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CSC 447: Parallel Programming for Multi-Core and Cluster Systems

Shared Parallel Programming Using OpenMP

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More on Sharing and Synchronizing Variables in OpenMP

`firstprivate` Example

- Variables initialized from shared variable

```
incr = 0;
#pragma omp parallel for firstprivate(incr)

for (i=0;i <= Max; i++) {
   if ((i%2)==0) incr++;
   A(i)= incr;
}
```

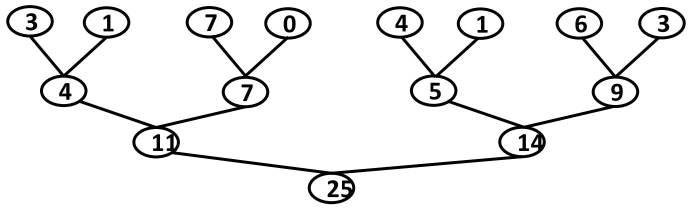

`lastprivate` Example

- Variables update shared variable using value from last iteration
- C++ objects are updated as if by assignment

```
void sq2(int n, double *lastterm)
{
  double x; int i;
  #pragma omp parallel
  #pragma omp for lastprivate(x)
  for (i = 0; i < n; i++){
     x = a[i]*a[i] + b[i]*b[i];
     b[i] = sqrt(x);
  }
  lastterm = x;
}
```

Reduction

- Perform a reduction of the data before transferring to the CPU
- **Tree based reduction approach** used within each thread block



Example of tree based SUM

- Reduction decomposed into multiple kernels to reduce number of threads issued in the later stages of tree based reduction

Reduction

- OpenMP reduction clause:
  - reduction (op : list)
- Inside a parallel or a work-sharing construct:
  - A local copy of each list variable is made and initialized depending on the "op" (e.g. 0 for "+").
  - Updates occur on the local copy.
  - Local copies are reduced into a single value and combined with the original global value.
- The variables in "list" must be shared in the enclosing parallel region.

```
double  ave=0.0, A[MAX];
int i;

#pragma omp parallel for reduction (+:ave)
for (i=0;i< MAX; i++) {
     ave + = A[i];
}
ave = ave/MAX;
```

C/C++ Reduction Operations

- A range of associative operands can be used with reduction
- Initial values are the ones that make sense

Operand	Initial Value
+	0
*	1
-	0
^	0

<table>
<tr><th>Operand</th><th>Initial Value</th></tr>
<tr><td>&</td><td>~0</td></tr>
<tr><td>|</td><td>0</td></tr>
<tr><td>&&</td><td>1</td></tr>
<tr><td>||</td><td>0</td></tr>
</table>

Synchronization

- Synchronization is used to impose order constraints and to protect access to shared data
- High level synchronization:
  - critical
  - atomic
  - barrier
  - ordered
- Low level synchronization
  - flush
  - locks (both simple and nested)

Synchronization

- OpenMP Synchronization
  - OpenMP Critical Sections
    - Defines a critical region on a structured code block
    - Named or unnamed
    - No explicit locks
  - Barrier directives
  - Explicit Lock functions
    - When all else fails – may require flush directive
    - More about this one later
  - Single-thread regions within parallel regions
    - master, single directives

```
#pragma omp critical [(lock_name)]
{
  /* Critical code here */
}
```

```
#pragma omp barrier
```

```
omp_set_lock( lock_l );
/* Code goes here */
omp_unset_lock( lock_l );
```

```
#pragma omp single
{
  /* Only executed once */
}
```


Barrier Construct

- Explicit barrier synchronization
  - Each thread waits until all threads arrive
  - We will talk about the shared construct later

```
#pragma omp parallel shared (A, B, C)
{
    DoSomeWork(A,B); // Processed A into B
    #pragma omp barrier

     DoSomeWork(B,C); // Processed B into C
}
```

