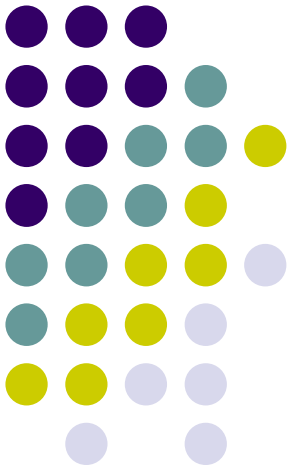
ME964
High Performance Computing for Engineering Applications

Parallel Computing using OpenMP

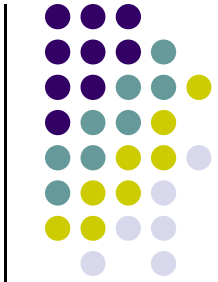
[Part 1 of 2]

March 31, 2011



"The competent programmer is fully aware of the strictly limited size of his own skull; therefore he approaches the programming task in full humility, and among other things he avoids clever tricks like the plague."
Edsger W. Dijkstra

Before We Get Started…

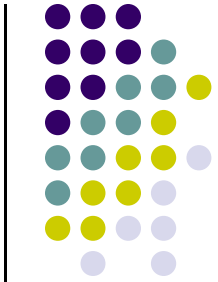


- Last time
  - Learn how to run an MPI executable on Newton
  - Point-to-Point Communication with MPI
  - Collective Communication in MPI

- Today
  - Parallel Computing using OpenMP, part 1 of 2.

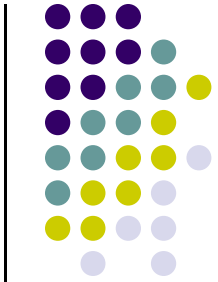
- Other issues
  - Assignment 7 was posted on the class website, due on April 7
  - Class website includes link to the OpenMP 3.0 Application Programming Interface
    - http://www.openmp.org/mp-documents/spec30.pdf

Acknowledgements



- The overwhelming majority of slides used for discussing OpenMP issues are from Intel's library of presentations for promoting OpenMP
  - The slides are used herein with permission
- Credit is given where due by a "Credit: IOMPP" or "Includes material from IOMPP" message at the bottom of the slide
  - IOMPP stands for "Intel OpenMP Presentation"

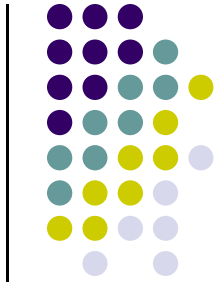
Data vs. Task Parallelism



- Data parallelism
  - You have a large amount of data elements and each data element (or possibly a subset of elements) needs to be processed to produce a result
  - When this processing can be done in parallel, we have data parallelism
  - Example:
    - Adding two long arrays of doubles to produce yet another array of doubles

- Task parallelism
  - You have a collection of tasks that need to be completed
  - If these tasks can be performed in parallel you are faced with a task parallel job
  - Examples:
    - Reading the newspaper, drinking coffee, and scratching your back
    - The breathing your lungs, beating of your heart, liver function, controlling the swallowing, etc.

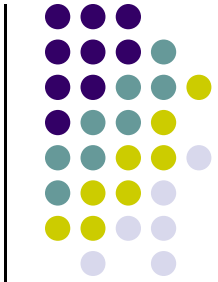
Objectives



- Understand OpenMP at the level where you can
  - Implement data parallelism
  - Implement task parallelism

Credit: IOMPP

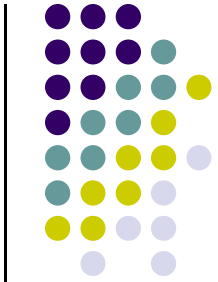
Work Plan



- What is OpenMP?
  Parallel regions
  Work sharing
  Data environment
  Synchronization
- Advanced topics

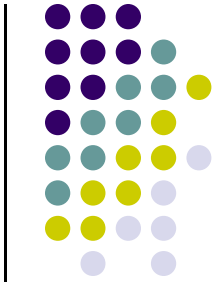
Credit: IOMPP

OpenMP: Target Hardware



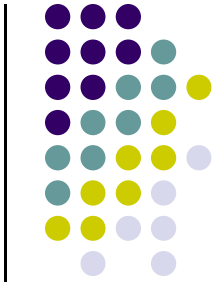
- CUDA: targeted parallelism on the GPU
- MPI: targeted parallelism on a cluster (distributed computing)
  - Note that MPI implementation can handle transparently a SMP architecture such as a workstation with two hexcore CPUs that use a large amount of shared memory
- OpenMP: targets parallelism on SMP architectures
  - Handy when
    - You have a machine that has 12 cores, probably 24 if HTT is accounted for
    - You have a large amount of shared memory that is backed by a 64 bit OS

OpenMP: What to Expect



- If you have 12 cores available to you, it is *highly* unlikely to get a speedup of more than 12 (superlinear)
- Recall the trick that helped the GPU hide latency
  - Overcommitting the SPs and hiding memory access latency with warp execution
- This mechanism of hiding latency by overcommitment does not *explicitly* exist for parallel computing under OpenMP beyond what's offered by HTT

OpenMP: What Is It?

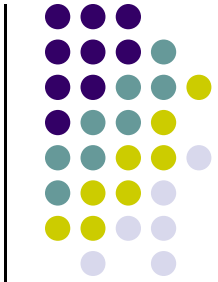


- Portable, shared-memory threading API
  - Fortran, C, and C++
  - Multi-vendor support for both Linux and Windows
- Standardizes task & loop-level parallelism
- Supports coarse-grained parallelism
- Combines serial and parallel code in single source
- Standardizes ~ 20 years of compiler-directed threading experience

- Current spec is OpenMP 3.0
  - http://www.openmp.org
  - 318 Pages

Credit: IOMPP

“pthreads”: An OpenMP Precursor

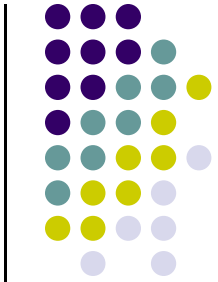


- Before there was OpenMP, a common approach to support parallel programming was by use of pthreads
  - “pthread”: POSIX thread
  - POSIX: Portable Operating System Interface [for Unix]

