ME759
High Performance Computing for Engineering Applications

Parallel Computing on Multicore CPUs

October 25, 2013

ME964 UW-Madison

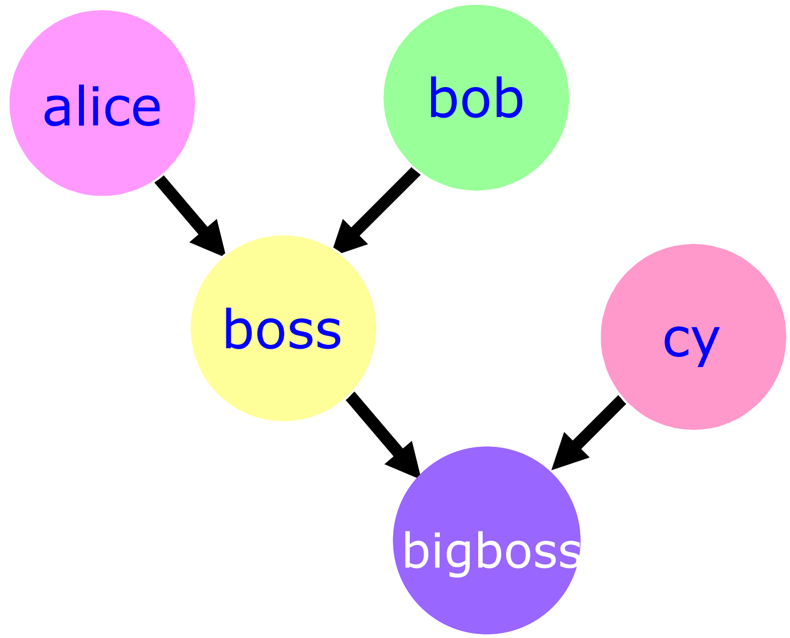
"A programming language is low level when its programs require attention to the irrelevant."
-- Allan Perlis

Before We Get Started…

- Last time
  - Parallel computing on the CPU
  - Got started with OpenMP for parallel computing on multicore CPUs
- Today:
  - Continue OpenMP discussion:
    - sections
    - tasks
    - data scoping
    - synchronization
- Miscellaneous
  - Exam on Monday, November 25 at 7:15 PM.
    - Room 1163ME
    - Review session held during regular class hour that Monday

