Parallelism (PAR)

Mastering your task decomposition strategies: going some steps further

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Additional learning material for this lesson

- Atenea: Unit 4 Task decomposition
  - Video lesson 6 (overview iterative vs. recursive task decompositions) and associated questionnaire
  - Additional Atenea quizzes
  - Going further: cut-off based on number of tasks pending to be executed (optional)
- Collection of Exercises: problems in Chapter 4

Outline

Video lesson 6

Task generation control
- Iterative task decompositions
- Recursive task decomposition

Exploratory recursive problems

Reducing overheads and serialization due to synchronization

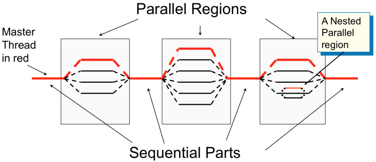
Hardware support for synchronization

Concepts in video lesson 6

- Linear task decomposition
  - Task = code block or procedure invocation
- (Linear) Iterative task decomposition
  - Tasks = body of iterative constructs, such as loops (countable or uncountable)
  - Examples: Pi computation, Mandelbrot and heat diffusion equation in lab sessions, vector and matrix operations, ...
- Recursive task decompostition
  - Tasks = recursive procedure invocations, for example in divide–and–conquer problems
  - Examples: Fibonacci, multisort in lab session, graph exploration problems, ...

Task creation in OpenMP (Labs summary)

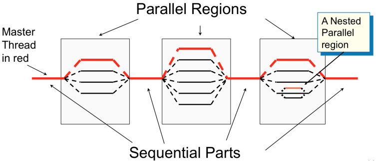
- `#pragma omp parallel`: One **implicit** task is created for each thread in the team (and immediately executed)



- `int omp_get_num_threads`: returns the number of threads in the current team. 1 if outside a parallel region
- `int omp_get_thread_num`: returns the identifier of the thread in the current team that is executing a task, a value between 0 and `omp_get_num_threads()-1`

Task creation in OpenMP (Labs summary)

- `#pragma omp parallel`: One **implicit** task is created for each thread in the team (and immediately executed)



- `#pragma omp task`: One **explicit** task is created, packaging code and data for (possible) deferred execution
- `#pragma omp taskloop`: **Explicit** tasks created for chunks of loop iterations
  - In both cases, tasks executed by threads in the `parallel` region

Outline

Task generation control

Excessive task generation may not be necessary (i.e. cause excessive overhead): need mechanisms to control number of tasks and/or their granularity

- In iterative task decomposition strategies one can control task granularity by setting the number of iterations executed by each task
- In recursive `task` decomposition strategies one can control task granularity by controlling recursion levels where tasks are generated (**cut-off control**)
    - after certain number of recursive calls (static control)
    - when the size of the vector is too small (static control)
    - when there are sufficient tasks pending to be executed (dynamic control)
    - ...

Outline

Video lesson 6

Task generation control

- Iterative task decompositions
- Recursive task decomposition

Exploratory recursive problems

Reducing overheads and serialization due to synchronization

Hardware support for synchronization

Iterative task decomposition (1)

Task granularity defined by the number of iterations out of the loop each task executes. For example, using **implicit tasks**:

```
void vector_add(int *A, int *B, int *C, int n) {
   int who = omp_get_thread_num();
   int nt = omp_get_num_threads();
   int BS = n / nt;
   for (int i = who*BS; i < (who+1)*BS; i++)
       C[i] = A[i] + B[i];
}

void main() {
   ....
   #pragma omp parallel
   vector_add(a, b, c, N);
   ...
}
```

Each implicit task executes a subset of iterations, based in the thread identifier executing the implicit task and the total number of implicit tasks (i.e., number of threads in the team).

Iterative task decomposition (2) (optional)

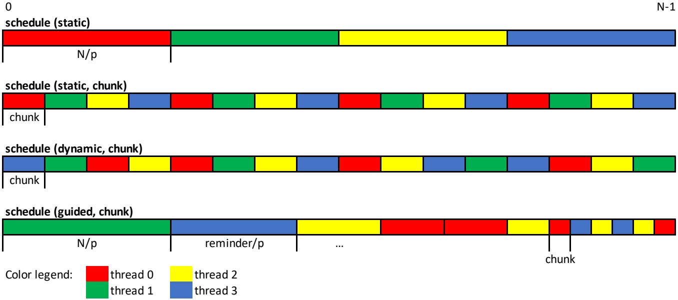
Using the **work–sharing model** in OpenMP (not covered in this course):

```
void vector_add(int *A, int *B, int *C, int n) {
   #pragma omp for schedule(static, BS)
   for (int i=0; i< n; i++)
       C[i] = A[i] + B[i];
}

void main() {
   ....
   #pragma omp parallel
   vector_add(a, b, c, N);
   ...
}
```

Each implicit task executes chunks of iterations, depending on what is specified in the `schedule` clause. Implicit barrier at the end of each work–sharing (`nowait` clause to skip it).

Schedule clause in `for` work–sharing (optional)

Different options to assign chunks of iterations to each implicit task through the `schedule` clause



Iterative task decomposition (3)

Task granularity defined by the number of iterations each task executes. For example, using **explicit tasks**:

```
void vector_add(int *A, int *B, int *C, int n) {
   for (int i=0; i< n; i++)
       #pragma omp task
       C[i] = A[i] + B[i];
}

void main() {
   ....
   #pragma omp parallel
   #pragma omp single
   vector_add(a, b, c, N);
   ...
}
```

each explicit task executes a single iteration of the `i` loop, large task creation overhead, very fine granularity!