Explicit Barrier

- Several OpenMP constructs have implicit barriers
  - Parallel – necessary barrier – cannot be removed
  - for
  - single
- Unnecessary barriers hurt performance and can be removed with the **`nowait`** clause

Explicit Barrier: Example

```
#pragma omp parallel shared (A, B, C) private(id)
{
    id=omp_get_thread_num();
    A[id] = big_calc1(id);
#pragma omp barrier

#pragma omp for
    for(i=0;i<N;i++){
       C[i]=big_calc3(i,A);
    }
#pragma omp for nowait
    for(i=0;i<N;i++){
      B[i]=big_calc2(C,  i);
    }
    A[id] = big_calc4(id);
}
```

implicit barrier at the end of a for work sharing construct

no implicit barrier due to nowait

implicit barrier at the end of a parallel region

Synchronization: ordered

- Specifies that code under a parallelized for loop should be executed like a sequential loop.

```
#pragma omp parallel private (tmp)
#pragma omp for ordered reduction(+:res)
   for (i=0;i < n;i++){
      tmp = Neat_Stuff(i);
     #pragma ordered
      res += consum(tmp);
   }
```


Avoiding Overhead: if clause

- The if clause is an integral expression that, if evaluates to true (nonzero), causes the code in the parallel region to execute in parallel
  - Used for optimization, e.g. avoid going parallel

```
#pragma omp parallel if(expr)
```

Avoiding Overhead: `if` clause

```
#include <stdio.h>
#include <omp.h>

void test(int val)
{
    #pragma omp parallel if (val)
    if (omp_in_parallel())
    {
        #pragma omp single
        printf_s("val = %d, parallelized with %d threads\n",
                 val, omp_get_num_threads());
    }
    else
        printf_s("val = %d, serialized\n", val);
    }
```

```
int main( )
{
    omp_set_num_threads(2);
    test(0);
    test(2);
}
```


Avoiding Overhead: `if` clause

- At times it maybe useful to identify conditions when a parallel region should be executed by a single thread or using parallel threads

```
    double  ave=0.0, A[MAX];
    int i;

     #pragma omp parallel for reduction (+:ave) if (MAX > 10000)
     for (i=0;i< MAX; i++) {
         ave + = A[i];
    }
   ave = ave/MAX;
```

Controlling Threads Execution

`single` Construct

- The single construct denotes a block of code that is executed by only one thread (not necessarily the master thread).
  - First thread to arrive is chosen
- A barrier is implied at the end of the single block (can remove the barrier with a `nowait` clause).

```
#pragma omp parallel
{
   DoManyThings();
   #pragma omp single
   {
     exchange_boundaries();
   }  // threads wait here for single
   do_many_more_things();
}
```

`master` Construct

- A `master` construct denotes block of code to be executed only by the master thread
  - The other threads just skip it (no synchronization is implied).
  - Identical to the **`omp single`**, except that the master thread is the thread chosen to do the work

```
#pragma omp parallel
{
   DoManyThings();
   #pragma omp master // if not master skip to next stmt
   {
     ExchangeBoundaries();
   }
   DoManyMoreThings();
}
```


Worksharing

SPMD vs. Worksharing

- A parallel construct by itself creates "Single Program Multiple Data (SPMD)" program
  - Each thread redundantly executes the same code.
- Worksharing
  - Split up pathways through the code between threads within a team
- OpenMP Constructs for Worksharing
  - Loop construct
  - Task construct
  - Sections/section constructs
  - Single construct

Worksharing

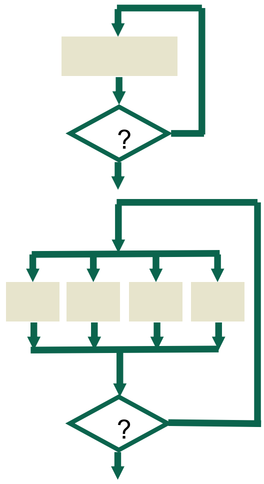
- Worksharing is the general term used in OpenMP to describe distribution of work across threads.
- Three examples of worksharing in OpenMP are:
  - `omp for` construct
  - `omp sections` construct
  - `omp task` construct

