) Check Sudoku
    - If invalid: skip
    - If valid: Go to next field
- Wait for completion

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

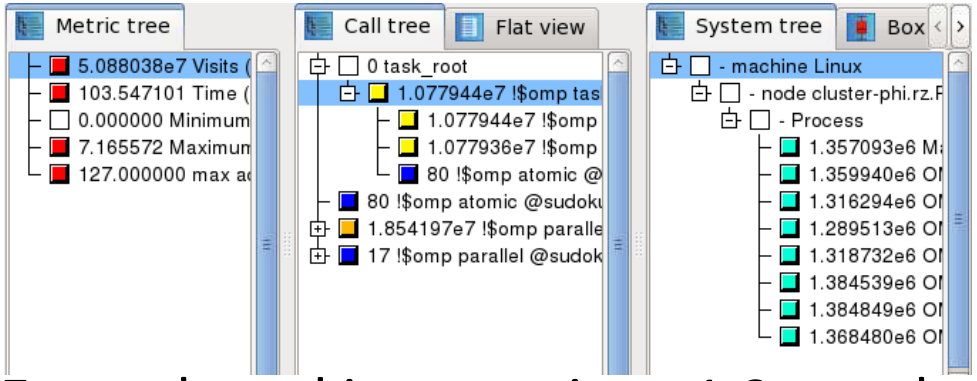
`#pragma omp taskwait`
wait for all child tasks

Performance Evaluation

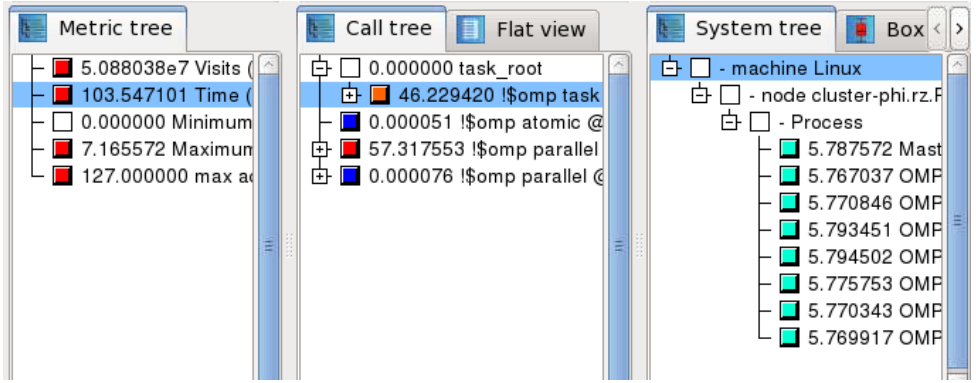


Performance Analysis

Event-based profiling provides a good overview :