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

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`, see below

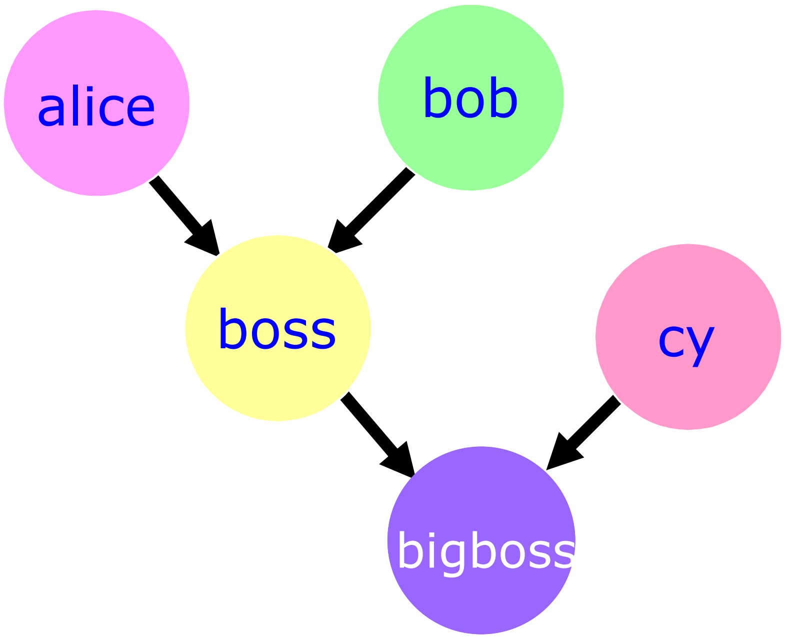
There is no “s” here

- `#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

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));
```

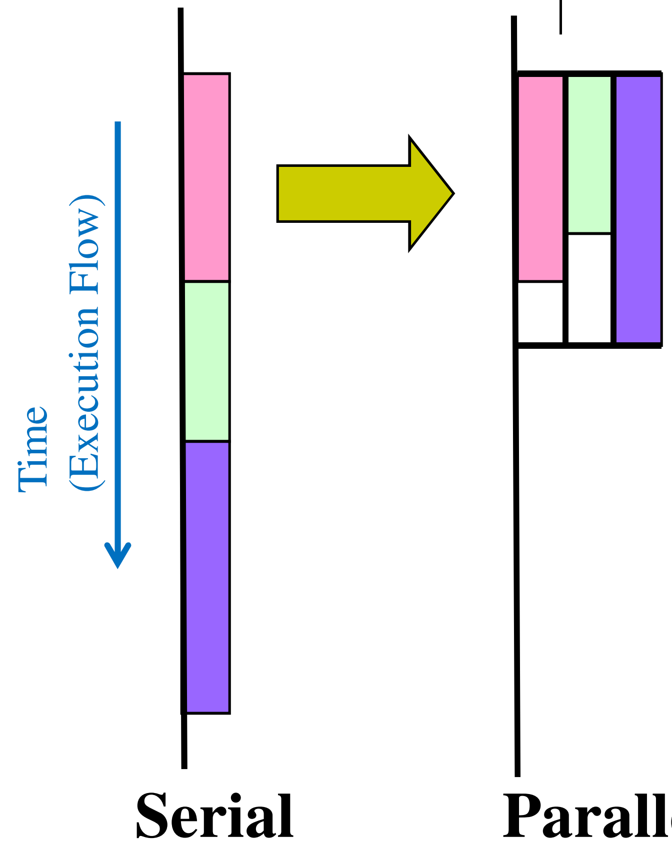


[IOMPP]→

Advantage of Parallel Sections

- Independent sections of code can execute concurrently → reduces execution time

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



The pink and green tasks are executed at no additional time-penalty in the shadow of the purple task

[IOMPP]→

sections, Example

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

int main() {
    printf("Start with 2 procs\n");
#pragma omp parallel sections num_threads(2)
    {
#pragma omp section
        {
            printf("Start work 1\n");
            double startTime = omp_get_wtime();
            while( (omp_get_wtime() - startTime) < 2.0);
            printf("Finish work 1\n");
        }
#pragma omp section
        {
            printf("Start work 2\n");
            double startTime = omp_get_wtime();
            while( (omp_get_wtime() - startTime) < 2.0);
            printf("Finish work 2\n");
        }
#pragma omp section
        {
            printf("Start work 3\n");
            double startTime = omp_get_wtime();
            while( (omp_get_wtime() - startTime) < 2.0);
            printf("Finish work 3\n");
        }
    }
    return 0;
}
```