Iterative task decomposition (4)

Granularity: chunk of BS loop iterations

- **Option 1:** requires loop transformation

```
void vector_add(int *A, int *B, int *C, int n) {
   int BS = ...
   for (int ii=0; ii< n; ii+=BS)
       #pragma omp task
       for (int i = ii; i < min(ii+BS, n); i++)
           C[i] = A[i] + B[i];
}
void main() {
   ...
   #pragma omp parallel
   #pragma omp single
   vector_add(a, b, c, N);
   ...
}
```

Outer loop jumps over chunks of BS iterations, inner loop traverses each chunk

Iterative task decomposition (5)

- **Option 2:** `taskloop` construct to specify tasks out of loop iterations:

```
void vector_add(int *A, int *B, int *C, int n) {
   int BS = ...
   #pragma omp taskloop grainsize(BS)       // or alternatively num_tasks(n/BS)
   for (int i=0; i< n; i++)
       C[i] = A[i] + B[i];
}
void main() {
   #pragma omp parallel
   #pragma omp single
   ... vector_add(a, b, c, N); ...
}
```

  - `grainsize(m)`: each task executes $[min(m, n) .. 2 \times m)$ consecutive iterations, being n the total number of iterations
  - `num_tasks(m)`: creates as many tasks as $min(m, n)$

Iterative task decomposition: uncountable loop

List of elements, traversed using a `while` loop while not end of list

```
int main() {
   struct node *p;

   p = init_list(n);
   ...
   #pragma omp parallel
   #pragma omp single
   while (p != NULL) {
       #pragma omp task firstprivate(p) // see note below
       process_work(p);
       p = p->next;
       }
   ...
}
```

Granularity is one iteration, hopefully with sufficient work to amortise task creation overhead.

Note: `firstprivate` needed to capture the value of p at task creation time to allow its deferred execution.

Outline

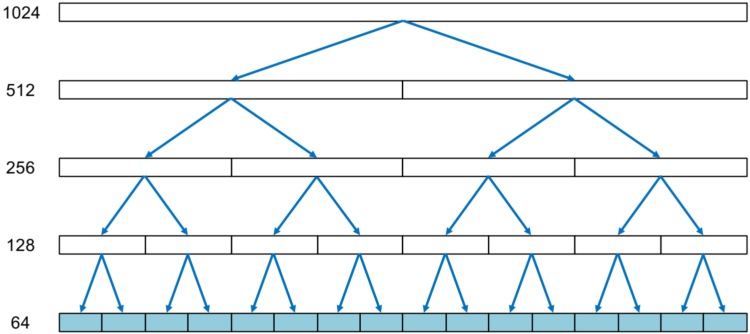
Recursive task decomposition: divide–and–conquer (1)

Recursively divide the problem into smaller sub-problems

```
#define N 1024
#define MIN_SIZE 64
int result = 0;

void dot_product(int *A, int *B, int n) {
   for (int i=0; i< n; i++)
       result += A[i] * B[i];
}

void rec_dot_product(int *A, int *B, int n) {
   if (n>MIN_SIZE) {
       int n2 = n / 2;
       rec_dot_product(A, B, n2);
       rec_dot_product(A+n2, B+n2, n-n2);
   }
   else
       dot_product(A, B, n);
}

void main() {
   rec_dot_product(a, b, N);
}
```

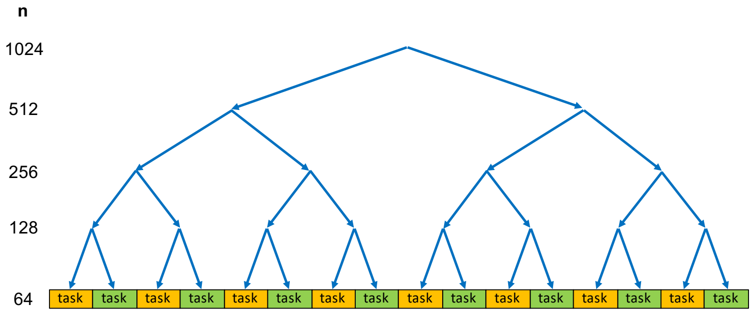
Recursive task decomposition: divide–and–conquer (2)

`N=1024, MIN_SIZE=64`



Recursive task decomposition: leaf strategy (1)

A task corresponds with each invocation of `dot_product` once the recursive invocations stop



- Sequential generation of tasks

Recursive task decomposition: leaf strategy (2)

```
#define N 1024
#define MIN_SIZE 64
int result = 0;

void dot_product(int *A, int *B, int n) {
   for (int i=0; i< n; i++)

       result += A[i] * B[i];
}

void rec_dot_product(int *A, int *B, int n) {
   if (n>MIN_SIZE) {
       int n2 = n / 2;
       rec_dot_product(A, B, n2);
       rec_dot_product(A+n2, B+n2, n-n2);
   }
   else
       #pragma omp task
       dot_product(A, B, n);
}

void main() {
   #pragma omp parallel
   #pragma omp single
   rec_dot_product(a, b, N);
}
```

Recursive task decomposition: leaf strategy (3)

```
#define N 1024
#define MIN_SIZE 64
int result = 0;

void dot_product(int *A, int *B, int n) {
   for (int i=0; i< n; i++)
       #pragma omp atomic
       result += A[i] * B[i];
}

void rec_dot_product(int *A, int *B, int n) {
   if (n>MIN_SIZE) {
       int n2 = n / 2;
       rec_dot_product(A, B, n2);
       rec_dot_product(A+n2, B+n2, n-n2);
   }
   else
       #pragma omp task
       dot_product(A, B, n);
}
```

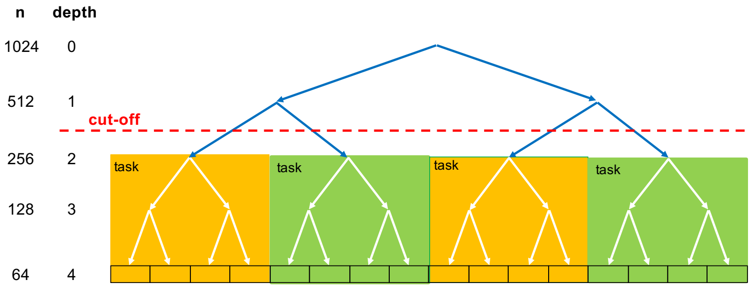
How could you reduce the overhead of updating variable `result`?