- pthreads
  - Available originally under Unix and Linux
  - Windows ports are also available some as open source projects

- Parallel programming with pthreads: relatively cumbersome, prone to mistakes, hard to maintain/scale/expand
  - Moreover, not envisioned as a mechanism for writing scientific computing software

“pthreads”: Example



```
int main(int argc, char *argv[]) {
          parm           *arg;
          pthread_t      *threads;
          pthread_attr_t  pthread_custom_attr;

          int n = atoi(argv[1]);

          threads = (pthread_t *) malloc(n * sizeof(*threads));
          pthread_attr_init(&pthread_custom_attr);

          barrier_init(&barrier1); /* setup barrier */
          finals = (double *) malloc(n * sizeof(double)); /* allocate space for final result */

          arg=(parm *)malloc(sizeof(parm)*n);
          for( int i = 0; i < n; i++)      { /* Spawn thread */
                    arg[i].id = i;
                    arg[i].noproc = n;
                    pthread_create(&threads[i], &pthread_custom_attr, cpi, (void *)(arg+i));
          }

          for( int i = 0; i < n; i++) /* Synchronize the completion of each thread. */
                    pthread_join(threads[i], NULL);

          free(arg);
          return 0;
}
```

```c
#include <stdio.h>
#include <math.h>
#include <time.h>
#include <sys/types.h>
#include <pthread.h>
#include <sys/time.h>

#define SOLARIS 1
#define ORIGIN  2
#define OS      SOLARIS

typedef struct {
   int          id;
   int          noproc;
   int          dim;
} parm;

typedef struct {
   int             cur_count;
   pthread_mutex_t barrier_mutex;
   pthread_cond_t  barrier_cond;
} barrier_t;


void barrier_init(barrier_t * mybarrier) { /* barrier */
   /* must run before spawning the thread */
   pthread_mutexattr_t attr;

# if (OS==ORIGIN)
   pthread_mutexattr_setprotocol(&attr, PTHREAD_PRIO_INHERIT);
   pthread_mutexattr_setprioceiling(&attr, 0);
   pthread_mutex_init(&(mybarrier->barrier_mutex), &attr);
# elif (OS==SOLARIS)
   pthread_mutex_init(&(mybarrier->barrier_mutex), NULL);
# else
# error "undefined OS"
# endif
   pthread_cond_init(&(mybarrier->barrier_cond), NULL);
   mybarrier->cur_count = 0;
}

void barrier(int numproc, barrier_t * mybarrier) {
   pthread_mutex_lock(&(mybarrier->barrier_mutex));
   mybarrier->cur_count++;
   if (mybarrier->cur_count!=numproc) {
      pthread_cond_wait(&(mybarrier->barrier_cond), &(mybarrier->barrier_mutex));
   }
   else {
      mybarrier->cur_count=0;
      pthread_cond_broadcast(&(mybarrier->barrier_cond));
   }
   pthread_mutex_unlock(&(mybarrier->barrier_mutex));
}
```

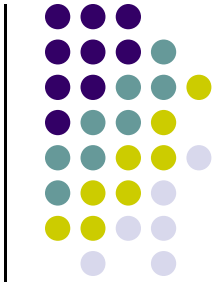
```c
void* cpi(void *arg) {
   parm           *p = (parm *) arg;
   int             myid = p->id;
   int             numprocs = p->noproc;
   double          PI25DT = 3.14159265358979323846264 3;
   double          mypi, pi, h, sum, x, a;
   double          startwtime, endwtime;

   if (myid == 0)   {
      startwtime = clock();
   }
   barrier(numprocs, &barrier1);
   if (rootn==0)
      finals[myid]=0;
   else {
      h = 1.0 / (double) rootn;
      sum = 0.0;
      for(int i = myid + 1; i <=rootn; i += numprocs) {
         x = h * ((double) i - 0.5);
         sum += f(x);
      }
      mypi = h * sum;
   }
   finals[myid] = mypi;

   barrier(numprocs, &barrier1);

   if (myid == 0){
      pi = 0.0;
      for(int i=0; i < numprocs; i++) pi += finals[i];
      endwtime = clock();
      printf("pi is approx %.16f, Error is %.16f\n", pi, fabs(pi - PI25DT));
      printf("wall clock time = %f\n",
          (endwtime - startwtime) / CLOCKS_PER_SEC);
   }
   return NULL;
}
```

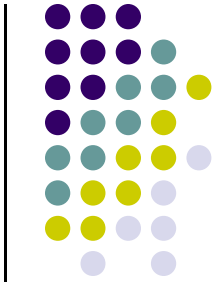
“pthreads”: Moving Away…



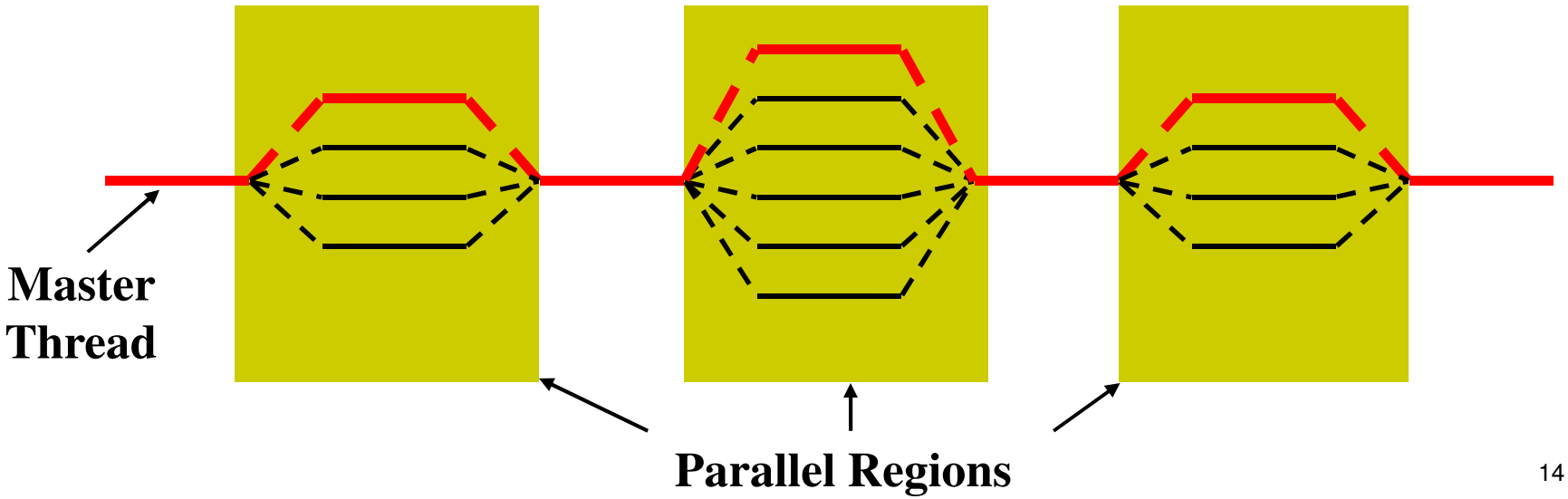
- Looking at the previous example (which is not the best written piece of code, lifted from the web…)
  - Code displays platform dependency (not portable)
  - Code is cryptic, low level, hard to read (not simple)
  - Requires busy work: fork and joining threads, etc.
    - Burdens the developer
    - Probably in the way of the compiler as well: rather low chances that the compiler will be able to optimize the implementation