sections, Example: 2 threads

C:\Windows\system32\cmd.exe

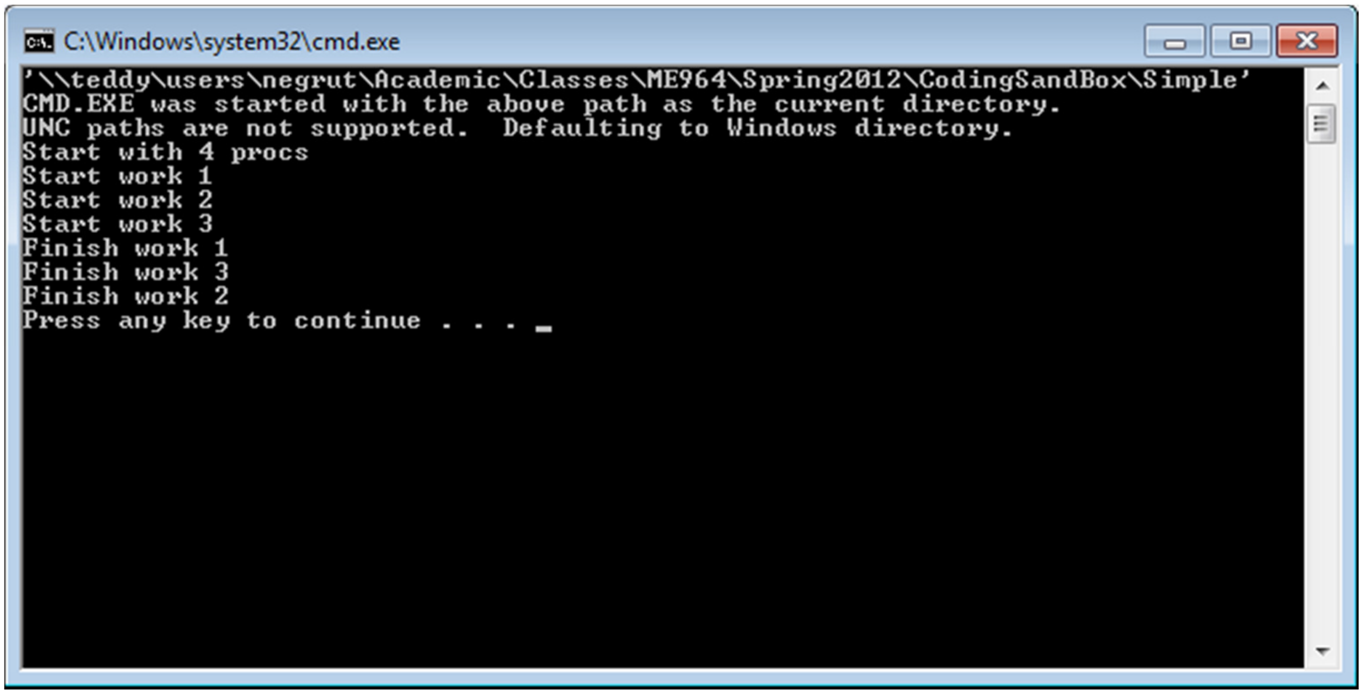
```
'\\teddy\users\negrut\Academic\Classes\ME964\Spring2012\CodingSandBox\Simple'
CMD.EXE was started with the above path as the current directory.
UNC paths are not supported.  Defaulting to Windows directory.
Start with 2 procs
Start work 1
Start work 2
Finish work 1
Start work 3
Finish work 2
Finish work 3
Press any key to continue . . .
```