Recursive task decomposition: leaf strategy (4)

```
#define N 1024
#define MIN_SIZE 64
int result = 0;

void dot_product(int *A, int *B, int n) {
   int tmp = 0;
   for (int i=0; i< n; i++)
       tmp += A[i] * B[i];
   #pragma omp atomic
   result += tmp;
}

void rec_dot_product(int *A, int *B, int n) {
   if (n>MIN_SIZE) {
       int n2 = n / 2;
       rec_dot_product(A, B, n2);
       rec_dot_product(A+n2, B+n2, n-n2);
   }
   else
       #pragma omp task
       dot_product(A, B, n);
}
```

How to control task granularity in leaf strategy (1)

Leaf parallelization with **depth recursion control**



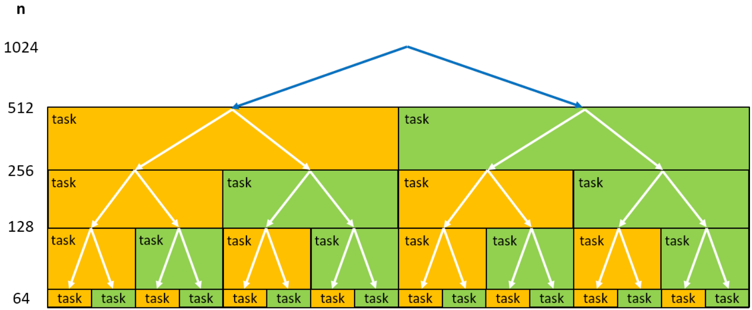
How to control task granularity in leaf strategy (2)

Leaf strategy with **depth recursion control**

```
#define CUTOFF 2
...
void rec_dot_product(int *A, int *B, int n, int depth) {
    if (n>MIN_SIZE) {
        int n2 = n / 2;
        if (depth == CUTOFF)
            #pragma omp task
            {
                rec_dot_product(A, B, n2, depth+1);
                rec_dot_product(A+n2, B+n2, n-n2, depth+1);
            }
        else {
            rec_dot_product(A, B, n2, depth+1);
            rec_dot_product(A+n2, B+n2, n-n2, depth+1);
        }
    }
    else    // if recursion finished, need to check if task has been generated
        if (depth <= CUTOFF)
            #pragma omp task
            dot_product(A, B, n);
        else
            dot_product(A, B, n);
}
...
```

Recursive task decomposition: tree strategy (1)

A task corresponds with each invocation of `rec_dot_product`



- Parallel generation of tasks
- Granularity: some tasks simply generate new tasks

Recursive task decomposition: different sequential code ...

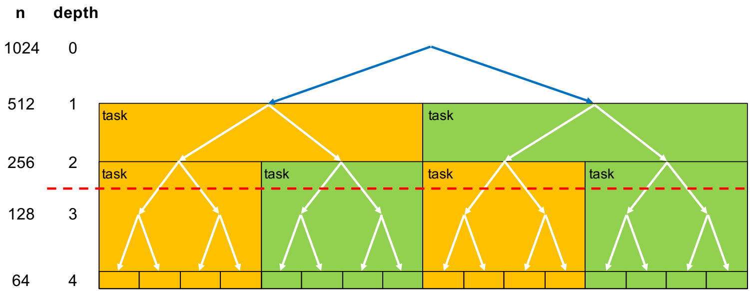
```
int dot_product(int *A, int *B, int n) {
   int tmp = 0;
   for (int i=0; i< n; i++) tmp += A[i] * B[i];
   return(tmp);
}

int rec_dot_product(int *A, int *B, int n) {
   int tmp1, tmp2 = 0;
   if (n>MIN_SIZE) {
       int n2 = n / 2;
       tmp1 = rec_dot_product(A, B, n2);
       tmp2 = rec_dot_product(A+n2, B+n2, n-n2);
   } else  tmp1 = dot_product(A, B, n);
   return(tmp1+tmp2);
}

void main() {
   result = rec_dot_product(a, b, N);
}
```

Recursive task decomposition: tree strategy (2)

```
int dot_product(int *A, int *B, int n) {
   int tmp = 0;
   for (int i=0; i< n; i++) tmp += A[i] * B[i];
   return(tmp);
}

int rec_dot_product(int *A, int *B, int n) {
   int tmp1, tmp2 = 0;
   if (n>MIN_SIZE) {
       int n2 = n / 2;
       #pragma omp task shared(tmp1) // firstprivate(A, B, n, n2) by default
       tmp1 = rec_dot_product(A, B, n2);
       #pragma omp task shared(tmp2) // firstprivate(A, B, n, n2) by default
       tmp2 = rec_dot_product(A+n2, B+n2, n-n2);
       #pragma omp taskwait
   } else tmp1 = dot_product(A, B, n);
   return(tmp1+tmp2);
}

void main() {
   #pragma omp parallel
   #pragma omp single
   result = rec_dot_product(a, b, N);
}
```

How to control task granularity in tree strategy (1)

Tree strategy with **depth recursion control**



How to control task granularity in tree strategy (2)

Tree strategy with **depth recursion control**

```
#define N 1024
#define MIN_SIZE 64
#define CUTOFF 3

int rec_dot_product(int *A, int *B, int n, int depth) {
   int tmp1, tmp2 = 0;
   if (n>MIN_SIZE) {
        int n2 = n / 2;
        if (depth < CUTOFF) {
           #pragma omp task shared(tmp1)
           tmp1 = rec_dot_product(A, B, n2, depth+1);
           #pragma omp task shared(tmp2)
           tmp2 = rec_dot_product(A+n2, B+n2, n-n2, depth+1);
           #pragma omp taskwait
        } else {
           tmp1 = rec_dot_product(A, B, n2, depth+1);
           tmp2 = rec_dot_product(A+n2, B+n2, n-n2, depth+1);
        }
   }
   else tmp = dot_product(A, B, n);
   return(tmp1+tmp2);
}
```

OpenMP support for cut-off (1)

- `final` clause: If the expression of a `final` clause evaluates to *true* the generated task and **all of its descendent tasks** will be final. The execution of a final task is sequentially **included** in the generating task (but the task is still generated)

- `omp_in_final()` intrinsic function: it returns true when executed in a final task region; otherwise, it returns false.