- Long time experience with “pthreads” suggested that a higher level approach to SMP parallel computing for *scientific applications* was in order

OpenMP Programming Model

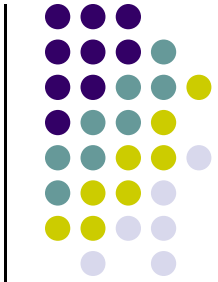


- Master thread spawns a team of threads as needed
  - Managed transparently on your behalf
  - It still relies on thread fork/join methodology to implement parallelism
    - The developer is spared the details
- Parallelism is added incrementally: that is, the sequential program evolves into a parallel program



Includes material from IOMPP

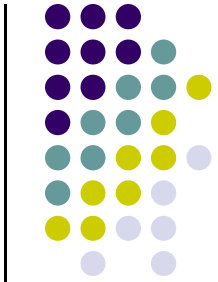
OpenMP: 20+ Library Routines



- Runtime environment routines:
  - Modify/check the number of threads
    `omp_[set|get]_num_threads()`
    `omp_get_thread_num()`
    `omp_get_max_threads()`
  - Are we in a parallel region?
    `omp_in_parallel()`
  - How many processors in the system?
    `omp_get_num_procs()`
  - Explicit locks
    `omp_[set|unset]_lock()`
  - And several more...

Credit: IOMPP

A Few Syntax Details to Get Started



- Most of the constructs in OpenMP are compiler directives or pragmas
  - For C and C++, the pragmas take the form:

```
#pragma omp construct [clause [clause]…]
```

  - For Fortran, the directives take one of the forms:

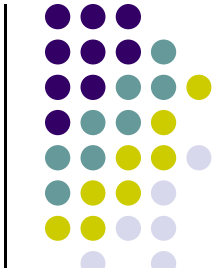
```
C$OMP construct [clause [clause]…]
!$OMP construct [clause [clause]…]
*$OMP construct [clause [clause]…]
```

- Header file or Fortran 90 module

```
#include “omp.h”
use omp_lib
```

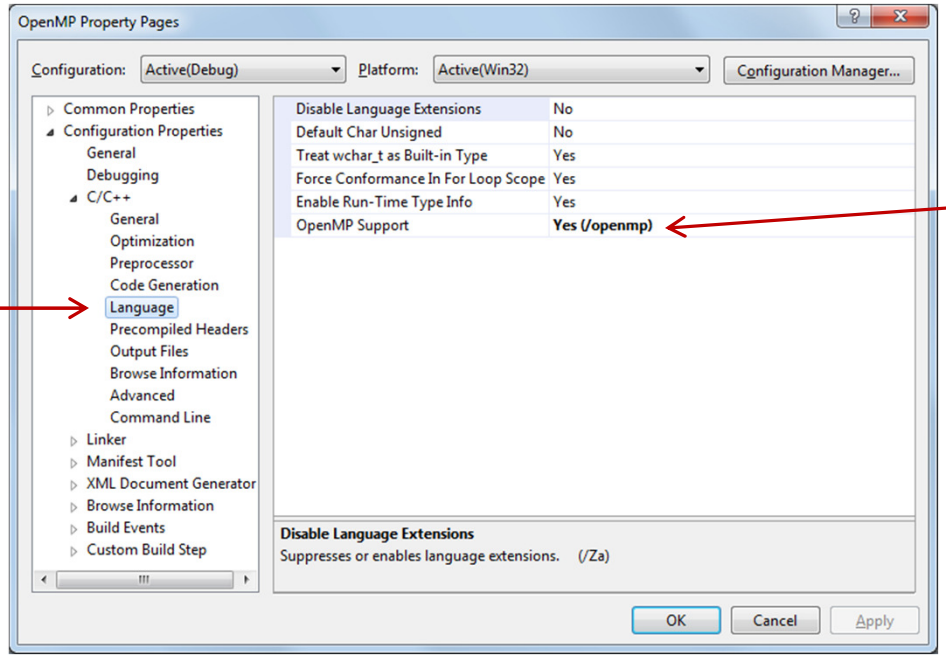

Credit: IOMPP

Why Compiler Directive and/or Pragmas?