Automatically divides work among threads

OpenMP: Concurrent Loops

- Basic approach
  - Find compute intensive loops
  - Make the loop iterations independent so they can safely execute in any order without loop-carried dependencies
  - Place the appropriate OpenMP directive and test

```
for( i=0; i < 25; i++ ) {
  BigTask(i);
}
```

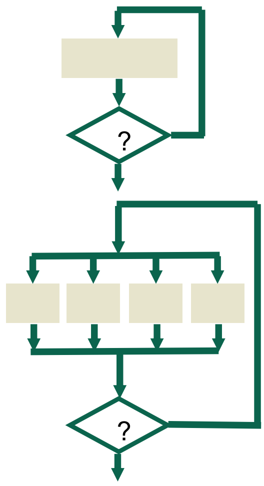


OpenMP: Concurrent Loops

- OpenMP easily parallelizes loops
  - No data dependencies between iterations!

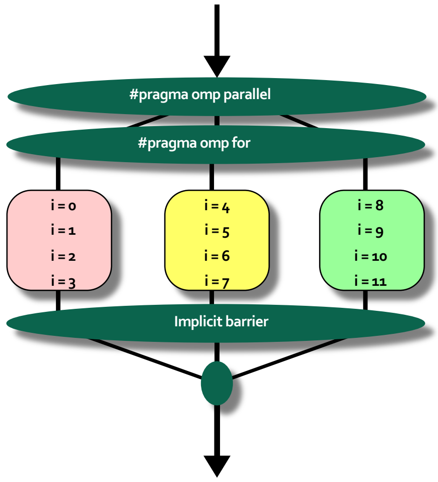
```
#pragma omp parallel for
for( i=0; i < 25; i++ ) {
  printf("Foo");
}
```

- Preprocessor calculates loop bounds for each thread directly from serial source



OpenMP: Concurrent Loops

```
// assume N=12
#pragma omp parallel for
for(i = 0; i < N; i++)
      c[i] = a[i] + b[i];
```



Working with Loops: schedule Clause

- Can control how loop iterations are divided among the thread team using the `schedule` clause
  - Static
  - Dynamic
  - Guided
- Although you can nest parallel loops in OpenMP, the compiler can choose to serialize the nested parallel region

Working with Loops: schedule Clause

- `Static` or `schedule(static, chunk-size)`
  - Divide the loop into equal-sized chunks or as equal as possible if the number of loop iterations is not evenly divisible by the number of threads multiplied by the chunk size.
  - By default, chunk size is `loop_count/number_of_threads`.
  - Set chunk to 1 to interleave the iterations.
  - Least work at runtime : scheduling done at compile-time

OpenMP: Loop Scheduling

```
#pragma omp parallel for schedule(static)
for( i=0; i<16; i++ )
{
  doIteration(i);
}
```

```
// static scheduling

int chunk = 16/T;
int base = tid * chunk;
int bound = (tid+1)*chunk;

for( i=base; i<bound; i++ )
{
  doIteration(i);
}

Barrier();
```

Schedule Clause Example

- Iterations are divided into chunks of 8
  - If start = 3, then first chunk is
  - i={3,5,7,9,11,13,15,17}

```
#pragma omp parallel for schedule (static, 8)
    for( int i = start; i <= end; i += 2 )
    {
       if ( TestForPrime(i) )
        gPrimesFound++;
    }
```



```
schedule(static):
****************
                ****************
                                ****************
                                                ****************
```

```
schedule(static, 4):
****            ****            ****            ****
    ****            ****            ****            ****
        ****            ****            ****            ****
            ****            ****            ****            ****
```

```
schedule(static, 8):
********                        ********
        ********                        ********
                ********                        ********
                        ********                        ********
```