OpenMP support for cut-off: tree strategy (1)

Making use of omp_in_final:

```
#define MIN_SIZE 64
#define CUTOFF 3
...
int rec_dot_product(int *A, int *B, int n, int depth) {
   int tmp1, tmp2 = 0;
   if (n>MIN_SIZE) {
       int n2 = n / 2;
       if (!omp_in_final()) {
           #pragma omp task shared(tmp1) final(depth >= CUTOFF)
           tmp1 = rec_dot_product(A, B, n2, depth+1);
           #pragma omp task shared(tmp2) final(depth >= CUTOFF)
           tmp2 = rec_dot_product(A+n2, B+n2, n-n2, depth+1);
           #pragma omp taskwait
       } else {
           tmp1 = rec_dot_product(A, B, n2, depth+1);
           tmp2 = rec_dot_product(A+n2, B+n2, n-n2, depth+1);
       }
   }
   else tmp1 = dot_product(A, B, n);
   return(tmp1+tmp2);
}
...
```

OpenMP support for cut-off (2)

- `mergeable` clause: when a mergeable clause is present on a task construct, and the generated task is an undeferred task or an included task, then the compiler may choose to generate a merged task instead. If a merged task is generated, then the behavior is as though there was no task directive at all
  - Not implemented in all compilers, so the optimization needs to be implemented by the programmer using the `omp_in_final` instrinsic

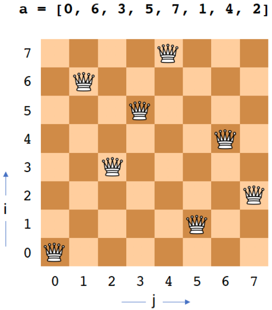
OpenMP support for cut-off: tree strategy (2)

```
#define MIN_SIZE 64
#define CUTOFF 3
...
int rec_dot_product(int *A, int *B, int n, int depth) {
   int tmp1, tmp2 = 0;
   if (n>MIN_SIZE) {
       int n2 = n / 2;
       #pragma omp task shared(tmp1) final(depth >= CUTOFF) mergeable
       tmp1 = rec_dot_product(A, B, n2, depth+1);
       #pragma omp task shared(tmp2) final(depth >= CUTOFF) mergeable
       tmp2 = rec_dot_product(A+n2, B+n2, n-n2, depth+1);
       #pragma omp taskwait
   }
   else tmp1 = dot_product(A, B, n);
   return(tmp1+tmp2);
}
...
```

Outline

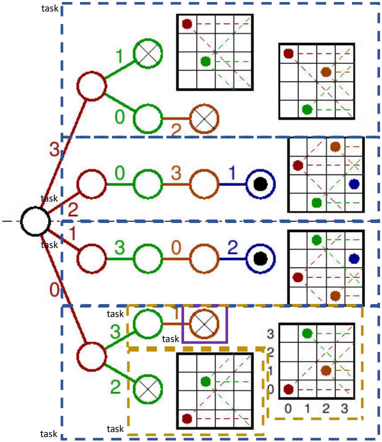
How would you address the N-queens problem? (1)

```
char *a; // Solution being explored
int sol_count = 0; // Total number of solutions found
int size = 8; // board size

void nqueens(int n, int j, char *a) {
    if (j == n) sol_count += 1;
    else
        // try each possible position for queen <j>
        for ( int i=0 ; i < n ; i++ ) {
            a[j] = (char) i;
            if (ok(j + 1, a)) nqueens(n, j + 1, a);
        }
}

int main() {
    a = alloca(size * sizeof(char));
    nqueens(size, 0, a);
}
```



How would you address the N-queens problem? (2)

For a 4x4 board, the recursion tree would be ...



How would you address the N-queens problem? (3)

```
void nqueens(int n, int j, char *a) {
     if (j == n)
          #pragma omp atomic
          sol_count += 1;
     else
        // try each possible position for queen <j>
        for ( int i=0 ; i < n ; i++ ) {
           a[j] = (char) i;
           if (ok(j + 1, a))
              #pragma omp task                        // all firstprivate by default
              nqueens(n, j + 1, a);
        }
     // Do we need to insert a task barrier at this point?
}

int main() {
     a = alloca(size * sizeof(char));
     #pragma omp parallel
     #pragma omp single
     nqueens(size, 0, a);
}
```

Do we need a new board for each task to be able to explore its own path? Is the implicit `firstprivate(a)` enough?

How would you address the N-queens problem? (4)

A new board has to be allocated if the path is explored as a task

```
void nqueens(int n, int j, char *a) {
     if (j == n)
          #pragma omp atomic
          sol_count += 1;
     else {
        // try each possible position for queen <j>
        for ( int i=0 ; i < n ; i++ ) {
           a[j] = (char) i;
           if (ok(j + 1, a)) {
              // allocate a temporary array and copy <a> into it
              char * b = alloca(n * sizeof(char));
              memcpy(b, a, (j + 1) * sizeof(char));
              #pragma omp task                        // all firstprivate by default
              nqueens(n, j + 1, b);
        }
        #pragma omp taskwait
     }
}
```

Important: `firstprivate(b)` (implicit for new board) captures the pointer to `b`, not the whole vector `b`

Where to dynamically allocate this memory?

- `ptr=malloc(size)`: allocates memory block of given `size` (in bytes) in the heap, not initialized
- `ptr=alloca(size)`: as `malloc` but within the current function's stack frame; this memory will be automatically deallocated from the stack when the current function returns!

