

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

Shared Parallel Programming Using OpenMP

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Why OpenMP?

- Thread libraries are hard to use
 - Pthreads have many library calls for initialization, synchronization, thread creation, condition variables, etc.
 - Programmer must code with multiple threads in mind
- Synchronization between threads introduces a new dimension of program correctness
- Wouldn't be nice to write serial programs and somehow parallelize them "automatically" through simple directives?

Why OpenMP?

- OpenMP is a parallel programming model for Shared-Memory machines
 - All threads have access to a shared main memory
 - Each thread may have private data.
- Parallelism has to be expressed explicitly by the programmer.
 - Base construct is a Parallel Region which is a team of threads that is provided by the runtime system.
- Using the Worksharing constructs, the work can be distributed among the threads of a team.
 - The Task construct defines an explicit task along with its data environment. Execution may be deferred.
- To control the parallelization, mutual exclusion as well as thread and task synchronization constructs are available.

Why OpenMP?

```
int main() {  
  
    // Do this part in parallel  
  
    printf( "Hello, World!\n" );  
  
    } return 0;
```

Why OpenMP? Pthread Version

```
int main() {
    pthread_attr_t attr;
    pthread_t threads[16];
    int tn;

    pthread_attr_init(&attr);

    for(tn=0; tn<16; tn++) {
        pthread_create(&threads[tn], &attr, SayHello, NULL);
    }

    for (tn=0; tn<16 ; tn++) {
        pthread_join(threads[tn], NULL);
    }
    return 0;
}

void* SayHello(void *foo) {
    printf( "Hello, world!\n" );
    return NULL;
}
```

Why OpenMP?

```
int main()
{
    omp_set_num_threads(16);

    // Do this part in parallel
    #pragma omp parallel
    {
        printf( "Hello, World!\n" );
    }

    return 0;
}
```

Why OpenMP?

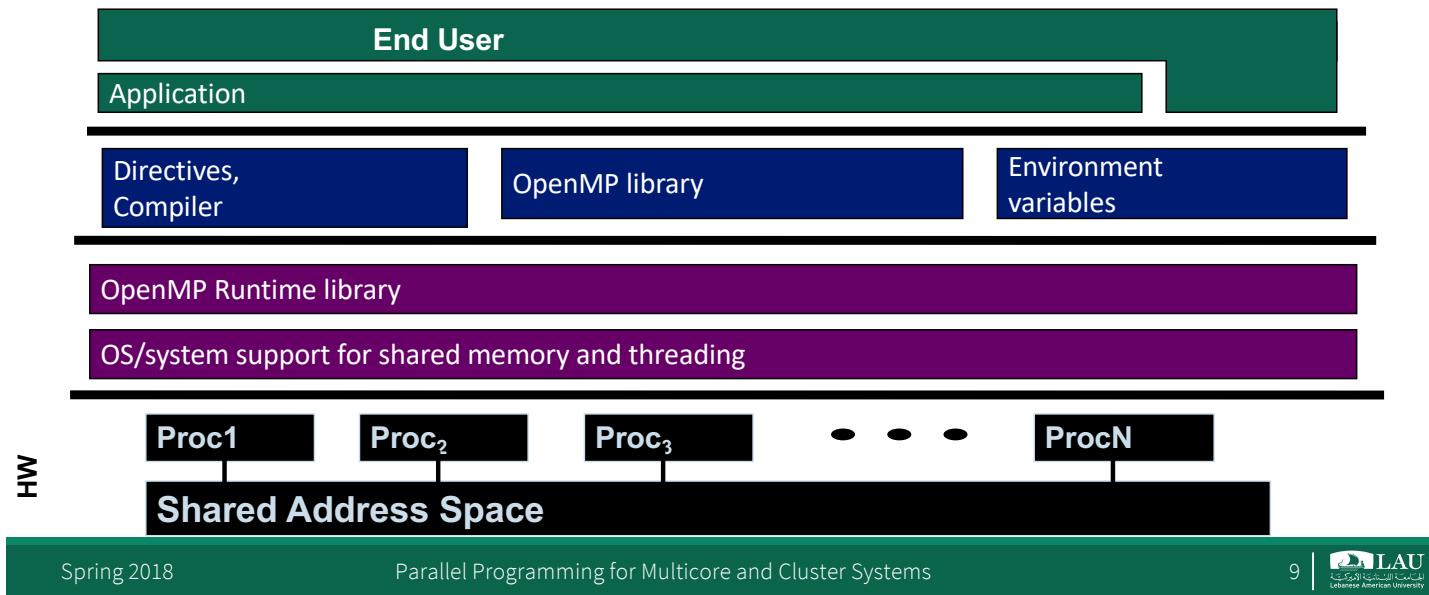
1. Start with *some* algorithm
 - Embarrassing parallelism is helpful, but not necessary
2. Implement serially, *ignoring*:
 - Data Races
 - Synchronization
 - Threading Syntax
3. Test and Debug
4. Automatically (*magically?*) parallelize
 - Expect linear speedup

What Is OpenMP?