Working with Loops: schedule Clause

- `dynamic`
  - Use the internal work queue to give a chunk-sized block of loop iterations to each thread.
  - When a thread is finished, it retrieves the next block of loop iterations from the top of the work queue.
  - By default, the chunk size is 1.
  - Be careful when using this scheduling type because of the extra overhead involved.
  - Least work at runtime: scheduling done at compile-time

OpenMP: Loop Scheduling

```
#pragma omp parallel for \
 schedule(dynamic)

for( i=0; i<16; i++ )
{
  doIteration(i);
}
```

```
// Dynamic Scheduling

int current_i;

while( workLeftToDo() )
{
  current_i = getNextIter();
  doIteration(i);
}

Barrier();
```

```
schedule(dynamic):
*   ** **  * * *  *      *  *    **   *  *  * *       *  *   *
  *       *     *    * *     * *   *    *        * *   *    *
 *       *    *     * *   *   *     *  *       *  *  *  *  *   *
   *  *     *    * *    *  *    *    *    ** *  *   *     *   *
```

```
schedule(dynamic, 1):
    *    *     *        *   *    * *  *  *         *  * *  * *
*  *  *   * *     *  * * *    * *      *   ***  *   *         *
 *   *  *  *  *    ** *    *      *  *  * *   *  *   *   *
  *    *     *  **        *  * *    *          *  *    *  * *  *
```

```
schedule(dynamic, 4):
            ****                    ****                    ****
****            ****    ****            ****        ****
    ****            ****    ****            ****        ****
        ****                    ****            ****
```

```
schedule(dynamic, 8):
                ********                                ********
                        ********        ********
********                        ********        ********
        ********
```


Working with Loops: schedule Clause

- `guided`
  - Similar to dynamic scheduling, but the chunk size starts off large and decreases to better handle load imbalance between iterations.
  - The optional chunk parameter specifies them minimum size chunk to use.
  - By default the chunk size is approximately `loop_count/number_of_threads`.

Parallel Programming for Multicore and Cluster Systems

Working with Loops: schedule Clause

- `auto`
  - When schedule (auto) is specified, the decision regarding scheduling is delegated to the compiler.
  - The programmer gives the compiler the freedom to choose any possible mapping of iterations to threads in the team.

Working with Loops: schedule Clause

- `runtime`
  - Uses the `OMP_ SCHEDULE` environment variable to specify which one of the three loop-scheduling types should be used.
  - `OMP_SCHEDULE` is a string formatted exactly the same as would appear on the parallel construct.

Avoiding Overhead: `nowait` Clause

- Use when threads unnecessarily *wait* between independent computations

```
#pragma omp for nowait
   for(...)
     {...};
```

```
#pragma single nowait
{ [...] }
```

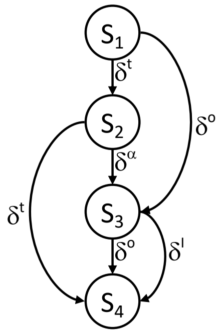
```
#pragma omp for schedule(dynamic,1) nowait
 for(int i=0; i<n; i++)
   a[i] = bigFunc1(i);

#pragma omp for schedule(dynamic,1)
 for(int j=0; j<m; j++)
   b[j] = bigFunc2(j);
```


Loop Dependence

Data Dependence

- Data dependence in a program may be represented using a dependence graph G=(V,E), where the nodes V represent statements in the program and the directed edges E represent dependence relations.