Important: we must insert `taskwait` if using `alloca`. For `malloc` not strictly necessary, but we have to deallocate memory

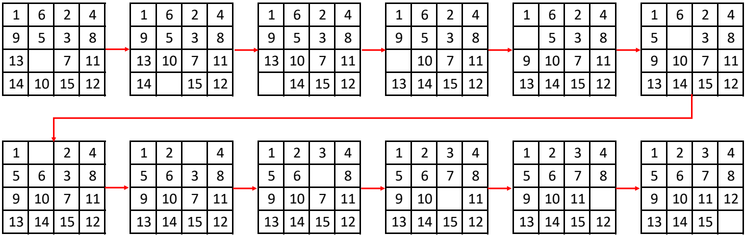
```
...
char * b = malloc(n * sizeof(char));
memcpy(b, a, (j + 1) * sizeof(char));
#pragma omp task
{
    nqueens(n, j + 1, b);
    free(b);
}
...
```

Adding cut-off to N-queens (recursion level)

```
void nqueens(int n, int j, char *a) {
     if (j == n)
          #pragma omp atomic
          sol_count += 1;
     else
        // try each possible position for queen <j>
        if (!omp_in_final()) {
           for ( int i=0 ; i < n ; i++ ) {
              a[j] = (char) i;
              if (ok(j + 1, a))
                 // allocate a temporary array and copy <a> into it
                 char * b = alloca(n * sizeof(char));
                 memcpy(b, a, (j + 1) * sizeof(char));
                 #pragma omp task final(j>CUT_OFF)
                 nqueens(n, j + 1, b);
            }
            #pragma omp taskwait
        } else
           for ( int i=0 ; i < n ; i++ ) {
              a[j] = (char) i;
              if (ok(j + 1, a)) nqueens(n, j + 1, a);
           }
}
```

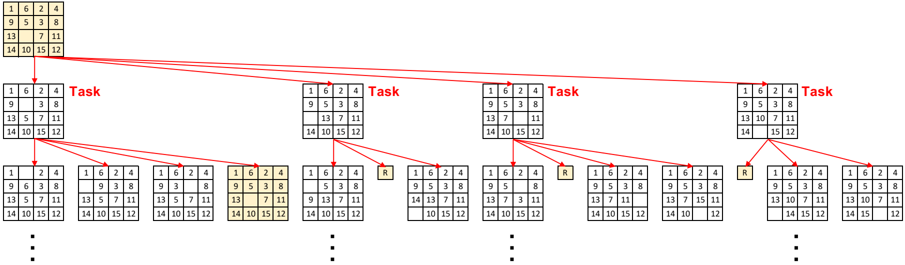
Another example: 15-puzzle (without code) ... (optional)

The solution to a 15-puzzle (a tile puzzle). Possible movements of the empty cell: UP, RIGHT, LEFT and DOWN. Here we show a series of moves that transform a given initial state to the desired final state:



Another example: 15-puzzle (without code) ... (optional)

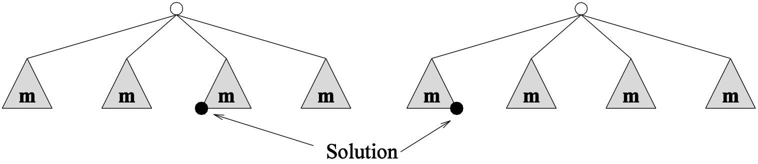
The state space can be explored by generating various successor states of the current state and to view them as independent tasks



R: repeated configuration

Another example: 15-puzzle (without code) ... (optional)

Anomalous speed–ups of the parallel formulation of the problem: the speed–up depends on where the solution is found ...



- Left: $T_1 = 2 \times m + 1$ and $T_4 = 1$, therefore ... $S_4 = 2 \times m + 1$
- Right: $T_1 = m$ and $T_4 = m$, therefore ... $S_4 = 1$

And the parallel efficiency (i.e. how well used are processors)? Observe that on the right three processors waste their computation

Cancellation points in OpenMP (optional)

Tasks induced by exploratory decomposition can be terminated before finishing as soon as the desired solution is found

- `#pragma omp cancel [parallel | taskgroup]`: this directive activates the cancellation of the enclosing `[parallel | taskgroup]` region. The thread that finds the directive finishes its execution; the other threads continue their execution as normal.
- `#pragma omp cancellation point [parallel | taskgroup]`: introduces a point to check if cancellation has been activated. When found by a thread, if the enclosing `[parallel | taskgroup]` region has been already cancelled, then it finishes its execution.

Cancellation points in OpenMP: very simple example (optional)

```
#pragma omp taskgroup
for (i=0; i<1000; i=i+100)
    #pragma omp task firstprivate(i) private(j)
    {
        for (j=i; j<i+100; j++) {
            if (do_computation(j) == 0) {
                #pragma omp cancel taskgroup
            }
            #pragma omp cancellation point taskgroup
        }
    }
```

The first task with 0 as a result of `do_computation` will finalise the execution of all the tasks in the `taskgroup`

Outline

Protecting task interactions in OpenMP (Labs summary)

Two mechanisms:

1. Atomic accesses: mechanism to guarantee atomicity in load/store instructions

   ```
   #pragma omp atomic [update | read | write]
        expression
   ```

   - Atomic updates: `x += 1`, `x = x - foo()`, `x[index[i]]++`
   - Atomic reads: `value = *p`
   - Atomic writes: `*p = value`

Protecting task interactions in OpenMP (Labs summary)

Two mechanisms:

2. Mutual exclusion: mechanism to ensure that only one task at a time executes the code within a critical section
   - `critical` pragma: a thread waits at the beginning of a critical region until no other thread is executing a critical region (anywhere in the program)
   - `critical(name)` pragma: the `name` allows the programmer to differentiate disjoint sets of critical sections (name is a label, not a program variable)
   - `omp_lock_t` OpenMP intrinsics and low-level synchronization primitives (next in this chapter)

Reducing task interactions: overhead (1)