- 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 4.5 (<http://www.openmp.org>), 355 Pages
(combined C/C++ and Fortran)

OpenMP: Solution Stack

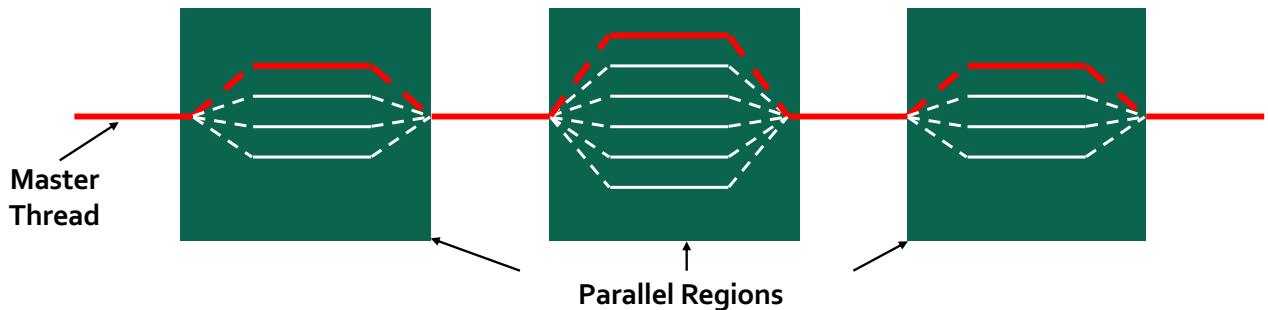


Execution Model

- A thread-based “fork-join” model
 - Initially, a single thread is executed by a master thread.
 - Parallel regions (sections of code) can be executed by multiple threads (a team of threads).
- Parallel directive creates a team of threads with a specified block of code executed by the multiple threads in parallel.
 - The exact number of threads in the team determined by one of several ways.
- Other directives used within a parallel construct to specify parallel for loops and different blocks of code for threads.

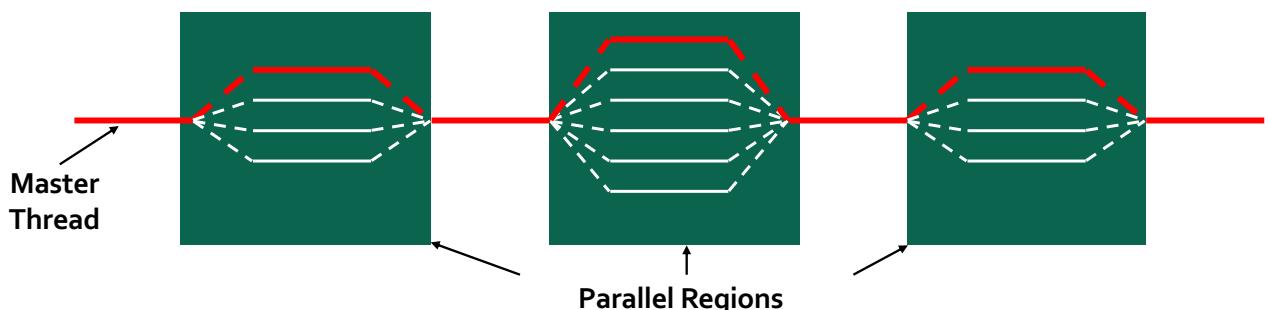
Execution Model

- Fork-Join Parallelism:
 - Master thread spawns a team of threads as needed
 - Parallelism is added incrementally: that is, the sequential program evolves into a parallel program



Execution Model

- Worker threads are spawned at Parallel Regions, together with the Master they form the Team of threads.
- In between Parallel Regions the Worker threads are put to sleep.
- The OpenMP Runtime takes care of all thread management work



OpenMP: How is OpenMP typically used?

- OpenMP is usually used to parallelize loops:

- Find your most time consuming loops.
 - Split them up between threads.

Split-up this loop among multiple threads

```
void main()
{
    double Res[1000];

    for(int i=0;i<1000;i++) {
        do_huge_comp(Res[i]);
    }
}
```

Sequential Program

```
void main()
{
    double Res[1000];
#pragma omp parallel for
    for(int i=0;i<1000;i++) {
        do_huge_comp(Res[i]);
    }
}
```

Parallel Program

OpenMP: How do Threads Interact?

- OpenMP is a shared memory model.
 - Threads communicate by sharing variables.
- Unintended sharing of data can lead to race conditions:
 - race condition: when the program's outcome changes as the threads are scheduled differently.
- To control race conditions:
 - Use synchronization to protect data conflicts.
- Synchronization is expensive so:
 - Change how data is stored to minimize the need for synchronization.