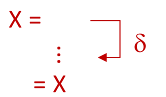
S_1 : A = 1.0
S_2 : B = A + 2.0
S_3 : A = C – D
⋮
S_4 : A = B/C



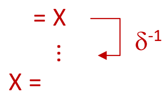
True Dependence and Anti-Dependence

- Given statements S1 and S2,
  - S1;
  - S2;

- S2 has a true (flow) dependence on S1 if and only if S2 reads a value written by S1



- S2 has an anti-dependence on S1 if and only if S2 writes a value read by S1



Output Dependence

- Given statements S1 and S2,
  S1;
  S2;

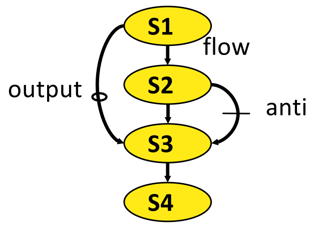
- S2 has an output dependence on S1 if and only if S2 writes a variable written by S1

X =
⋮
X =
δ^0

- Anti- and output dependences are "name" dependencies
  – Are they "true" dependences?
- How can you get rid of output dependences?
  – Are there cases where you can not?

Statement Dependency Graphs

- Can use graphs to show dependence relationships
- Example
  S1: a=1;
  S2: b=a;
  S3: a=b+1;
  S4: c=a;



- $S_2\ \delta\ S_3$: S_3 is flow-dependent on S_2
- $S_1\ \delta^0\ S_3$: S_3 is output-dependent on S_1
- $S_2\ \delta^{-1}\ S_3$: S_3 is anti-dependent on S_2

When can two statements execute in parallel?

- Statements S1 and S2 can execute in parallel if and only if there are *no dependences* between S1 and S2
  - True dependences
  - Anti-dependences
  - Output dependences
- Some dependences can be removed by modifying the program
  - Rearranging statements
  - Eliminating statements

How do you determine dependencies?

- Data dependence relations can be found by comparing the IN and OUT sets of each node
- The IN and OUT sets of a statement S are defined as:
  - IN(S) : set of memory locations (variables) that may be used in S
  - OUT(S) : set of memory locations (variables) that may be modified by S
- Note that these sets include all memory locations that may be fetched or modified
  - As such, the sets can be conservatively large

IN / OUT Sets and Computing Dependence

- Assuming that there is a path from S1 to S2 , the following shows how to intersect the IN and OUT sets to test for data dependence

$$out(S_1) \cap in(S_2) \neq \varnothing \qquad S_1 \, \delta \; S_2 \qquad \text{flow dependence}$$

$$in(S_1) \cap out(S_2) \neq \varnothing \qquad S_1 \, \delta^{-1} \, S_2 \qquad \text{anti - dependence}$$

$$out(S_1) \cap out(S_2) \neq \varnothing \qquad S_1 \, \delta^{0} S_2 \qquad \text{output dependence}$$

Loop-Level Parallelism

- Significant parallelism can be identified within loops

```
for (i=0; i<100; i++)
    S1: a[i] = i;
```

```
for (i=0; i<100; i++) {
    S1: a[i] = i;
    S2: b[i] = 2*i;
}
```

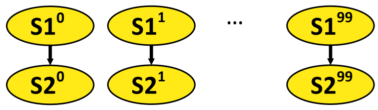
- Dependencies? What about *i*, the loop index?
- **`#pragma omp parallel for`**
  - All iterations are independent of each other
  - All statements be executed in parallel at the same time
    - Is this really true?

Iteration Space

- Unroll loop into separate statements / iterations
- Show dependences between iterations

```
for (i=0; i<100; i++)
    S1: a[i] = i;
```


```
for (i=0; i<100; i++) {
    S1: a[i] = i;
    S2: b[i] = 2*i;
}
```



Examples

Example 1
- S1: a=1;
- S2: b=1;

Statements are independent

Example 2
- S1: a=1;
- S2: b=a;

Dependent (true (flow) dependence)
- Second is dependent on first
- Can you remove dependency?

Example 3
- S1: a=f(x);
- S2: a=b;

Dependent (output dependence)
- Second is dependent on first
- Can you remove dependency? How?

Example 4
- S1: a=b;
- S2: b=1;

Dependent (anti-dependence)
- First is dependent on second
- Can you remove dependency? How?