Reductions: replicate key data structures and locally working with these local structures; when appropriate, locally replicated data structures are combined into the final global result

```
int result = 0;
// Assume this function is instantiated as a task
void dot_product(int *A, int *B, int n) {
   for (int i=0; i< n; i++)
       #pragma omp atomic
       result += A[i] * B[i];
}
```

could be easily transformed into

```
void dot_product(int *A, int *B, int n) {
   int tmp = 0;
   for (int i=0; i< n; i++)
       tmp += A[i] * B[i];

    #pragma omp atomic
    result += tmp;
}
```

Reducing task interactions: overhead (2)

Specifying reduction operations in explicit tasks generated with either `task`:

```
#pragma omp parallel
#pragma omp single
{
    #pragma omp taskgroup task_reduction(+: sum)
    for (i=0; i< SIZE; i++)
        #pragma omp task firstprivate(i) in_reduction(+: sum)
        sum += X[i];
}
```

or `taskloop`:

```
#pragma omp parallel
#pragma omp single
{
    // implicit taskgroup in taskloop construct
    #pragma omp taskloop reduction(+: sum)
    for (i=0; i< SIZE; i++)
        sum += X[i];
}
```

Low-level synchronization functions using *locks*

Locks: special variables that live in memory with two basic operations:

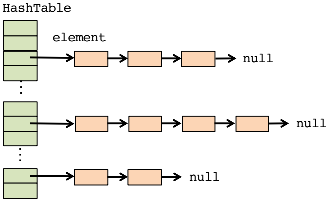
- Acquire: while a thread has the lock, nobody else gets it; this allows the thread to do its work in private, not bothered by other threads
- Release: allow other threads to acquire the lock and do their work (one at a time) in private

Type definition and instrinsics:

```
void omp_init_lock(omp_lock_t *lock)
void omp_destroy_lock(omp_lock_t *lock)

void omp_set_lock(omp_lock_t *lock)
void omp_unset_lock(omp_lock_t *lock)

int omp_test_lock(omp_lock_t *lock)
```

Reducing task interactions: serialization (1)

Example: inserting elements in hash table defined as a collection of linked lists




```
typedef struct {
    int data;
    element *next;
} element;

int dataTable[SIZE_TABLE];
element * HashTable[SIZE_HASH];

for (i = 0; i < SIZE_TABLE; i++) {
    int index = hash_function (dataTable[i], SIZE_HASH);
    insert_element (dataTable[i], index, HashTable);
}
```

Reducing task interactions: serialization (2)

Easily parallelizable using an iterative task decomposition using `taskloop`. However ...

- ... updates to the list in any particular slot must be protected to prevent a race condition

```
typedef struct {
    int data;
    element *next;
} element;

int dataTable[SIZE_TABLE];
element * HashTable[SIZE_HASH];

#pragma omp taskloop
for (i = 0; i < elements; i++) {
    int index = hash_function (dataTable[i], SIZE_HASH);
    #pragma omp critical  // atomic not possible here
    insert_element (dataTable[i], index, HashTable);
}
```

- Serialization in the insertion of elements

Reducing task interactions: serialization (3)

Associate a lock variable with each slot in the hash table, protecting the chain of elements in an slot

```
omp_lock_t hash_lock[SIZE_HASH];

#pragma omp parallel
#pragma omp single
{
for (i = 0; i < SIZE_HASH; i++) omp_init_lock(&hash_lock[i]);

#pragma omp taskloop
for (i = 0; i < SIZE_TABLE; i++) {
    int index = hash_function (dataTable[i], SIZE_HASH);
    omp_set_lock (&hash_lock[index]);
    insert_element (dataTable[i], index, HashTable);
    omp_unset_lock (&hash_lock[index]);
}

for (i = 0; i < SIZE_HASH; i++) omp_destroy_lock(&hash_lock[i]);
}
```

Threads may be inserting elements into the hash table in parallel, as long as these elements hash to different slots

Task ordering in OpenMP (Labs summary)

- Thread barriers: wait for all threads to finish previous work (`#pragma omp barrier` and implicit barriers at the end of OpenMP constructs)
- Task barriers:
  - `taskwait`: Suspends the execution of the current task, waiting on the completion of its **child tasks**. The taskwait construct is a stand-alone directive.
  - `taskgroup`: Suspends the execution of the current task at the end of structured block, waiting on the completion of **child tasks** of the current task **and their descendent** tasks.
- Task dependences (next ...)

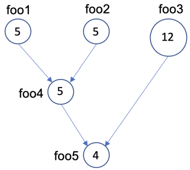
taskwait vs. taskgroup

```
#pragma omp task {}      // T1
#pragma omp task        // T2
{
    #pragma omp task {}  // T3
}
#pragma omp task {}      // T4

#pragma omp taskwait
// Only T1, T2 and T4 are guaranteed to have finished at this point when T5 is created
#pragma omp task {}      // T5
```

```
#pragma omp task {}          // T1
#pragma omp taskgroup
{
    #pragma omp task         // T2
    {
        #pragma omp task {}  // T3
    }
    #pragma omp task {}      // T4
}
// Only T2, T3 and T4 are guaranteed to have finished at this point when T5 is created
#pragma omp task {}          // T5
```

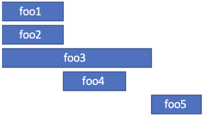
Serialisation caused by task barriers (1)

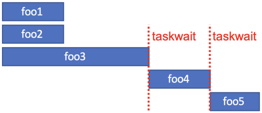
Given a TDG to implement with the OpenMP tasking model:




```
#pragma omp task
foo1()
#pragma omp task
foo2()
#pragma omp task
foo3()
#pragma omp taskwait
#pragma omp task
foo4()
#pragma omp taskwait
#pragma omp task
foo5()
```

```
#pragma omp task
foo1()
#pragma omp task
foo2()
#pragma omp taskwait
#pragma omp task
foo3()
#pragma omp task
foo4()
#pragma omp taskwait
#pragma omp task
foo5()
```