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 directive-name [clause[ [,] clause] ... ] new-line
```

Structured Blocks

- Exactly one entry point at the top
- Exactly one exit point at the bottom
- Branching in or out is not allowed
- Terminating the program is allowed (abort / exit)

Parallel Region & Structured Blocks

- Most OpenMP constructs apply to structured blocks
 - The only “branches” allowed are 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

OpenMP: Parallel Regions

- Create threads in OpenMP using the “omp parallel” pragma.
- For example, To create a 4 thread Parallel region:

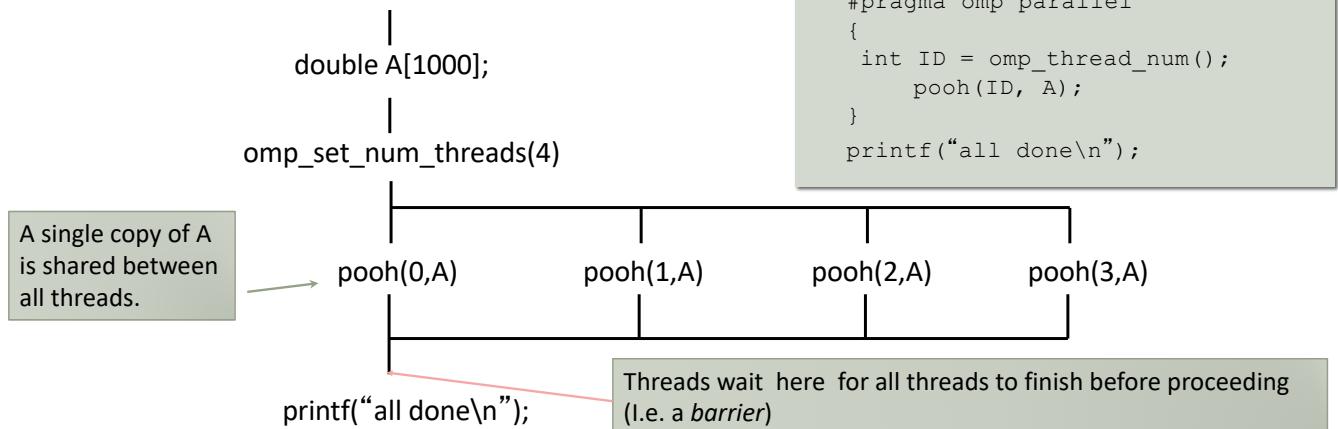
Each thread
redundantly
executes the code
within the
structured block

```
double A[1000];
omp_set_num_threads(4);
#pragma omp parallel
{
    int ID = omp_thread_num();
    pooh(ID,A);
}
```

Each thread calls pooh(ID) for ID = 0 to 3

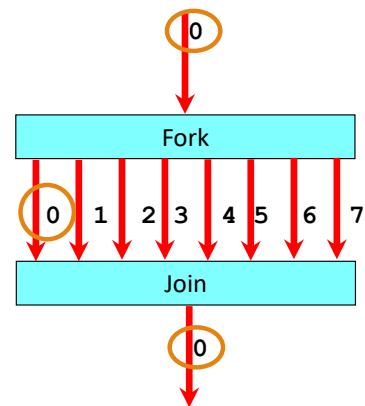
OpenMP: Parallel Regions

Each thread executes the same code redundantly.



OpenMP: Thread Identification

- Master Thread
 - Thread with ID=0
 - Only thread that exists in sequential regions
 - Depending on implementation, may have special purpose inside parallel regions
 - Some special directives affect only the master thread (like `master`)



Hello Worlds

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

int main() {
    #pragma omp parallel
    { ←
        int i;
        int ID = omp_get_thread_num(); ←

        printf("Hello World\n");
        for(i=0;i<6;i++)
            printf("Iter:%d, %d\n",i, ID);
    } ←
    printf("GoodBye World\n");
}
```

Switches for compiling and linking:
gcc -fopenmp filename

Begin Parallel region

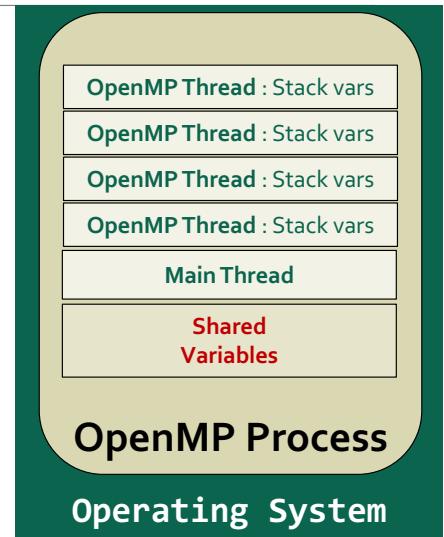
Runtime library function to return a thread ID.

End Parallel region

Sharing Variables in OpenMP

OpenMP shared-memory model

- OpenMP worker threads and the master thread share the same process and some variables.
- If variable scope includes the parallel region, it is shared by default : all the threads will read and write to the same memory location.



Scoping Rules

- OpenMP uses a shared-memory programming model
 - A shared variable is 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
 - File scope variables, namespace scope variables, static variables, Variables with const-qualified type having no mutable member are shared, Static variables which are declared in a scope inside the construct are shared

Scoping Rules

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

Global Data

- Global data is shared and requires special care
- A problem may arise in case multiple threads access the same memory section simultaneously:
 - Read-only data is no problem
 - Updates have to be checked for race conditions
 - It is the programmer's responsibility to deal with this situation
- In general one can do the following:
 - Split the global data into a part that is accessed in serial parts only and a part that is accessed in parallel
 - Manually create thread private copies of the latter
 - Use the thread ID to access these private copies

Shared by default

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

- This code is executing correctly in serial, but may give a different results in parallel. Why?