Example: Loop-Carried Dependencies

- A dependency that exists across iterations
  - if the loop is removed, the dependency *no longer exists.*

```
for(i=1; i<n; i++) {
   S1: a[i] = a[i-1] + 1;
   S2: b[i] = a[i];
}
```

```
S1[i] → T S1[i+1]: loop-carried
S1[i] → T S2[i]: loop-independent
```

```
for(i=1; i<n; i++)
   for(j=1; j<n; j++)
      S3: a[i][j] = a[i][j-1] + 1;
```

```
S3[i,j] → T S3[i,j+1]:
•  loop-carried on for j loop
•  no loop-carried dependence in
   for i loop
```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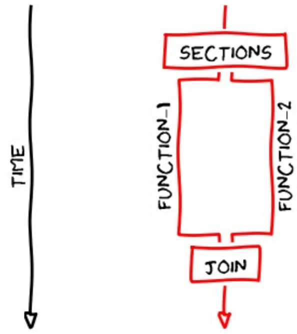
Sections and Tasks

Sections worksharing Construct

- OpenMP supports non-iterative parallel task assignment using the sections directive.
  - `#pragma omp sections`
    - Must be inside a parallel region
    - Precedes a code block containing of N blocks of code that may be executed concurrently by N threads
    - Encompasses each omp section
  - `#pragma omp section`
    - Precedes each block of code within the encompassing block described above
    - May be omitted for first parallel section after the parallel sections pragma
    - Enclosed program segments are distributed for parallel execution among available threads

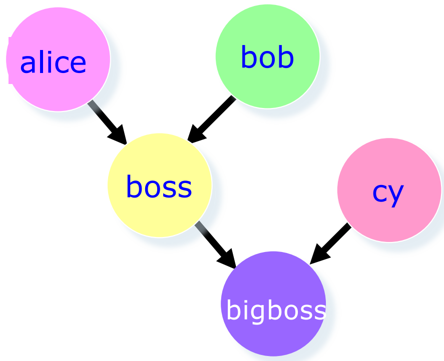


Sections Worksharing Construct

- The `omp sections` directive supports the following OpenMP clauses:
  - shared(list)
  - private(list) firstprivate(list) lastprivate(list)
  - default(shared | none)
  - nowait
  - reduction

Decomposition

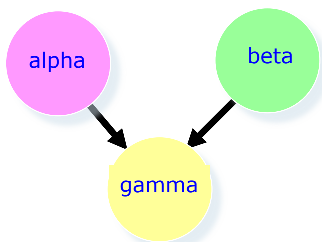
```
a = alice();
b = bob();
s = boss(a, b);
c = cy();
printf ("%6.2f\n", bigboss(s,c));
```



Alice ,bob, and cy can be computed in parallel

Sections work sharing Construct

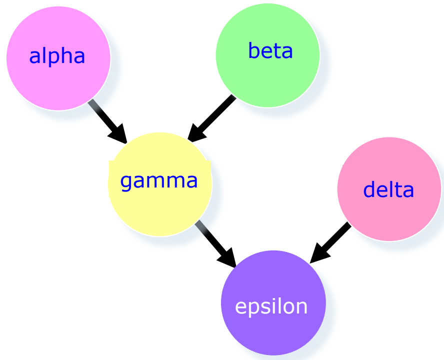
```
#pragma omp parallel sections
{
#pragma omp section  /* Optional */
   a = alpha();
#pragma omp section
   b = beta();
}

printf ("%6.2f\n", gamma(a, b) );
```



By default, there is a barrier at the end of the "omp sections". Use the "nowait" clause to turn off the barrier.