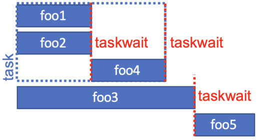


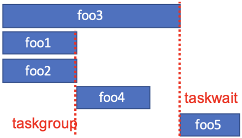
Serialisation caused by task barriers (2)

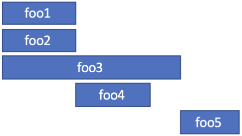
```
#pragma omp task
   {
   #pragma omp task
   foo1()
   #pragma omp task
   foo2()
   #pragma omp taskwait
   #pragma omp task
   foo4()
   #pragma omp taskwait
   }
#pragma omp task
foo3()
#pragma omp taskwait
#pragma omp task
foo5()
```

```
#pragma omp task
foo3()
#pragma omp taskgroup
   {
   #pragma omp task
   foo1()
   #pragma omp task
   foo2()
   }
#pragma omp task
foo4()
#pragma omp taskwait
#pragma omp task
foo5()
```

```
#pragma omp task depend(out: a)
foo1()
#pragma omp task depend(out: b)
foo2()
#pragma omp task depend(out: c)
foo3()
#pragma omp task depend(in: a, b)
                 depend(out: d)
foo4()
#pragma omp task depend(in: c, d)
foo5()
```







Avoiding task barriers: task dependences (1)

- The OpenMP runtime detects dependences between sibling tasks (i.e. from the same parent task) through the specification of the directionality for the variables used in the tasks

```
#pragma omp task [depend (in : var_list)]
                 [depend (out : var_list)]
                 [depend (inout : var_list)]
```

Task dependences are derived from the directionality type (`in`, `out` or `inout`) and its items in `var_list`; this list may include array sections (e.g. v[0:n])

Avoiding task barriers: task dependences (2)

- `in` specifier: the generated task will be a dependent task of all previously generated sibling tasks that reference at least one of the list items in an `out` or `inout` list [1]
- `out` and `inout` specifier: the generated task will be a dependent task of all previously generated sibling tasks that reference at least one of the list items in an `in`, `out`, or `inout` list

Types of dependences:

- *read–after–write*: caused by matched out – in
- *write–after–read*: caused by matched in – out
- *write–after–write*: caused by matched out – out

[1] Note: if a list item is an array section, the matching should occur with an identically defined array section.

Example: wavefront execution with task dependences

- Function `foo(i, j)` processes *block(i, j)*
- Wave-front execution: the execution of `foo(i,j)` depends on `foo(i-1, j)` and `foo(i, j-1)`

```
#pragma omp parallel private(i, j)
#pragma omp single
{
   for (i=1; i<n i++) {
        for (j=1; j<n;j++) {
           #pragma omp task // firstprivate(i, j) by default
                            depend(in : block[i-1][j], block[i][j-1])
                            depend(out: block[i][j])
           foo(i,j);
         }
    }
}
```

Additional functionalities (1) (optional)

- `taskwait` with `depend` clause: instead of waiting for all child tasks to complete execution, it only waits for the predecessor child tasks according to the `in`, `out` and `inout` specifiers

```
int x=0; y=2;

#pragma omp task depend(out: x) shared(x)
compute_short1(&x);

#pragma omp task shared(y)
compute_long(&y);

#pragma omp taskwait depend(in: x)   // y not waited for at this point
printf("intermediate value for x=%d\n",x);

#pragma omp task shared(x)
compute_short2(&x)

#pragma omp taskwait
printf("final values for x=%d ; y=%d\n", x, y);
```

Additional functionalities (2) (optional)

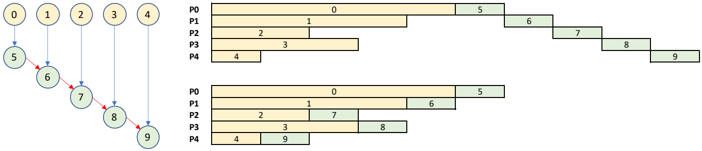
- An `iterator` can be used in the `depend` clause, expanding to multiple values in the specifier they appear

```
for (i = 0; i < n; ++i)
    if (i%2) {
        #pragma omp task depend(out: v[i])
        compute_element(&v[i], i);
    }

#pragma omp task depend(iterator(it = 0:n), in: v[it])
                              // could also be depend(iterator(it = 1:n:2), in: v[it])
odd = sum_odd_elements(v, n);

even = sum_even_elements(v, n);
```

Note: this is not equivalent to the use of an array section in the `in` specifier (i.e. `depend(in:v[0:n])`), why not?

Additional functionalities (3) (optional)

- `mutexinoutset` specifier: equivalent to `inout` but all dependent tasks can be executed in any order, one after the other



Red dependence expressed with `depend(inout:x)` (top temporal diagram) or with `depend(mutexinoutset:x)` (bottom temporal diagram). Observe that tasks can be executed in any order, but only one at a time.

Outline

How are synchronizations implemented?

```
#pragma omp atomic
var += non_protected_func();
```

```
#pragma omp critical
{
    // exclusive access
}
```

```
omp_set_lock(&lock_var);
// exclusive access
omp_unset_lock(&lock_var);
```

- In fact, entry to and exit from `critical` is the same as `omp_set_lock` and `omp_unset_lock`, respectively, but using an implicit (hidden) `omp_lock_t` variable
- `atomic` could also be implemented with `omp_lock_t`, but usually there is much better support at the architecture level (see later ...)
- How to implement lock-based synchronisation mechanisms?

Example: a simple, but incorrect, lock

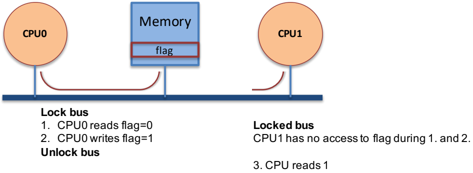
- What's wrong with ...?
  (assume flag=0 means lock is free; taken otherwise)

```
             CPU0                                 CPU1

             // omp_lock_t flag                   // omp_lock_t flag
init_lock:   st flag, #0              init_lock:  st flag, 0
             ...                                  ...
set_lock:    ld r1, flag              set_lock:   ld r1, flag
             bnez r1, set_lock                    bnez r1, set_lock
             st flag, #1                          st flag, #1
             ...                                 ...
             // safe access                       // safe access
             ...                                 ...
unset_lock:  st flag, #0              unset_lock: st flag, #0
             ...                                  ...
```

- Problem: data race because sequence load–test–store is not atomic!