sections, Example

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

int main() {
    printf("Start with 4 procs\n");
#pragma omp parallel sections num_threads(4)
    {
#pragma omp section
        {
            printf("Start work 1\n");
            double startTime = omp_get_wtime();
            while( (omp_get_wtime() - startTime) < 2.0);
            printf("Finish work 1\n");
        }
#pragma omp section
        {
            printf("Start work 2\n");
            double startTime = omp_get_wtime();
            while( (omp_get_wtime() - startTime) < 6.0);
            printf("Finish work 2\n");
        }
#pragma omp section
        {
            printf("Start work 3\n");
            double startTime = omp_get_wtime();
            while( (omp_get_wtime() - startTime) < 2.0);
            printf("Finish work 3\n");
        }
    }
    return 0;
}
```

`sections`, Example: 4 threads



Work Plan

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

OpenMP Tasks

- Task – Most important feature added in the 3.0 version of OpenMP

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

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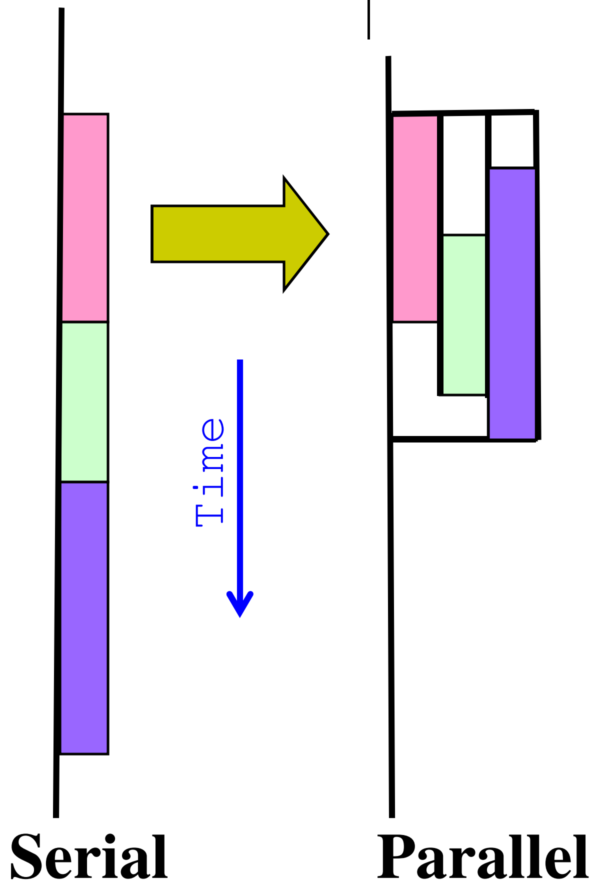
Tasks: What Are They?

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



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Tasks: What Are They?

[More specifics…]

- Code to execute
  - The literal code in your program enclosed by the task directive
- Data environment
  - The shared & private data manipulated by the task
- Internal control variables
  - Thread scheduling and environment variable type controls

- A task is a specific instance of executable code and its data environment, generated when a thread encounters a `task` construct

- Two activities: (1) packaging, and (2) execution
  - A thread packages new instances of a task (code and data)
  - Some thread in the team executes the task at some later time

```cpp
#include <omp.h>
#include <list>
#include <iostream>
#include <math.h>
```

```cpp
using namespace std ;
typedef list<double> LISTDBL;

void doSomething(LISTDBL::iterator& itrtr) {
    *itrtr *= 2.;
}
int main() {
    LISTDBL test;                   // default constructor
    LISTDBL::iterator it;

    for( int i=0;i<4;++i)
        for( int j=0;j<8;++j) test.insert(test.end(), pow(10.0,i+1)+j);
    for( it = test.begin(); it!= test.end(); it++ ) cout << *it << endl;

    it =  test.begin();
#pragma omp parallel num_threads(8)
    {
#pragma omp single
        {
            while( it != test.end() ) {
#pragma omp task private(it)
                {
                    doSomething(it);
                }
                it++;
            }
        }
    }
    for( it = test.begin(); it != test.end(); it++ ) cout << *it << endl;
    return 0;
}
```

```cpp
#include <omp.h>
#include <list>
#include <iostream>
#include <math.h>

using namespace std ;
typedef list<double> LISTDBL;

void doSomething(LISTDBL::iterator& itrtr) {
    *itrtr *= 2.;
}
int main() {
    LISTDBL test;                // default constructor
    LISTDBL::iterator it;

    for( int i=0;i<4;++i)
        for( int j=0;j<8;++j) test.insert(test.end(), pow(10.0,i+1)+j);
    for( it =  test.begin();it!= test.end(); it++ ) cout << *it << endl;

    it =  test.begin();
#pragma omp parallel num_threads(8)
    {
#pragma omp single private(it)
        {
            while( it != test.end() ) {
#pragma omp task
                {
                    doSomething(it);
                }
                it++;
            }
        }
    }
    for( it =  test.begin();it!= test.end(); it++ ) cout << *it << endl;
    return 0;
}
```