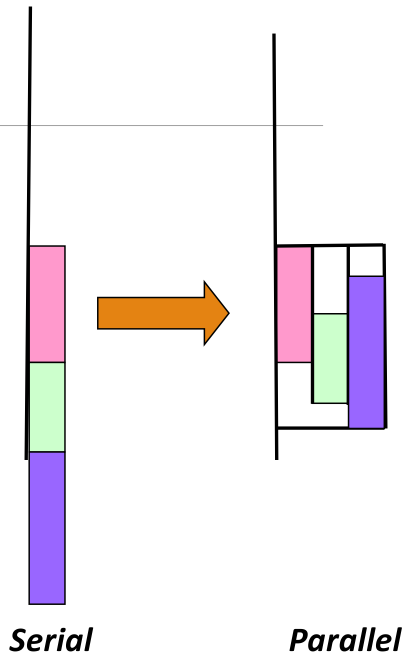
Sections work sharing Construct

```
#pragma omp parallel sections
{
#pragma omp section  /* Optional */
   a = alpha();
#pragma omp section
   b = beta();
}
#pragma omp parallel sections
{
#pragma omp section  /* Optional */
   c = delta();
#pragma omp section
   s = gamma(a, b);
}
printf ("%6.2f\n", epsilon(s,c));
```



Tasks

- Tasks are independent units of work
- Threads are assigned to perform the work of each task
  - Tasks may be deferred or executed immediately
  - The system determines at runtime which case of the above
- Tasks are composed of:
  - code to execute
  - data environment
  - internal control variables (ICV)



OpenMP `task` Worksharing Construct

- The OpenMP tasking model enables the parallelization of a large range of applications.
- The `task` pragma can be used to explicitly define a task.
  - Used to identify a block of code to be executed in parallel with the code outside the task region
  - The task pragma can be useful for parallelizing irregular algorithms such as pointer chasing or recursive algorithms.

OpenMP `task` Worksharing Construct

- The omp task pragma has the following syntax:

```
#pragma omp task [clause[[,] clause] ...] new-line structured-block
```

  - Where a clause is one of the following:
    - if(scalar-expression)
    - final (scalar expression)
    - Untied
    - default(shared | none)
    - Mergeable
    - private(list)
    - firstprivate(list)
    - shared(list)

OpenMP `task` Worksharing Construct

- OpenMP Run Time System
  - When a thread encounters a task construct, a new task is generated
  - The moment of execution of the task is up to the runtime system
  - Execution can either be immediate or delayed
  - Completion of a task can be enforced through task synchronization

Tasks versus Sections

- In contrast to tasks, sections are enclosed within the sections construct and (unless the nowait clause was specified) threads will not leave it until all sections have been executed
- Tasks are queued and executed whenever possible at the so-called task scheduling points

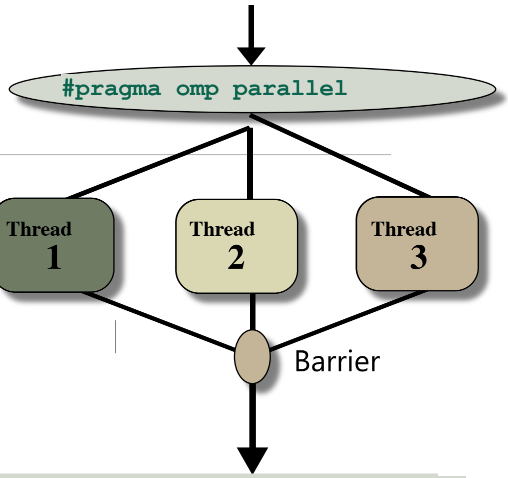
Task synchronization

```
#pragma omp parallel num_threads(np)
{
#pragma omp task
   function_A();
#pragma omp barrier
#pragma omp single
{
      #pragma omp task
      function_B();
   }
}
```

- `#pragma omp task` (first) ← np Tasks created here, one for each thread
- `#pragma omp barrier` ← All Tasks guaranteed to be completed here
- `#pragma omp task` (inside single) ← 1 Task created here
- closing `}` ← B-Task guaranteed to be completed here