Support for synchronization at the architecture level

- Need hardware support to guarantee atomic (indivisible) instruction to fetch and update memory



- `test-and-set`: read value in location and set to 1
  Example: test-and-set based lock implementation

```
set_lock:   t&s r2, flag
            bnez r2, set_lock     // already locked?
            ...
unset_lock: st flag, #0           // free lock
```

Support for synchronization at the architecture level

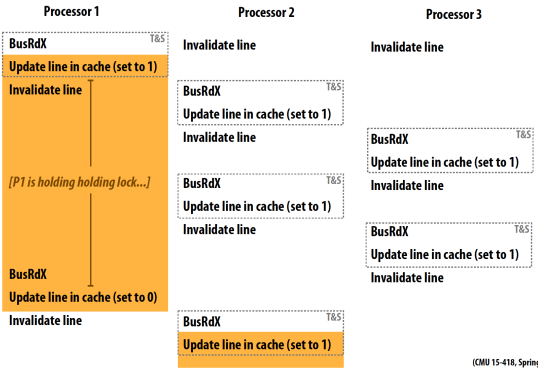
- Atomic exchange: interchange of a value in a register with a value in memory
  Example: atomic exchange based lock implementation

```
             mov r2, #1
set_lock:    exch r2, flag         // atomic exchange
             bnez r2, set_lock     // already locked?
             ...
unset_lock:  st flag, #0           // free lock
```

- `fetch-and-op`: read value in location and replace with result after simple arithmetic operation (usually add, increment, sub or decrement). **Valid to implement** `#pragma omp atomic`

test-and-set lock coherence traffic

```
set_lock:   t&s r2, flag           // test and acquire lock if free
            bnez r2, set_lock      // do it again if already locked
            ...
unset_lock: st flag, #0            // free the lock
```



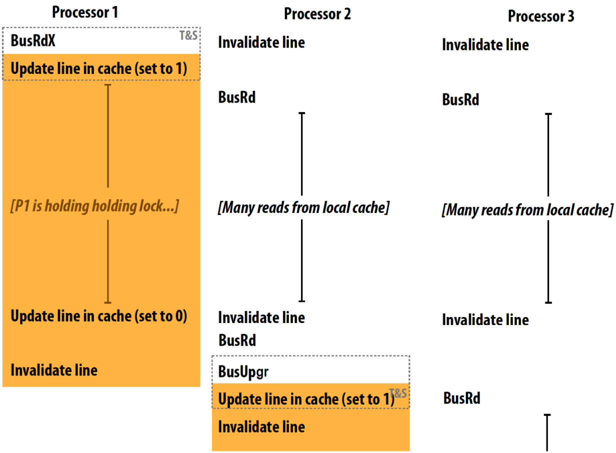
(CMU 15-418, Spring 2012)

Reducing synchronization cost: `test-test-and-set`

- `test-test-and-set` technique reduces the necessary memory bandwidth and coherence protocol operations required by a pure `test-and-set` based synchronization:
  - Wait using a regular load instruction (lock will be cached)
  - When lock is released, try to acquire using `test-and-set`

```
set_lock:   ld r2, flag               // test with regular load
                                      // lock is cached meanwhile it is not updated
            bnez r2, set_lock         // test if the lock is free
            t&s r2, flag              // test and acquire lock if STILL free
            bnez r2, set_lock
            ...
unset_lock: st flag, #0               // free the lock
```

test-test-and-set lock coherence traffic



Support for synchronization at the architecture level

- Atomicity difficult or inefficient in large systems. Alternative: **Load-linked Store-conditional** `ll-sc`
  - `ll` returns the current value of a memory location
  - `sc` stores a new value in that memory location if no updates have occurred to it since the `ll`; otherwise, the store fails
  - `sc` returns success (1) or failure (0)

- Examples implementing atomic exchange (left) and fetch-and-increment (right):

```
// exchange r4 with location.
try: mov r3, r4
     ll r2, location
     sc r3, location
     beqz r3, try
     mov r4, r2
```

```
// add 1 to location
try: ll r2, location
     add r3, r2, #1
     sc r3, location
     beqz r3, try
```

Reducing synchronization cost: `test-test-and-set`

- `test-test-and-set` technique can also be implemented with `ll-sc`
  - First, wait using load linked instruction `ll` (lock will be cached)
  - Second, use store conditional `sc` operation to test if someone else did it first

```
set_lock:   ll r2, flag            // first test with load linked
                                  // lock is cached meanwhile it is not updated
            bnez r2, set_lock      // test if the lock is free
            mov r2, #1
            sc r2, flag            // try to store 1
            beqz r2, set_lock      // repeat if someone else did it before me
            ...
unset_lock: st flag, #0            // free the lock
```

Other synchronization primitives

- How to implement a `barrier` synchronization primitive?
  - Threads arriving wait until all have reached the barrier
  - Structure with fields {lock, counter, flag}

```
barrier:
      acquire_lock(&barr.lock);
      if (barr.counter == 0)
         barr.flag = 0            // reset flag if first
      mycount =  barr.counter++;
      release_lock(&barr.lock);

      if (mycount == P) {          // last to arrive?
         barr.counter = 0         // reset counter for next barrier
         barr.flag = 1            // release waiting processors
      } else
         while (barr.flag == 0)   // busy wait for release
      ...
```

- Does it work when consecutive barriers appear? Try to solve it

Parallelism (PAR)

Mastering your task decomposition strategies: going some steps further

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Course 2021/22 (Fall semester)