Problem 1 : Race condition

- A race condition is **nondeterministic behavior** caused by the times at which two or more threads access a **shared variable**.
- Let's suppose we have 2 threads executing :
 $x = a[i]; y = b[i];$
 $c[i] = x + y;$
- If a thread can execute the two lines without having the other thread changing variables x and y, good
 - **Not guaranteed**.
- If the two threads have a mixed execution, the result c will be **wrong**.

Problem 1 : Race condition

- Race conditions may or may not be visible depending on various experimental conditions (number of cores, other software running, luck, ...)

Problem 2 : Corruption

- Independently from race conditions, writing to the same object or memory location from different threads without protection is risky.
 - Example : Different threads write to the serial output (console) at the same time.
 - If you are lucky, messages will intercalate nicely.
 - If you are not, the output may become garbled as bits of information representing the output text will be mixed together.

Problem 3 : Initialization

- If you use local copies instead of global variables to prevent race conditions and corruption, the last problem is initialization.
- Local variables created by the OpenMP layer may or may not be initialized, or initialized differently depending on the directive used :
 - PRIVATE
 - THREADPRIVATE
 - FIRSTPRIVATE
 - ...

Solutions

- The solutions exist :
 - Large : force the execution of a block of code in serial with a critical section. Only one thread will execute this block at a given time.
 - Finer : protect a variable (force serial execution of write operations).
 - Finest : protect a variable with detailed information about the kind of operation.
 - Example : reduction.
- Ideal : recode to prevent sharing.

Scalability

- Thanks to Amdahl's law, we know serial parts will rapidly decrease the scalability of your parallel software.
- But forcing the serial execution of a block of code or serial access to a variable is a serial part, even if it's inside a parallel region.
- Try to rewrite or rethink your algorithm to prevent variable sharing and synchronization.
- If you have to synchronize, select the finest granularity to minimize the serial part.

Solution 1: Explicitly Change the Scope

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

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

Before : variables defined with global scope from the master thread, shared between threads.

After : local variables defined locally.
Nothing shared.

Efficient and safe.

Solution 2: forcing serial execution of the critical block

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

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

Before : variables defined with global scope from the master thread, shared between threads.

After : same thing, but serial execution forced.

Safe but not scaling.

Solution 3: atomic

- Instead of protecting an entire block of code, is it enough to protect write accesses to a single shared variable only ?
- If yes, use atomic it will be a lot faster than critical :
 - atomic is like a mini critical section for a variable.

```
#pragma omp parallel for
shared(sum)
for(i=0; i<N; i++) {
#pragma omp atomic
    sum += a[i] * b[i];
}
```

Solution 4: Changing the Scope Using the private Clause

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

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;
}
```

Before : global variables shared between threads.

After : local copies of global variables.
Nothing shared.

Efficient and safe.

Solution 4: Changing the Scope Using the private Clause

- 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

```
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;
    }
}
```

Other Data Scope Clauses

- **shared**
 - Declares variables in its list to be shared among all threads in the team
- **firstprivate**
 - Combines the behavior of the **private** clause with automatic initialization of the variables in its list
- **lastprivate**
 - Combines the behavior of the **private** clause with a copy from the last loop iteration or section to the original variable object
- Reduction
- Other clauses include **copyin** and **copyprivate**

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;
}
```

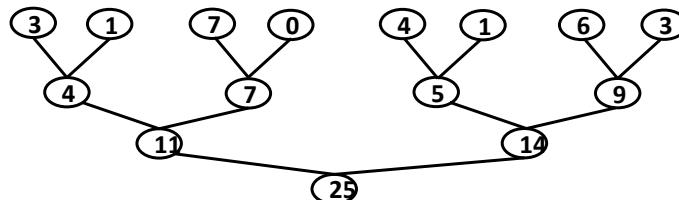
lastprivate Example

- 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;
```

Conditional Serial Execution of Parallel Regions

- 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;
```

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

Operand	Initial Value
&	~ 0
	0
&&	1
	0

A Data Environment Example

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

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

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

A, index, count

temp *temp* *temp*

A, index, count

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?

Multiple threads modifying sum with no protection – this is a race condition!

Synchronization

Programming Model: 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
 - Single-thread regions within parallel regions
 - master, single directives

```
#pragma omp critical [(lock_name)]  
{  
    /* Critical code here */  
}  
  
#pragma omp barrier  
  
omp_set_lock( lock_1 );  
/* Code goes here */  
omp_unset_lock( lock_1 );  
  
#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

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);
```

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);
}
```

The diagram illustrates the execution flow and implicit barriers in the provided OpenMP code. It consists of three main vertical columns separated by double-headed arrows:

- Top Column:** Contains the first two lines of the code. An arrow points from the text "implicit barrier at the end of a for work sharing construct" to the closing brace of the parallel region.
- Middle Column:** Contains the third line of the code. An arrow points from the text "no implicit barrier due to nowait" to the "nowait" keyword in the pragma.
- Bottom Column:** Contains the last two lines of the code. An arrow points from the text "implicit barrier at the end of a parallel region" to the closing brace of the parallel region.

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);
}
```

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)

OpenMP critical: Example

- Threads wait their turn – only one at a time calls `consume()` thereby protecting RES from race conditions