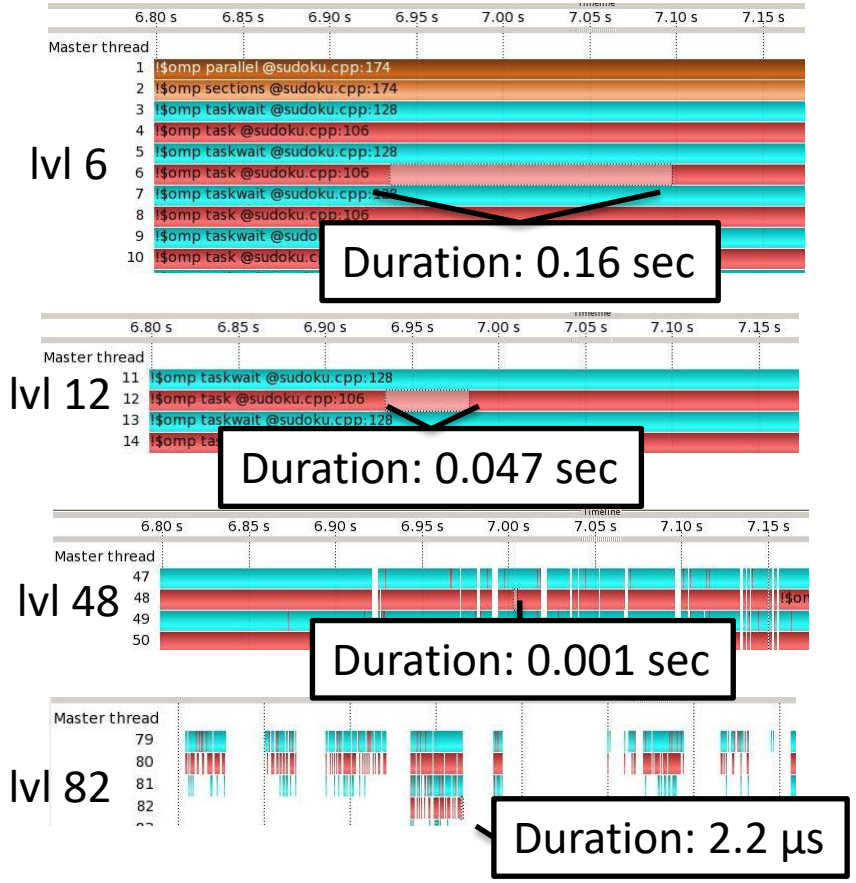
Every thread is executing ~1.3m tasks…



… in ~5.7 seconds.

=> average duration of a task is ~4.4 µs

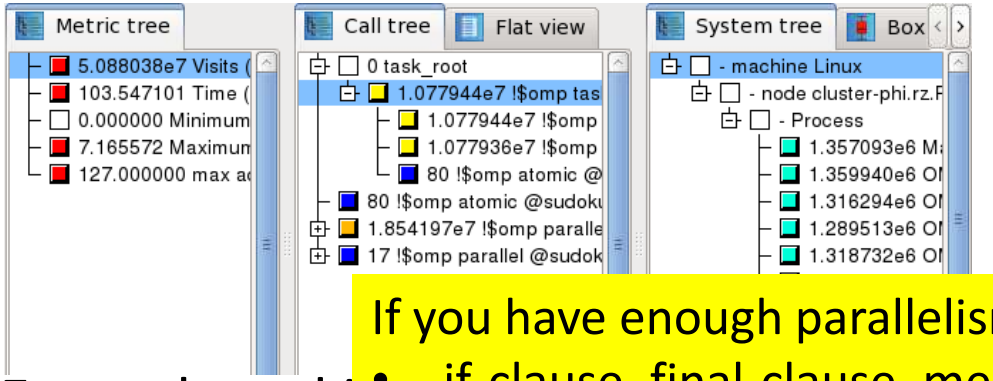
Tracing provides more details:



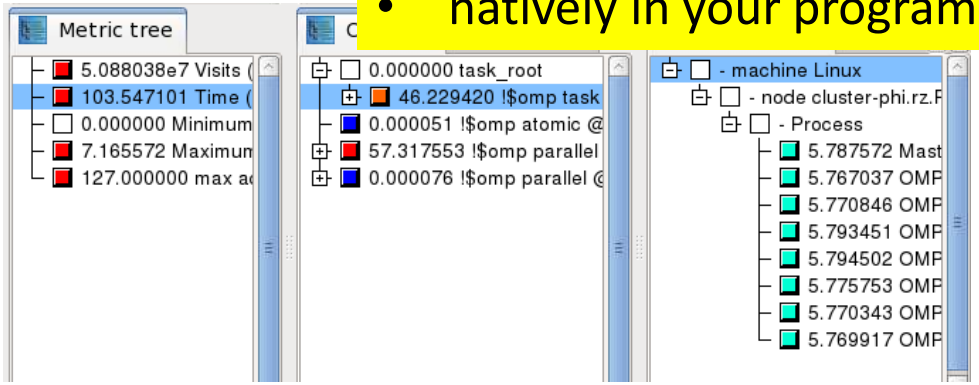
Tasks get much smaller down the call-stack.