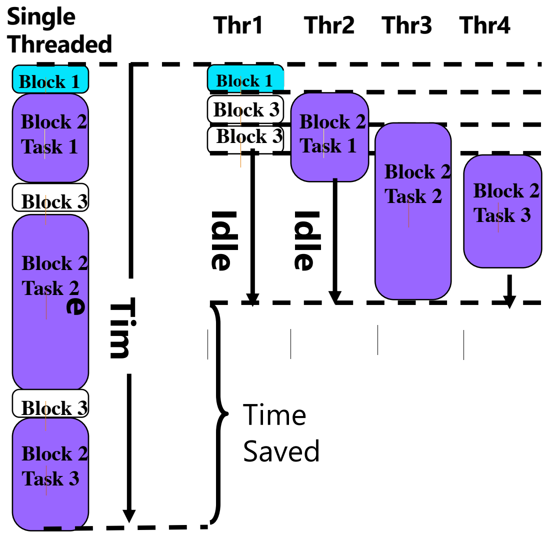
Parallel Construct Implicit Task View

- Tasks are created in OpenMP even without an explicit `task` directive.
  - Let's look at how tasks are created implicitly for the code snippet below
    - Thread encountering parallel construct packages up a set of implicit tasks
    - Team of threads is created.
    - Each thread in team is assigned to one of the tasks (and tied to it).
    - Barrier holds original master thread until all implicit tasks are finished.




```
#pragma omp parallel
   {
      int mydata;
      code…
   }
```

Why are tasks useful?



When are tasks guaranteed to be complete?

- Tasks are guaranteed to be complete at thread or task barriers
  - At the directive: #pragma omp barrier
  - At the directive: #pragma omp taskwait
- Task barrier: `taskwait`
  - Encountering task is suspended until children tasks are complete
  - Applies only to direct children, not descendants!

Avoiding Overhead: `taskyield` Clause

- The **`taskyield`** directive specifies that the current task can be suspended in favor of execution of a different task.
  - Hint to the runtime for optimization and/or deadlock prevention

```
#pragma omp taskyield
```


Avoiding Overhead: `taskyield` Clause

```
#include <omp.h>
void something_useful();
void something_critical();
void foo(omp_lock_t * lock, int n)
{
 for(int i = 0; i < n; i++)
 #pragma omp task
 {
   something_useful();
   while( !omp_test_lock(lock) ) {
   #pragma omp taskyield
 }
 something_critical();
 omp_unset_lock(lock);
 }
}
```

The waiting task may be suspended here and allow the executing thread to perform other work. This may also avoid deadlock situations

Avoiding Overhead: `final` Clause

`#pragma omp task final(expr)`

- `final` clause is useful for recursive problems that perform task decomposition
- Stop task creation at a certain depth in order to expose enough parallelism and reduces the overhead.
- The generated task will be a final one if the `expr` evaluates to nonzero value
- All task constructs encountered inside a final task create final and included tasks

Avoiding Overhead: `final` Clause

```
void foo(int arg)
{
  int i = 3;

  #pragma omp task final(arg < 10) firstprivate(i)
   i++;

   printf(“%d\n”, i); // will print 3 or 4 depending on arg
}
```

A couple of Notes…

- A task is untied if the code can be executed by more than one thread, so that different threads execute different parts of the code.
  – By default, tasks are tied

Closing Comments: Explicit Threads Versus Directive Based Programming

- Directives layered on top of threads facilitate a variety of thread-related tasks.
- A programmer is rid of the tasks of initializing attributes objects, setting up arguments to threads, partitioning iteration spaces, etc.
- There are some drawbacks to using directives as well.
- An artifact of explicit threading is that data exchange is more apparent. This helps in alleviating some of the overheads from data movement, false sharing, and contention.
- Explicit threading also provides a richer API in the form of condition waits, locks of different types, and increased flexibility for building composite synchronization operations.
- Finally, since explicit threading is used more widely than OpenMP, tools and support for Pthreads programs are easier to find.