- Naming the `critical` construct `RES_lock` is optional
- Good Practice – Name all `critical` sections

```
float RES;
#pragma omp parallel
{
float B;
#pragma omp for
for(int i=0; i < niters; i++)
{
    B = big_job(i);
    #pragma omp critical (RES_lock)
        consume (B, RES);
}
}
```

Synchronization: atomic

- Very similar to the `critical` directive
 - Difference is that `atomic` is only used for the update of a memory location
 - `atomic` is referred to as a mini critical section with a block of one statement

```
#pragma omp parallel
{
double tmp, B;
B = DoIt();
tmp = big_ugly(B);
#pragma omp atomic
x += tmp;
}
```

Atomic only protects
the read/update of X

Synchronization: atomic Example

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

Synchronization: Lock Functions

- Simple Lock routines:
 - A simple lock is available if it is unset.
 - `omp_init_lock()`, `omp_set_lock()`, `omp_unset_lock()`, `omp_test_lock()`, `omp_destroy_lock()`
- Nested Locks
 - A nested lock is available if it is unset or if it is set but owned by the thread executing the nested lock function
 - `omp_init_nest_lock()`, `omp_set_nest_lock()`, `omp_unset_nest_lock()`, `omp_test_nest_lock()`, `omp_destroy_nest_lock()`

A lock implies a memory fence of all thread visible variables

Synchronization: Lock Functions

- Protect resources with locks.

```
omp_lock_t lck;
omp_init_lock(&lck);
#pragma omp parallel private (tmp, id)
{
    id = omp_get_thread_num();
    tmp = do_lots_of_work(id);
    omp_set_lock(&lck);
    printf("%d %d", id, tmp);
    omp_unset_lock(&lck);
}
omp_destroy_lock(&lck);
```

Wait here for your turn.

Release the lock so the next thread gets a turn.

Free-up storage when done.

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();
}
```

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: collapse Clause

- Fuse or collapse perfectly nested loops to exploit a larger iteration space for the parallelization
 - Increase the total number of iterations that will be partitioned across the available number of OMP threads by reducing the granularity of work to be done by each thread
 - If the amount of work to be done by each thread is non-trivial (after collapsing is applied), this may improve the parallel scalability of the OMP application

Avoiding Overhead: collapse Clause

```
#pragma omp for collapse(2)
for(i = 1; i < N; i++)
    for(j = 1; j < M; j++)
        for(k = 1; k < K; k++)
            foo(i, j, k);
```

Iteration space from *i*-loop and *j*-loop is collapsed into a single one, if loops are perfectly nested and form a rectangular iteration space.

SPMD vs. Worksharing

- A parallel construct by itself creates an SPMD or “Single Program Multiple Data” program ... i.e., each thread redundantly executes the same code.
- How do you split up pathways through the code between threads within a team?
 - This is called worksharing
 - Loop construct
 - Task construct
 - Sections/section constructs
 - Single construct

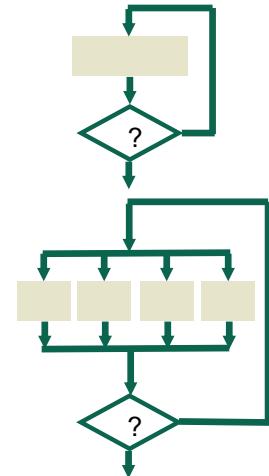
Worksharing

- 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

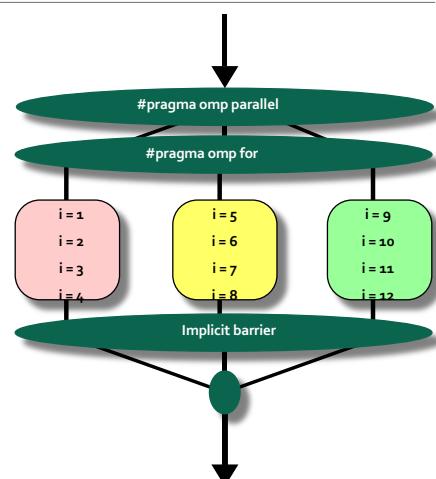
OpenMP: Concurrent Loops

- 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



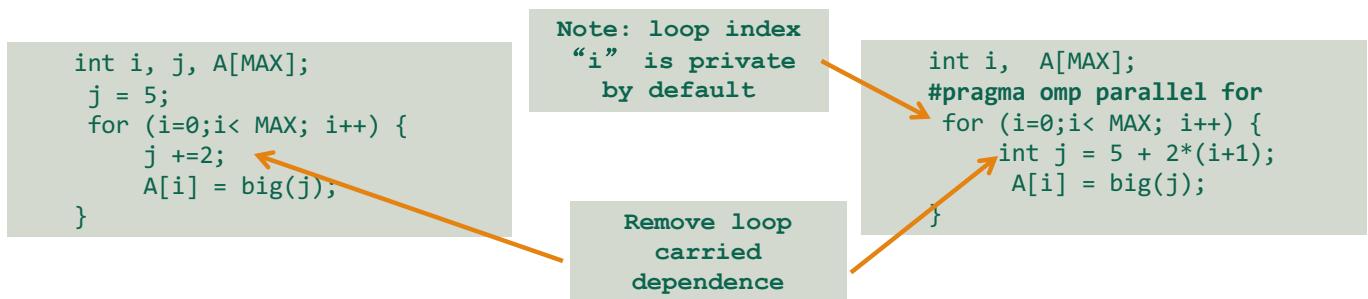
OpenMP: Concurrent Loops

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



Working with 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



Working with Loops: Subtle Details

- Dynamic mode (the default mode)
 - The number of threads used in a parallel region can vary from one parallel region to another.
 - Setting the number of threads only sets the maximum number of threads - you could get less.
- Static mode
 - The number of threads is fixed and controlled by the programmer.
- Although you can nest parallel loops in OpenMP, the compiler can choose to serialize the nested parallel region

OpenMP schedule Clause

- Determine how loop iterations are divided among the thread team
 - `static([chunk])` divides iterations statically between threads
 - Each thread receives `[chunk]` iterations, rounding as necessary to account for all iterations
 - Default `[chunk]` is `ceil(# iterations / # threads)`
 - `dynamic([chunk])` allocates `[chunk]` iterations per thread, allocating an additional `[chunk]` iterations when a thread finishes
 - Forms a logical work queue, consisting of all loop iterations
 - Default `[chunk]` is 1
 - `guided([chunk])` allocates dynamically, but `[chunk]` is exponentially reduced with each allocation

Loop Work-Sharing: The `schedule` clause

Schedule Clause	When To Use	
STATIC	Pre-determined and predictable by the programmer	<i>Least work at runtime : scheduling done at compile-time</i>
DYNAMIC	Unpredictable, highly variable work per iteration	<i>Most work at runtime : complex scheduling logic used at run-time</i>
GUIDED	Special case of dynamic to reduce scheduling overhead	

OpenMP: Loop Scheduling