```
[negrut@euler22 CodeBits]$ ./testOMP.exe
10
11
12
13
14
15
16
17
100
101
102
103
104
105
106
107
1000
1001
1002
1003
1004
1005
1006
1007
10000
10001
10002
10003
10004
10005
10006
10007
20
22
24
26
28
30
32
34
200
202
204
206
208
210
212
214
2000
2002
2004
2006
2008
2010
2012
2014
20000
20002
20004
20006
20008
20010
```

Initial values…

Final values…

Compile like:

`$ g++ -o testOMP.exe testOMP.cpp`

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 runs 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

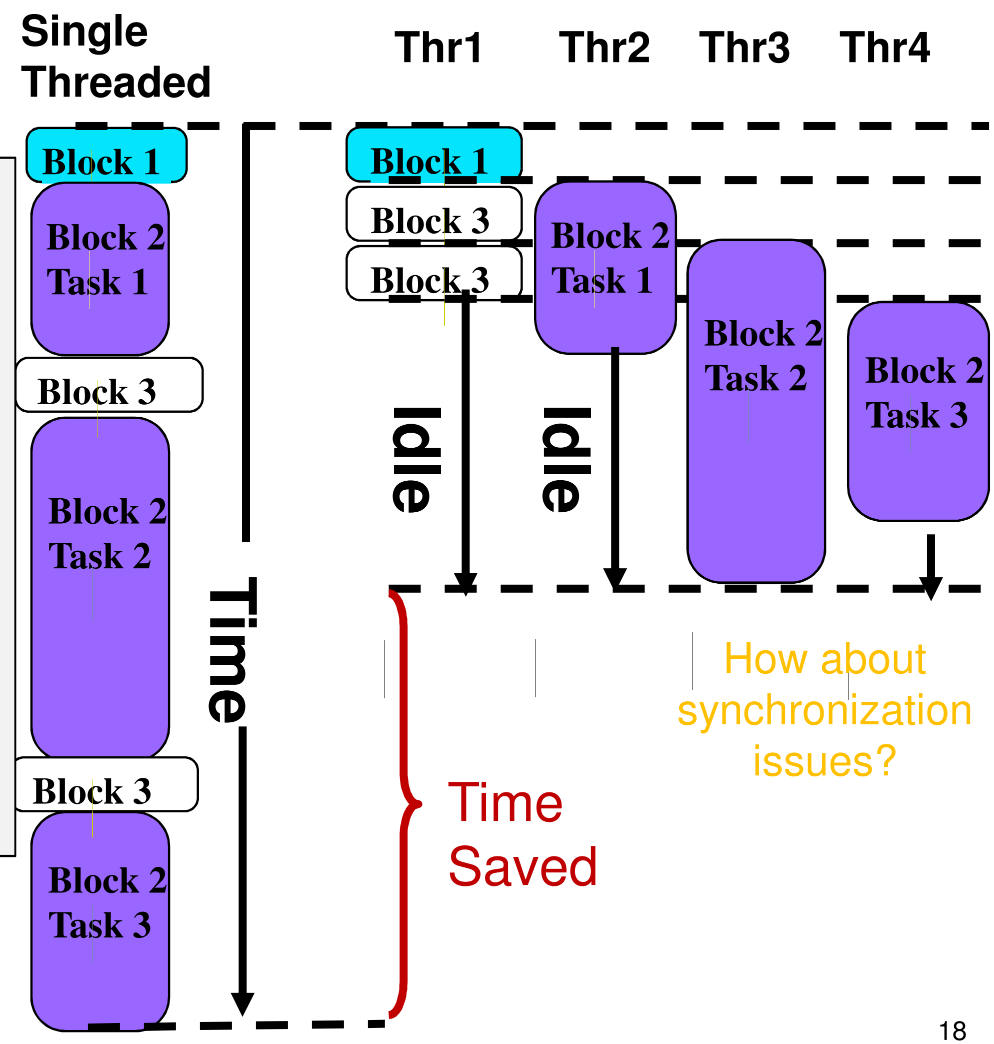
```
#pragma omp parallel
//threads are ready to go now
{
   #pragma omp single
   {  // block 1
      node *p = head_of_list;
      while (p!=listEnd) {  //block 2
         #pragma omp task private(p)
         process(p);
         p = p->next;  //block 3
      }
   }
}
```

- All tasks complete at the barrier at the end of the parallel region's construct
- Each task has its own stack space that will be destroyed when the task is completed
  - See an example in a bit

Why are tasks useful?

Have potential to parallelize irregular patterns and recursive function calls