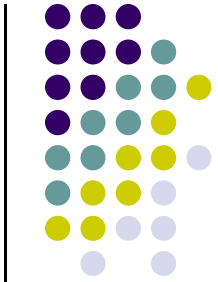
- One of OpenMP's design principles was to have the same code, with no modifications and have it run either on one core machine, or a multiple core machine
- Therefore, you have to "hide" all the compiler directives behind Comments and/or Pragmas
- These hidden directives would be picked up by the compiler only if you instruct it to compile in OpenMP mode
  - Example: Visual Studio – you have to have the /openmp flag on in order to compile OpenMP code
  - Also need to indicate that you want to use the OpenMP API by having the right header included: #include <omp.h>

Step 1:
Go here



Step 2:
Select /openmp

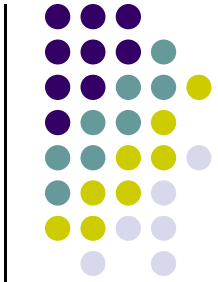
Work Plan



- What is OpenMP?
  - Parallel regions
  - Work sharing
  - Data environment
  - Synchronization
- Advanced topics

Credit: IOMPP

Parallel Region & Structured Blocks (C/C++)



- Most OpenMP constructs apply to structured blocks
  - Structured block: a block with one point of entry at the top and one point of exit at the bottom
  - The only "branches" allowed are STOP statements in Fortran and exit() in C/C++

```
#pragma omp parallel
{
  int id = omp_get_thread_num();

more: res[id] = do_big_job (id);

  if (conv (res[id]) goto more;
}
printf ("All done\n");
```

A structured block

```
if (go_now()) goto more;
#pragma omp parallel
{
  int id = omp_get_thread_num();
more:  res[id] = do_big_job(id);
  if (conv (res[id]) goto done;
  goto more;
}
done: if (!really_done()) goto more;
```

Not a structured block

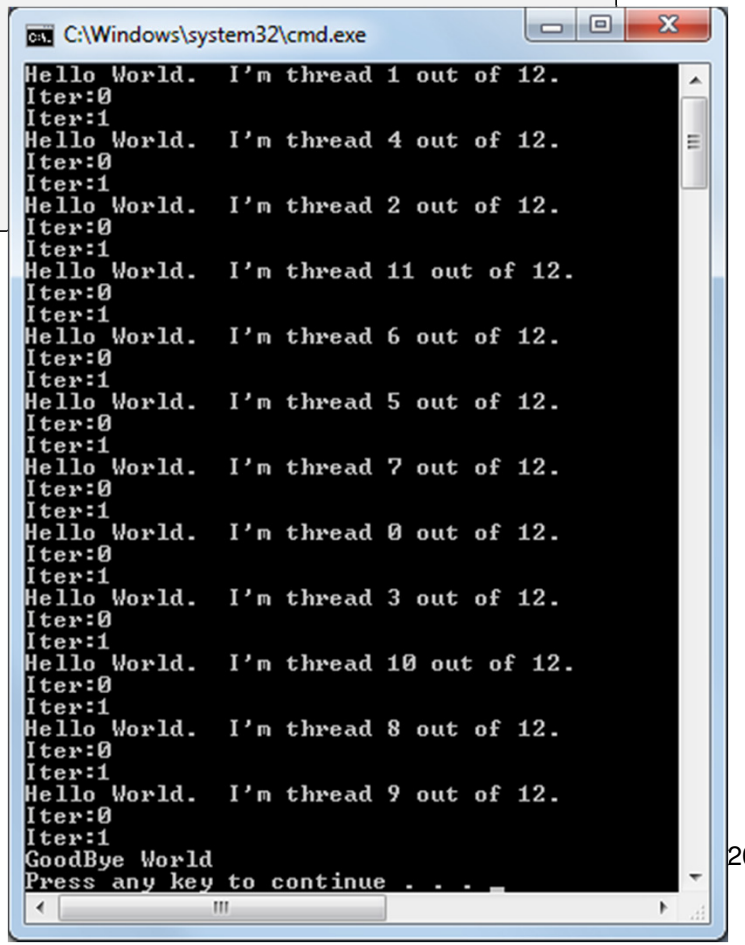
Credit: IOMPP

Example: Hello World on my Machine

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

int main() {
#pragma omp parallel
    {
        int myId = omp_get_thread_num();
        int nThreads = omp_get_num_threads();

        printf("Hello World.  I'm thread %d out of %d.\n", myId, nThreads);
        for( int i=0; i<2 ;i++ )
            printf("Iter:%d\n",i);
    }
    printf("GoodBye World\n");
}
```

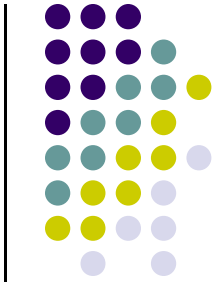


- Here's my machine (12 core machine)

Two Intel Xeon X5650 Westmere 2.66GHz 12MB L3 Cache LGA 1366 95Watts Six-Core Processors

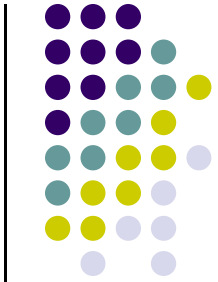
Credit: OpenMP code from IOMPP

OpenMP: Important Remark



- One of the key tenets of OpenMP is that of data independence across parallel jobs
- Specifically, when distributing work among parallel threads it is assumed that there is no data dependency
- Since you place the omp parallel directive around some code, it is your responsibility to make sure that data dependency is ruled out
  - Compilers are not smart enough and sometimes it is outright impossible to rule out data dependency between what might look as independent parallel jobs

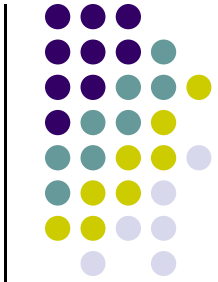
Work Plan



- What is OpenMP?
  - Parallel regions
  - Work sharing – Parallel For
  - Data environment
  - Synchronization
- Advanced topics

Credit: IOMPP

Work Sharing



- **Work sharing** is the general term used in OpenMP to describe distribution of work across threads

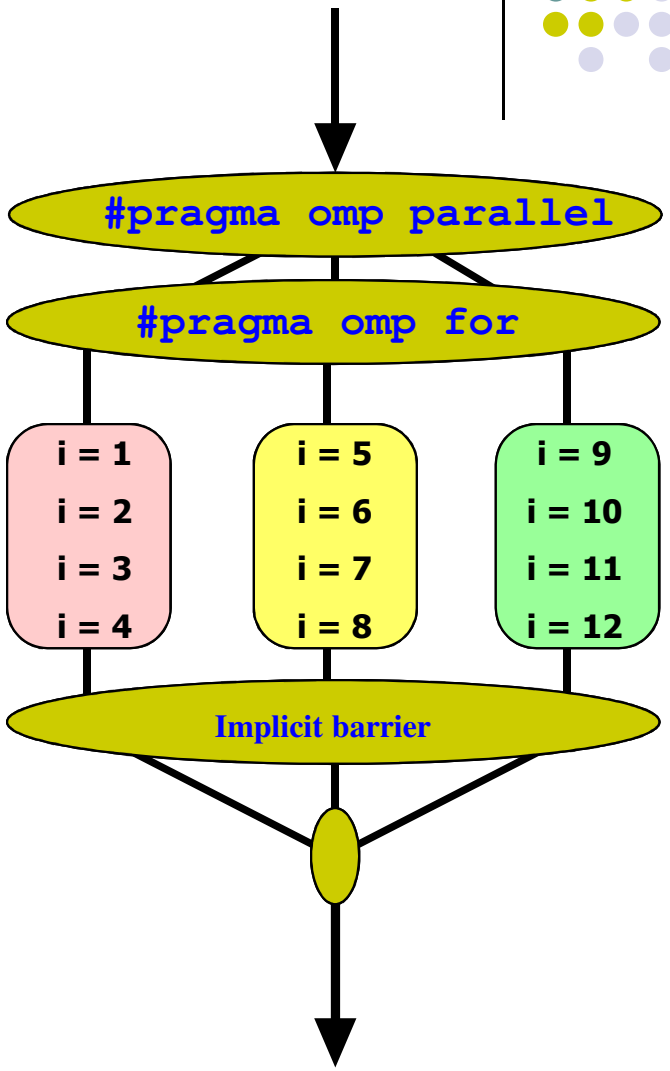
- Three categories of worksharing in OpenMP:
  - "omp for" construct
  - "omp sections" construct
  - "omp task" construct

Automatically divides work among threads

Credit: IOMPP

"omp for" construct

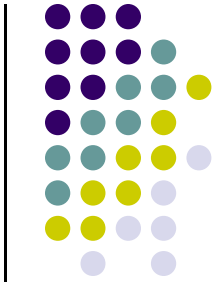
```
// assume N=12
#pragma omp parallel
#pragma omp for
    for(i = 1, i < N+1, i++)
        c[i] = a[i] + b[i];
```



- Threads are assigned an independent set of iterations
- Threads must wait at the end of work-sharing construct

Credit: IOMPP

Combining Constructs



- These two code segments are equivalent

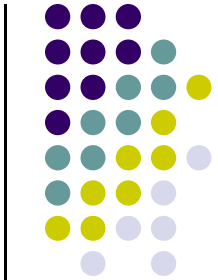
```
#pragma omp parallel
{
    #pragma omp for
    for ( int i=0;i< MAX; i++) {