```
// static scheduling

#pragma omp parallel for schedule(static)

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

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

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

Barrier();
```



OpenMP: Loop Scheduling

```
// Dynamic Scheduling

#pragma omp parallel for \
schedule(dynamic)

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

int current_i;

while( workLeftToDo() )
{
    current_i = getNextIter();
    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++;
    }
```

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**

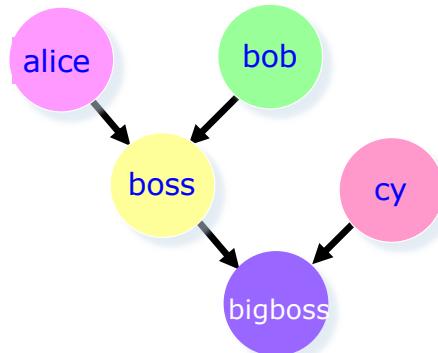
- Precedes each block of code within the encompassing block described above
 - May be omitted for first parallel section after the parallel sections pragma
 - Enclosed program segments are distributed for parallel execution among available threads

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));
```

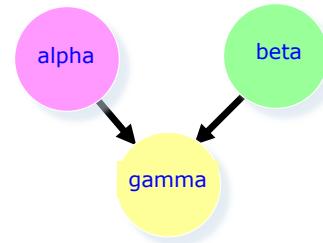


Alice , bob, and cy can be computed in parallel

Sections work sharing Construct

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

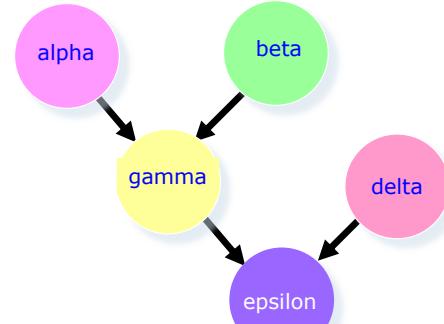
printf ("%6.2f\n", gamma(a, b) );
```



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

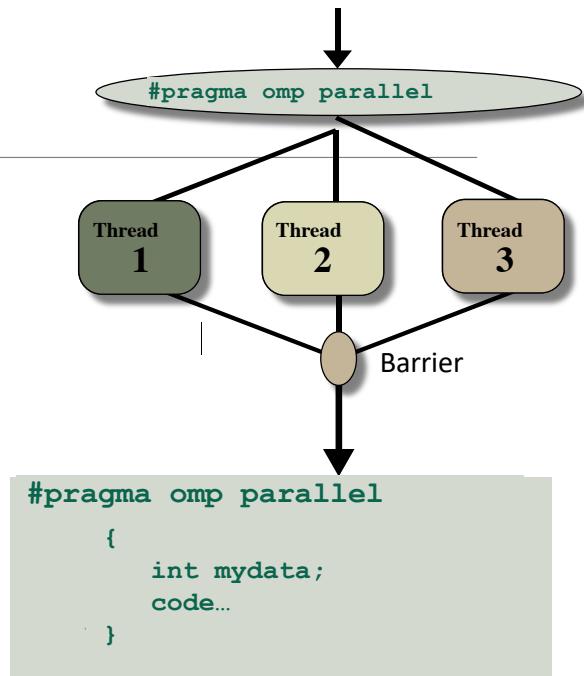
Sections work sharing Construct