Performance Analysis

Event-based profiling provides a good overview :



Every thread i



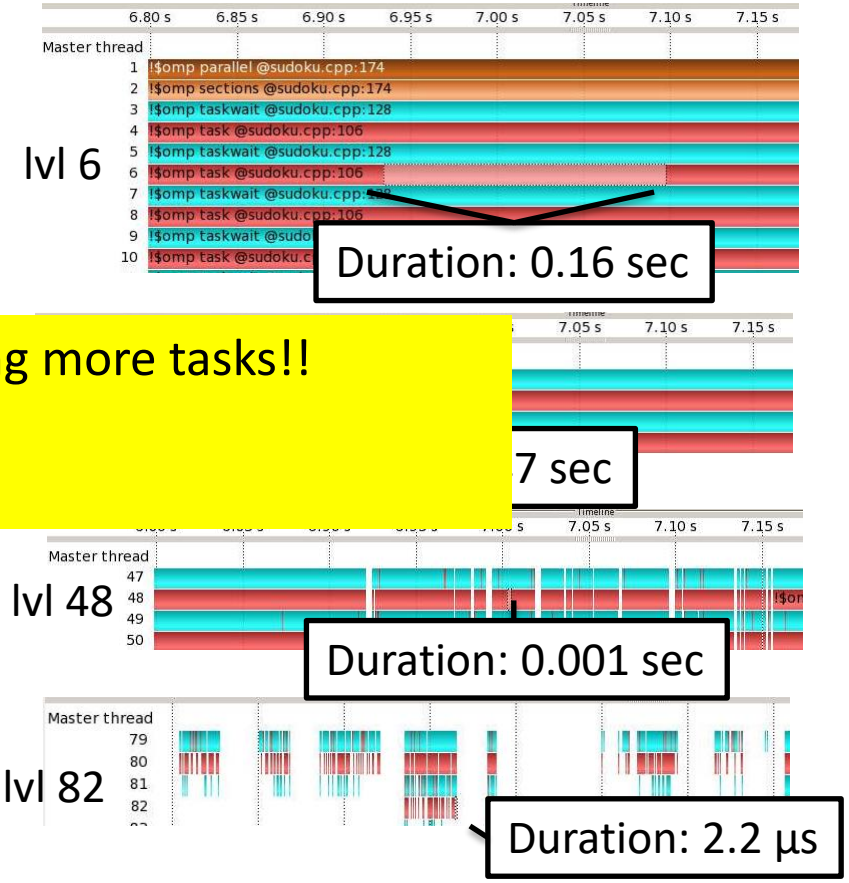
… in ~5.7 seconds.

=> average duration of a task is ~4.4 µs

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

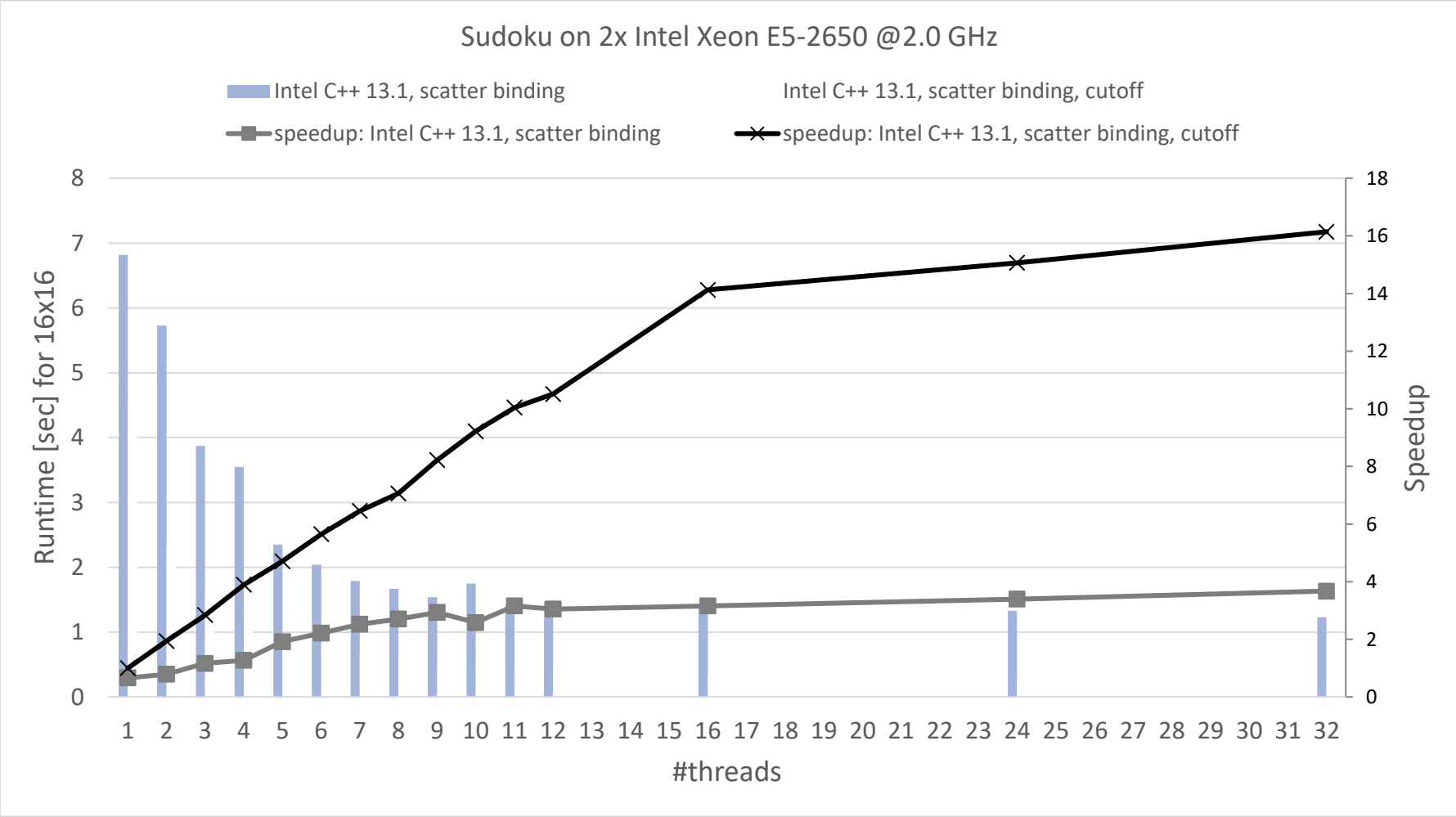
- if-clause, final-clause, mergeable-clause
- natively in your program code