```
#pragma omp parallel
//threads are ready to go now
{
   #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
      }
   }
}
```



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Tasks: Synchronization Issues

- Setup:
  - Assume Task B specifically relies on completion of Task A
  - You need to be in a position to guarantee 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`

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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

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Comments: sections vs. tasks

- sections have a "*static*" attribute: things are mostly settled at compile time

- The tasks construct is more recent and more sophisticated
  - They have a "*dynamic*" attribute: things are figured out at run time and the construct counts under the hood on the presence of a scheduling agent
  - They can encapsulate any block of code
    - Can handle nested loops and scenarios when the number of jobs is not clear
  - The run time system generates and executes the tasks, either at implicit <u>synchronization points</u> in the program or <u>under explicit control of the programmer</u>

- NOTE: It's the developer responsibility to ensure that different tasks can be executed concurrently

Work Plan

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

Data Scoping – What's shared

- OpenMP uses a shared-memory programming model
- **Shared variable** - a variable that can be read or written by multiple threads
- shared clause can be used to make items explicitly shared
  - Global variables are shared by default among tasks
  - Other examples of variables being shared among threads
    - File scope variables
    - Namespace scope variables
    - Variables with const-qualified type having no mutable member
    - Static variables which are declared in a scope inside the construct

[IOMPP]→

Data Scoping – What's Private

- Not everything is shared...
  - Examples of implicitly determined PRIVATE variables:
    - Stack (local) variables in functions called from parallel regions
    - Automatic variables within a statement block
    - Loop iteration variables
    - Implicitly declared private variables within `task`s will be treated as firstprivate

- **firstprivate**
  - Specifies that each thread should have its own instance of a variable, and that the variable should be initialized with the value of the variable, because it exists before the parallel construct

[IOMPP]→

Data Scoping – The Basic Rule

- When in doubt, explicitly indicate who’s what
  - Data scoping: one of the most common sources of errors in OpenMP

```c
#pragma omp parallel shared(a,b,c,d,nthreads) private(i,tid)
  {
  tid = omp_get_thread_num();
  if (tid == 0) {
    nthreads = omp_get_num_threads();
    printf("Number of threads = %d\n", nthreads);
    }

  printf("Thread %d starting...\n",tid);

  #pragma omp sections nowait
    {
    #pragma omp section
      {
      printf("Thread %d doing section 1\n",tid);
      for (i=0; i<N; i++)
        {
        c[i] = a[i] + b[i];
        printf("Thread %d: c[%d]= %f\n",tid,i,c[i]);
        }
      }

    #pragma omp section
      {
      printf("Thread %d doing section 2\n",tid);
      for (i=0; i<N; i++)
        {
        d[i] = a[i] * b[i];
        printf("Thread %d: d[%d]= %f\n",tid,i,d[i]);
        }
      }
    }  /* end of sections */

    printf("Thread %d done.\n",tid);
  }  /* end of parallel section */
```

When in doubt, explicitly indicate who's what

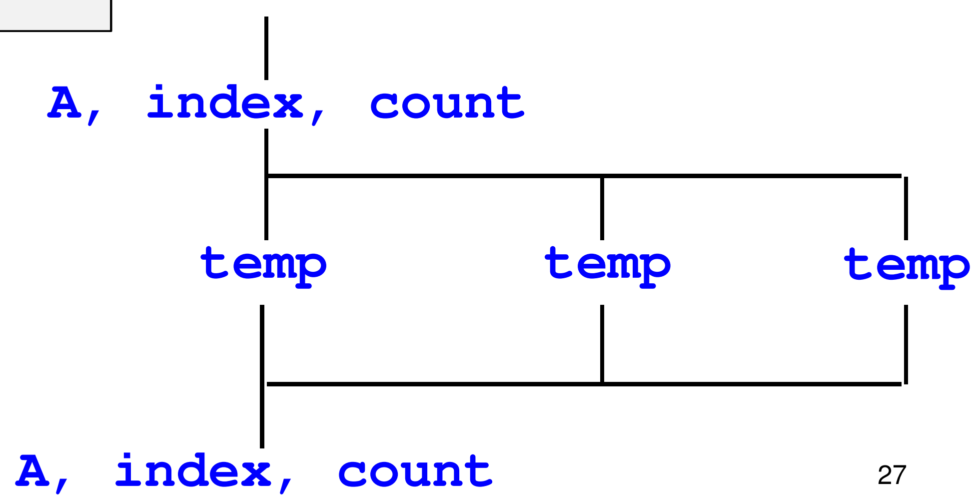
A Data Environment Example