```
#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));
```



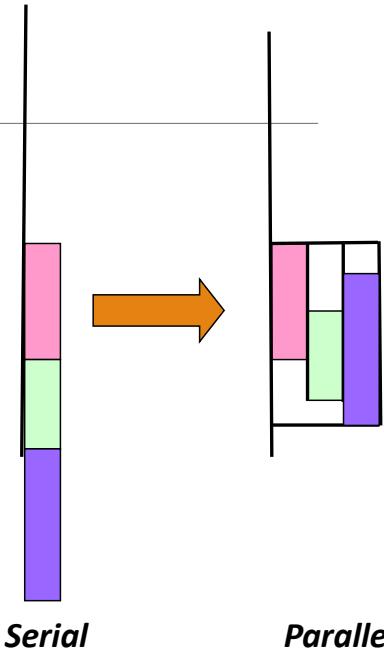
Parallel Construct Implicit Task View

- 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.



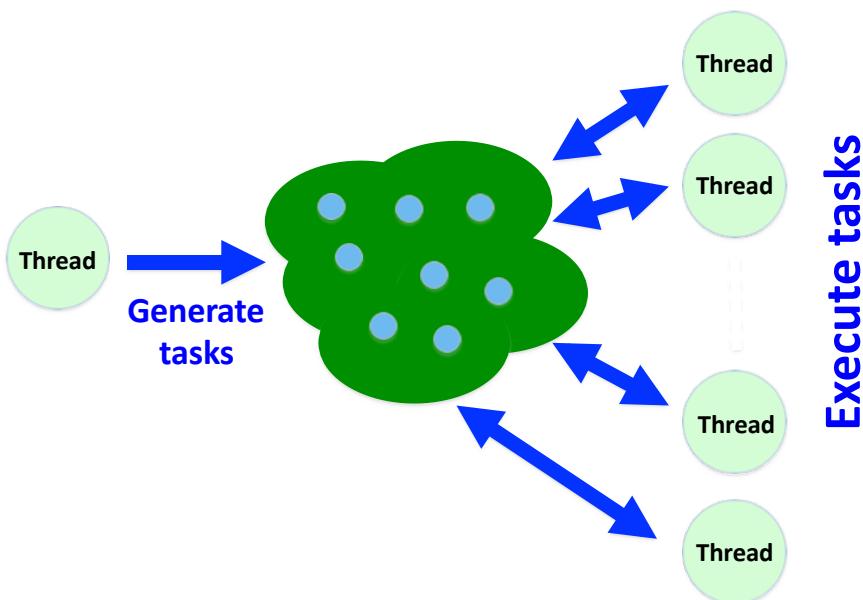
Tasks

- 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)

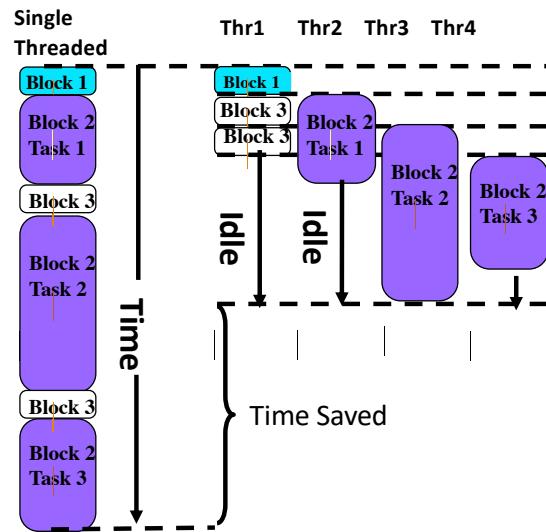


OpenMP Tasks

- Developers use a pragma to specify where the tasks are using the assumption that all tasks can be executed independently
- 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



Why are tasks useful?



OpenMP task clause

#pragma omp task

- 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.

Simple Example 1

**Write a program that prints either “A race car” or
“A car race” and maximize the parallelism**

Simple Example 1

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

int main(int argc, char *argv[]) {
    printf("A ");
    printf("race ");
    printf("car ");

    printf("\n");
    return(0);
}
```

Output?

Parallel Simple Example 1

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

int main(int argc, char *argv[]) {
#pragma omp parallel
{
    printf("A ");
    printf("race ");
    printf("car ");
}
printf("\n"); return(0);
}
```

A A A A A A A race A A A A A A race race
race race race race race car race race race
race race race car car car car car car
car car car car car car car

Parallel Simple Example 1 Using Single

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

int main(int argc, char *argv[]) {
#pragma omp parallel
{
    #pragma omp single
    {
        printf("A ");
        printf("race ");
        printf("car ");
    }
}
printf("\n"); return(0);
}
```

Output?

Parallel Simple Example 1 Using Tasks

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

int main(int argc, char *argv[]) {
#pragma omp parallel
{
    #pragma omp single
    {
        printf("A ");
        #pragma omp task
        printf("race ");
        #pragma omp task
        printf("car ");
    }
    printf("\n");  return(0);
}
```

Output?

A car race

A race car

Parallel Simple Example 1 Using Tasks

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

int main(int argc, char *argv[]) {
#pragma omp parallel
{
    #pragma omp single
    {
        printf("A ");
        #pragma omp task
        {
            printf("race "); printf("race ");
            printf("race "); printf("race ");
        }
        #pragma omp task
        printf("car ");
    }
    printf("\n");  return(0);
}
```

And Now?