Tracing provides more details:



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");
}
```

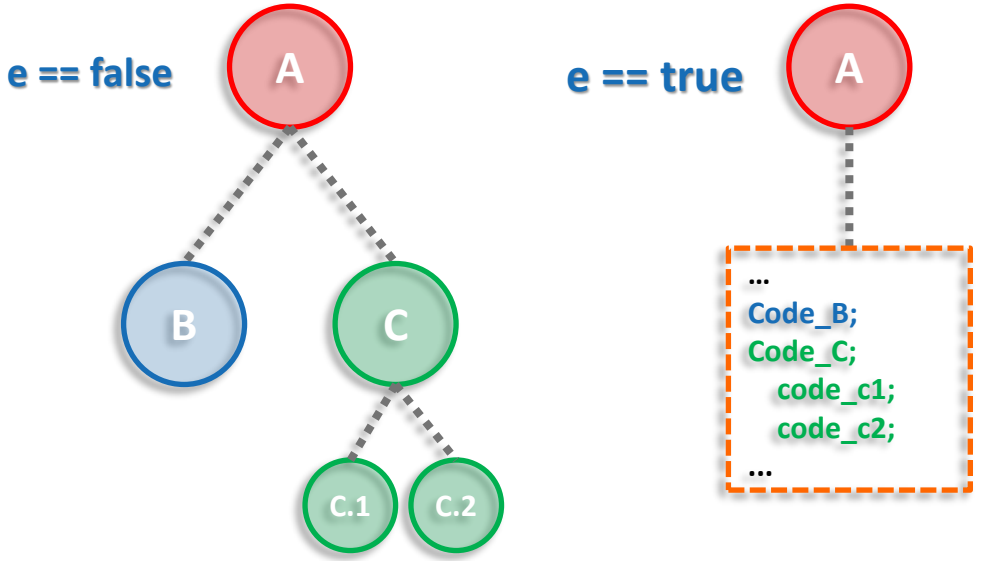
Really useful to debug tasking applications!

- 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

Hands-on Exercises

Christian Terboven

Michael Klemm

RWTH AACHEN UNIVERSITY

Webinar Exercises

- We have implemented a series of small hands-on examples that you can use and play with.
  - → Download: `git clone https://github.com/cterboven/OpenMP-tutorial-EUROfusion.git`
  - → Build: `make`
  - → You can then find the compiled code in the “bin” folder to run it
  - → We use the GCC compiler mostly, some examples require Intel’s Math Kernel Library

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