```
float A[10];
main () {
   int index[10];
   #pragma omp parallel
   {
          Work (index);
   }
      printf ("%d\n", index[1]);
}
```

```
extern float A[10];
void Work (int *index)
{
   float temp[10];
   static integer count;
   <...>
}
```

Assumed to be in another translation unit

A, `index`, and `count` are shared by all threads, but `temp` is local to each thread



Includes material from IOMPP

Data Scoping Issue: fib Example

Assume that the parallel region exists outside of `fib` and that `fib` and the tasks inside it are in the dynamic extent of a parallel region

```
int fib ( int n ) {

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

return x+y;
}
```

n is private in both tasks

x is a private variable
y is a private variable

This is very important here

What's wrong here?

Values of the private variables not available outside of tasks

Credit: IOMPP

Data Scoping Issue: fib Example

```
int fib ( int n ) {

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

return x+y
}
```

x is a private variable
y is a private variable

Values of the private variables not available outside of tasks

Credit: IOMPP

Data Scoping Issue: fib Example

```
int fib ( int n ) {

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

return x+y;
}
```

n is private in both tasks

x & y are now shared
we need both values to
compute the sum

The values of the x & y variables will be available outside each task construct – after the taskwait

Credit: IOMPP

Work Plan

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

Credit: IOMPP

Implicit Barriers

- 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
  - The **nowait** clause is applicable to:
    - for clause
    - single clause

Credit: IOMPP

Nowait Clause

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

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

- Use when threads unnecessarily wait between independent computations

```
#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);
```


Credit: IOMPP

Barrier Construct

- Explicit barrier synchronization
- Each thread waits until all threads arrive

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

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


Credit: IOMPP

Atomic Construct

- Applies only to simple update of memory location
- Special case of a `critical` section, to be discussed shortly
  - Atomic introduces less overhead than `critical`

```
index[0] = 2;
index[1] = 3;
index[2] = 4;
index[3] = 0;
index[4] = 5;
index[5] = 5;
index[6] = 5;
index[7] = 1;
```

```
#pragma omp parallel for shared(x, y, index)
    for (i = 0; i < n; i++) {
#pragma omp atomic
        x[index[i]] += work1(i);
        y[i] += work2(i);
    }
```


Credit: IOMPP

Example: Dot Product