        res[i] = huge();
    }
}
```

```
#pragma omp parallel for
    for (int i=0;i< MAX; i++) {
         res[i] = huge();
    }
```


Credit: IOMPP

The Private Clause

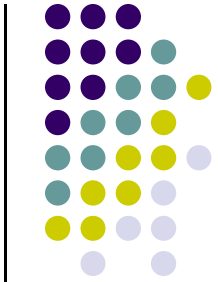


- Reproduces the variable for each task
  - Variables are un-initialized; C++ object is default constructed
  - Any value external to the parallel region is undefined
  - By declaring a variable as being private it means that each thread will have a private copy of that variable
    - The value that thread 1 stores in x is different than the value that thread 2 stores in the variable x

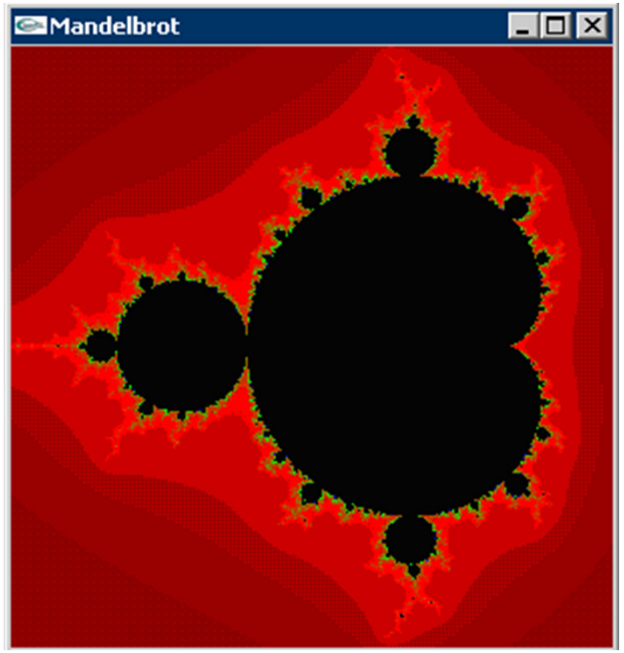
```
void* work(float* c, int N) {
    float x, y; int i;
#pragma omp parallel for private(x,y)
    for(i=0; i<N; i++) {
        x = a[i]; y = b[i];
        c[i] = x + y;
    }
}
```

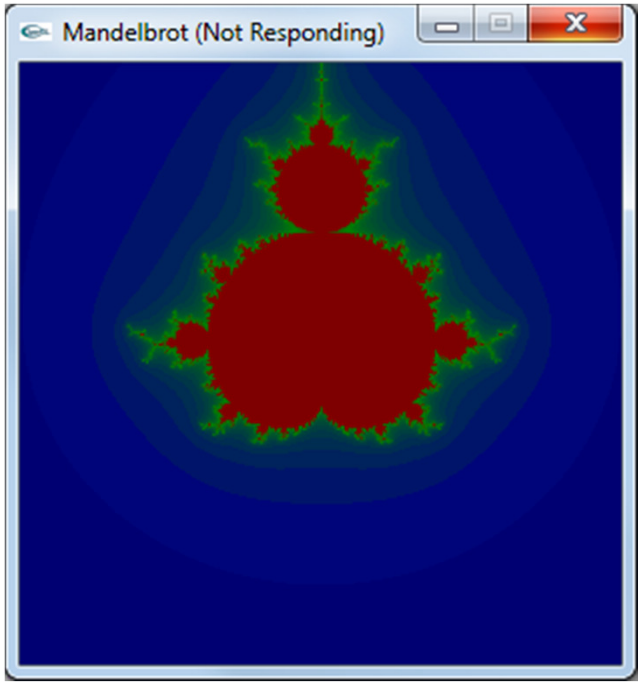
Credit: IOMPP

Example: Parallel Mandelbrot



- Objective: create a parallel version of Mandelbrot using OpenMP work sharing clauses to parallelize the computation of Mandelbrot.

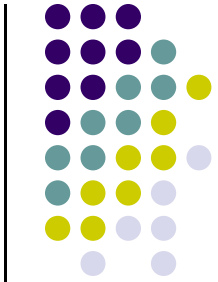




Includes material from IOMPP

Example: Parallel Mandelbrot

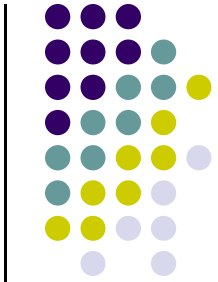
[The Important Function; Includes material from IOMPP]



```
int Mandelbrot (float z_r[][JMAX],float z_i[][JMAX],float z_color[][JMAX], char gAxis ){
    float xinc = (float)XDELTA/(IMAX-1);
    float yinc = (float)YDELTA/(JMAX-1);

#pragma omp parallel for private(i,j) schedule(static,8)
    for (int i=0; i<IMAX; i++) {
        for (int j=0; j<JMAX; j++) {
            z_r[i][j] = (float) -1.0*XDELTA/2.0 + xinc * i;
            z_i[i][j] = (float) 1.0*YDELTA/2.0 - yinc * j;
            switch (gAxis) {
                case 'V':
                    z_color[i][j] = CalcMandelbrot(z_r[i][j], z_i[i][j] ) /1.0001;
                    break;
                case 'H':
                    z_color[i][j] = CalcMandelbrot(z_i[i][j], z_r[i][j] ) /1.0001;
                default:
                    break;
            }
        }
    }
    return 1;
}
```

The schedule Clause



- The schedule clause affects how loop iterations are mapped onto threads

`schedule(static [,chunk])`

- Blocks of iterations of size “chunk” to threads
- Round robin distribution
- Low overhead, may cause load imbalance

`schedule(dynamic[,chunk])`

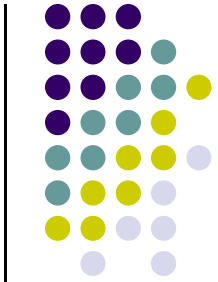
- Threads grab “chunk” iterations
- When done with iterations, thread requests next set
- Higher threading overhead, can reduce load imbalance

`schedule(guided[,chunk])`

- Dynamic schedule starting with large block
- Size of the blocks shrink; no smaller than “chunk”

Credit: IOMPP

schedule Clause Example



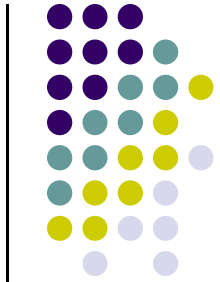
```
#pragma omp parallel for schedule (static, 8)
    for( int i = start; i <= end; i += 2 )
    {
       if ( TestForPrime(i) )  gPrimesFound++;
    }
```

- Iterations are divided into chunks of 8
- If start = 3, then first chunk is

$$\mathbf{i}=\{3,5,7,9,11,13,15,17\}$$

Credit: IOMPP

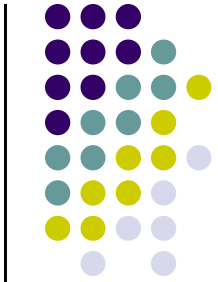
Work Plan



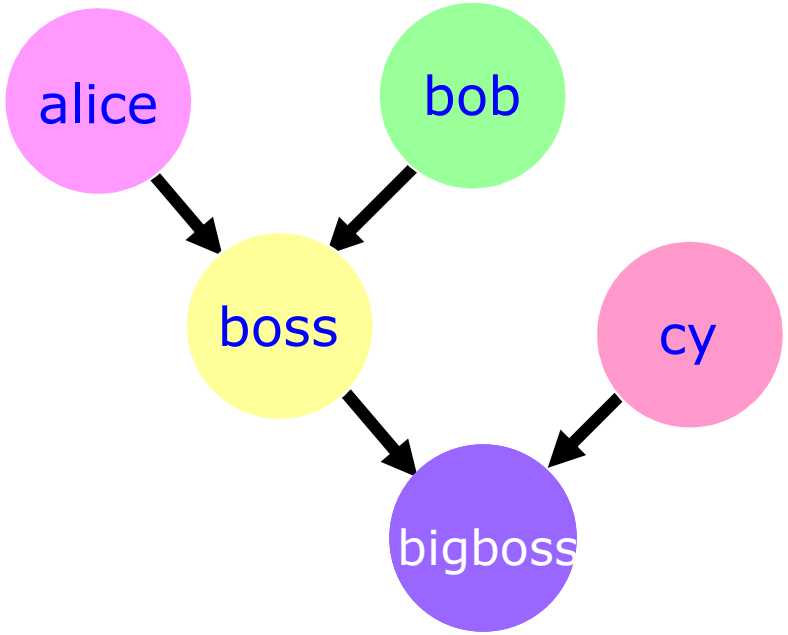
- What is OpenMP?
  - Parallel regions
  - Work sharing – Parallel Sections
  - Data environment
  - Synchronization
- Advanced topics

Credit: IOMPP

Function Level Parallelism



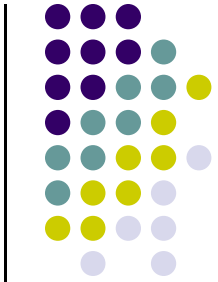
```
a = alice();
b = bob();
s = boss(a, b);
c = cy();
printf ("%6.2f\n", bigboss(s,c));
```



alice,bob, and cy can be computed in parallel

Credit: IOMPP

omp sections



There is an “s” here

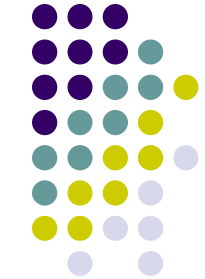
- `#pragma omp sections`
- Must be inside a parallel region
- Precedes a code block containing *N* sub-blocks of code that may be executed concurrently by *N* threads
- Encompasses each omp section

There is no “s” here

- `#pragma omp section`
- Precedes each sub-block of code within the encompassing block described above
- Enclosed program segments are distributed for parallel execution among available threads

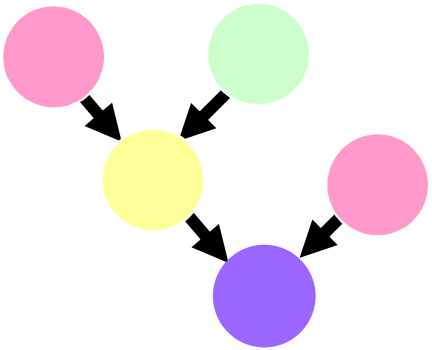
Credit: IOMPP

Functional Level Parallelism Using omp sections



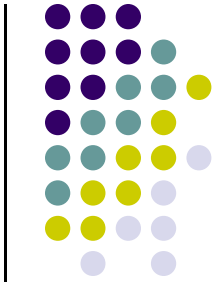
```
#pragma omp parallel sections
{
#pragma omp section
    double a = alice();
#pragma omp section
    double b = bob();
#pragma omp section
    double c = cy();
}