```
float dot_prod(float* a, float* b, int N)
{
    float sum = 0.0;
#pragma omp parallel for shared(sum)
    for(int i=0; i<N; i++) {
        sum += a[i] * b[i];
    }
    return sum;
}
```

What is Wrong?

Credit: IOMPP

Race Condition

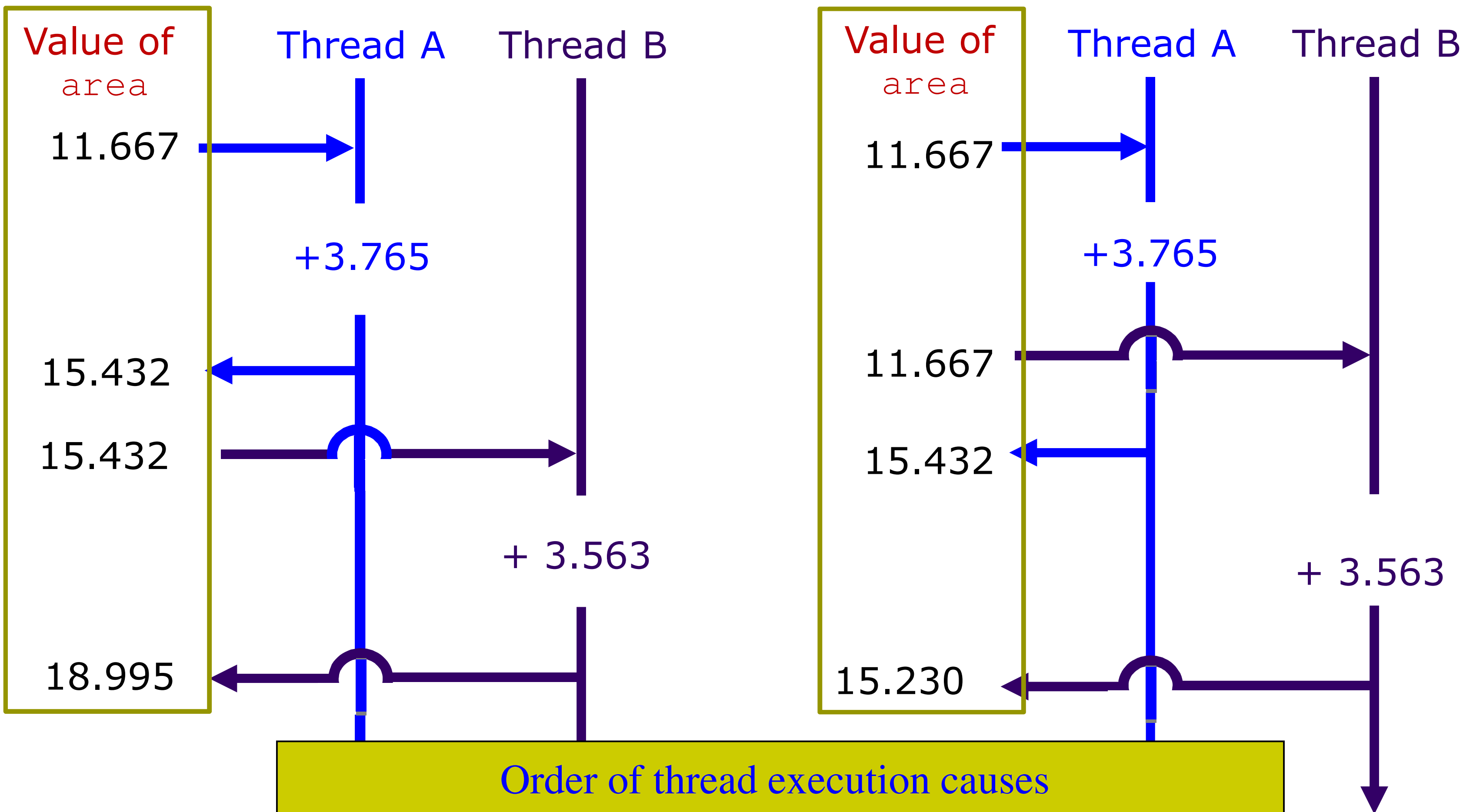
- A *race condition* is nondeterministic behavior produced when two or more threads access a shared variable at the same time

- For example, suppose that `area` is shared and both Thread A and Thread B are executing the statement

```
area += 4.0 / (1.0 + x*x);
```


Credit: IOMPP

Two Possible Scenarios



Order of thread execution causes
non determinant behavior in a data race

Credit: IOMPP

Protect Shared Data

- The `critical` construct: protects access to shared, modifiable data
- The critical section allows only one thread to enter it at a given time

```
float dot_prod(float* a, float* b, int N)
{
    float sum = 0.0;
#pragma omp parallel for shared(sum)
    for(int i=0; i<N; i++) {
#pragma omp critical
        sum += a[i] * b[i];
    }
    return sum;
}
```


Credit: IOMPP