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



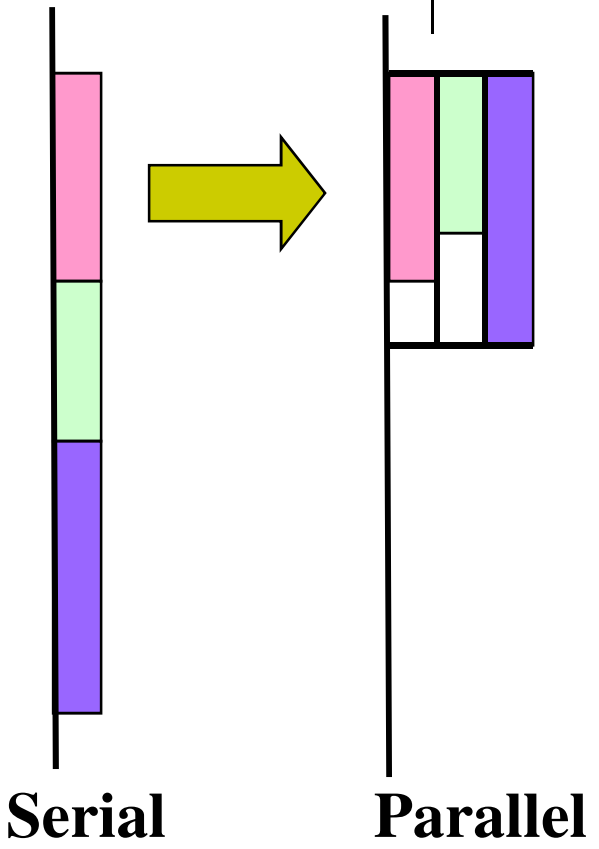
Credit: IOMPP

Advantage of Parallel Sections



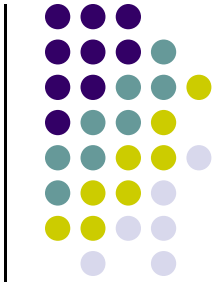
- Independent sections of code can execute concurrently – reduce execution time

```
#pragma omp parallel sections
{
#pragma omp section
        phase1();
#pragma omp section
        phase2();
#pragma omp section
        phase3();
}
```



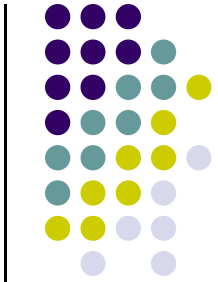
Credit: IOMPP

Work Plan



- What is OpenMP?
  - Parallel regions
  - Work sharing – Tasks
  - Data environment
  - Synchronization
- Advanced topics

New Addition to OpenMP



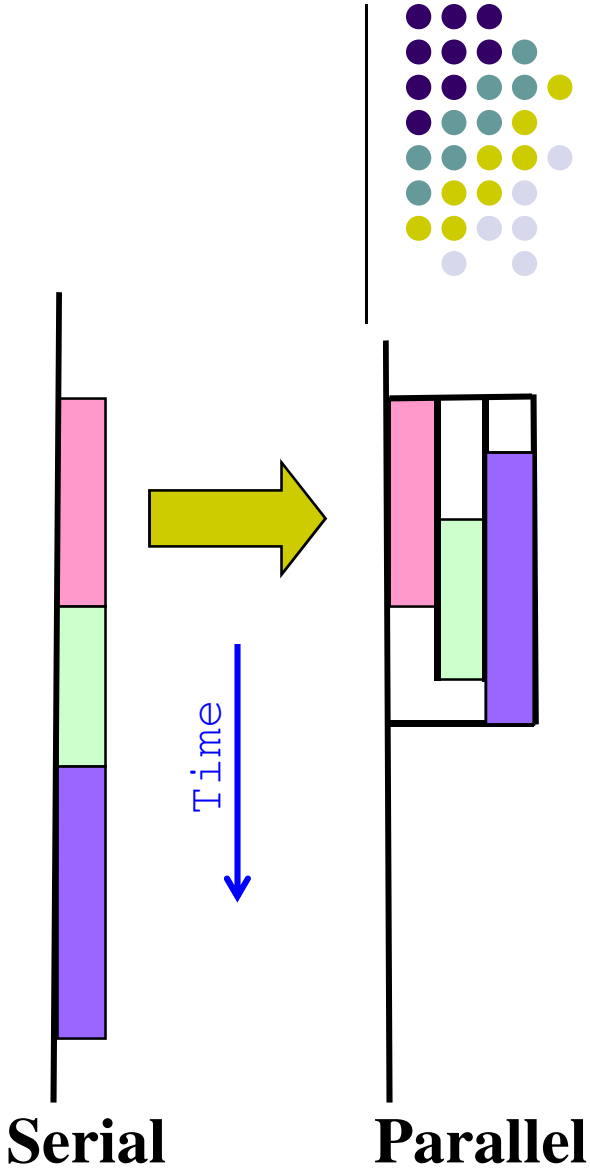
- Tasks – Main change for in the latest 3.0 version of OpenMP

- Allows parallelization of irregular problems
  - Unbounded loops
  - Recursive algorithms
  - Producer/consumer

Credit: IOMPP

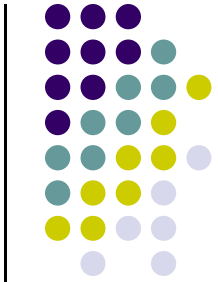
Tasks: What Are They?

- Tasks are independent units of work
- A thread is assigned to perform a task
- Tasks might be executed immediately or might be deferred
  - The runtime system decides which of the above
- Tasks are composed of
  - **code** to execute
  - **data** environment
  - **internal control variables** (ICV)



Credit: IOMPP

Simple Task Example



```
#pragma omp parallel
// assume 8 threads
{
  #pragma omp single private(p)
  {
    // some computation here…
    node *p = head_of_list;
    while( p != end_of_list ) {
    #pragma omp task
      {
        processwork(p);
      }
      p = p->next;
    }
  }
}
```

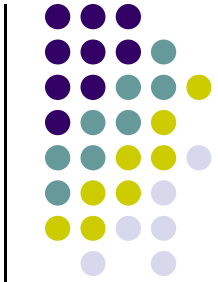
A pool of 8 threads is created here

Only one thread gets to execute the while loop

The single “while loop” thread creates a task for each instance of processwork()

Credit: IOMPP

Task Construct – Explicit Task View



- A team of threads is created at the omp parallel construct
- A single thread is chosen to execute the while loop – call this thread "L"
- Thread L operates the while loop, creates tasks, and fetches next pointers
- Each time L crosses the omp task construct it generates a new task and has a thread assigned to it
- Each task runs in its own thread
- All tasks complete at the barrier at the end of the parallel region's construct

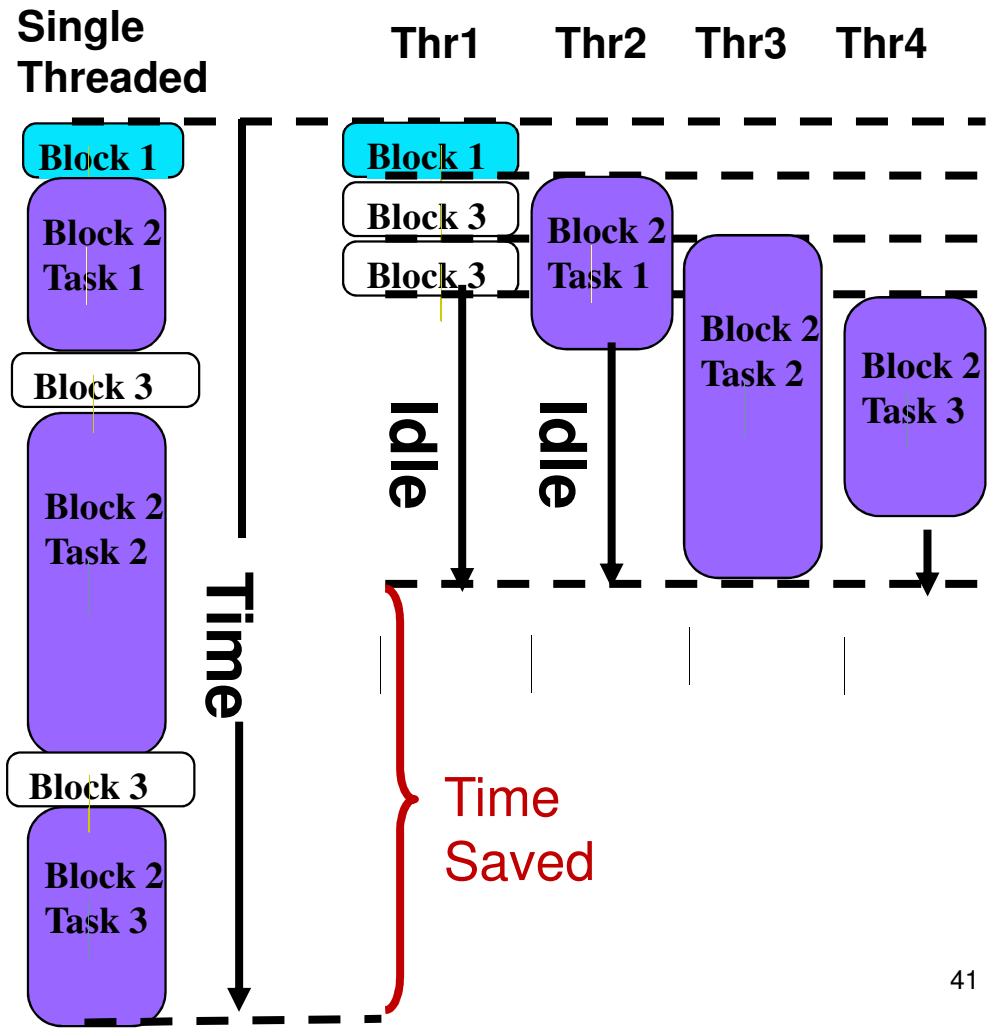
```
#pragma omp parallel
{
   #pragma omp single
   {  // block 1
      node *p = head_of_list;
      while (p) {  //block 2
         #pragma omp task private(p)
         process(p);
         p = p->next;  //block 3
      }
   }
}
```


Credit: IOMPP

Why are tasks useful?

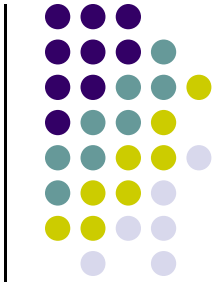
Have potential to parallelize irregular patterns and recursive function calls

```
#pragma omp parallel
{
   #pragma omp single
   {  // block 1
      node *p = head_of_list;
      while (p) {  //block 2
         #pragma omp task private(p)
         process(p);
         p = p->next;  //block 3
      }
   }
}
```



Includes material from IOMPP

Tasks: Synchronization Issues

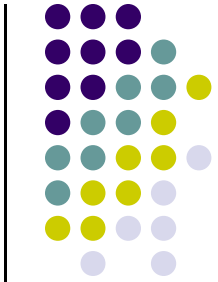


- Setup:
  - Assume Task B specifically relies on completion of Task A
  - You need to be in a position to guaranteed completion of Task A before invoking the execution of Task B

- Tasks are guaranteed to be complete at thread or task barriers:
  - At the directive: `#pragma omp barrier`
  - At the directive: `#pragma omp taskwait`

Includes material from IOMPP

Task Completion Example



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

Multiple foo tasks created here – one for each thread

All foo tasks guaranteed to be completed here

One bar task created here

bar task guaranteed to be completed here