A car race race race race

A race car race race race

Simple Example 2: || Linked List

```
#pragma omp parallel
// assume 8 threads
{
    #pragma omp single private(p)
    {
        ...
        while (p) {
            #pragma omp task
            {
                processwork(p);
            }
            p = p->next;
        }
    }
}
```

A pool of 8 threads is created here

One thread gets to execute the while loop

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

Task synchronization

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

np Tasks created here, one for each thread

All Tasks guaranteed to be completed here

1 Task created here

B-Task guaranteed to be completed here

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(bool arg)
{
    int i = 3;
    #pragma omp task final(arg) firstprivate(i)
        i++;
    printf("%d\n", i); // will print 3 or 4 depending
on expr
}
```

Avoiding Overhead: mergeable Clause

- The mergeable clause allows the implementation to merge the task's data environment with the enclosing region
 - if the generated task is *undeferred* or *included*
 - *undeferred*: if clause present and evaluates to false
 - *included*: final clause present and evaluates to true

```
#pragma omp task mergeable
```

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

OpenMP: Recap

- OpenMP is a parallel programming model for Shared-Memory machines
 - All threads have access to a shared main memory
 - Each thread may have private data.
- Parallelism has to be expressed explicitly by the programmer.
 - Base construct is a Parallel Region which is a team of threads that is provided by the runtime system.
- Using the Worksharing constructs, the work can be distributed among the threads of a team.
 - The Task construct defines an explicit task along with its data environment. Execution may be deferred.
- To control the parallelization, mutual exclusion as well as thread and task synchronization constructs are available.

Task Construct: Linked List Revisited

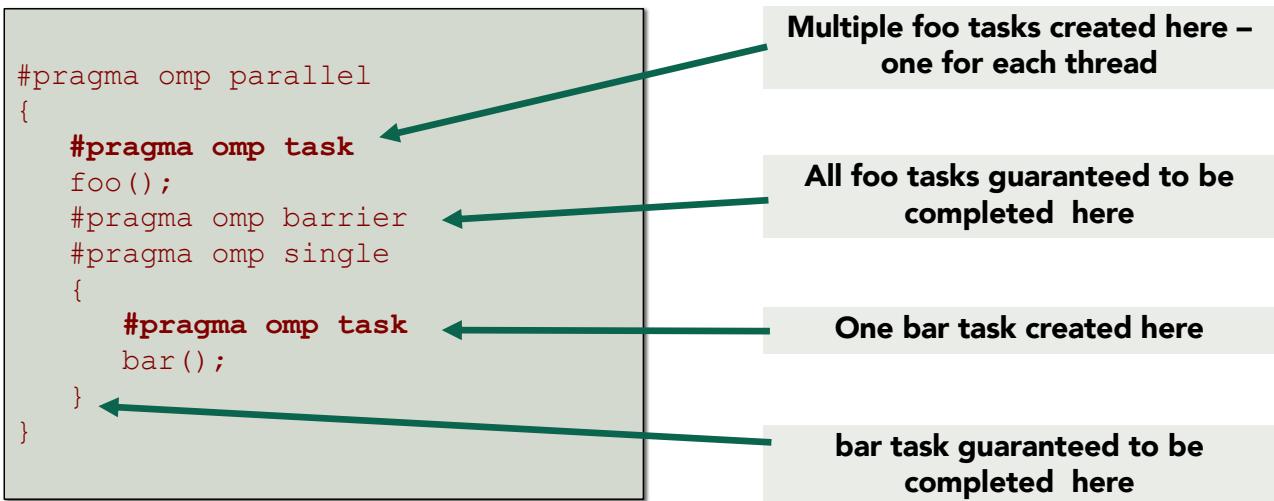
- A team of threads is created at the `omp parallel` construct
- A single thread is chosen to execute the `while` loop
 - o Lets call this thread "L"
- Thread L operates the while loop, creates tasks, and fetches next pointers
- Each time L crosses the `omp task`, construct it generates a new task and 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 `single` construct

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

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!

Task Completion Example



Using OpenMP

PORTABLE SHARED MEMORY PARALLEL PROGRAMMING

Environment Variables

Environment Variables

Name	Possible Values	Most Common Default
OMP_NUM_THREADS	Non-negative Integer	1 or #cores
OMP_SCHEDULE	„schedule [, chunk]“	„static, (N/P)“
OMP_DYNAMIC	{TRUE FALSE}	TRUE
OMP_NESTED	{TRUE FALSE}	FALSE
OMP_STACKSIZE	„size [B K M G]“	-
OMP_WAIT_POLICY	{ACTIVE PASSIVE}	PASSIVE
OMP_MAX_ACTIVE_LEVELS	Non-negative Integer	-
OMP_THREAD_LIMIT	Non-negative Integer	1024
OMP_PROC_BIND	{TRUE FALSE}	FALSE
OMP_PLACES	Place List	-
OMP_CANCELLATION	{TRUE FALSE}	FALSE
OMP_DISPLAY_ENV	{TRUE FALSE}	FALSE
OMP_DEFAULT_DEVICE	Non-negative Integer	-

Nesting parallel Directives

- Nested parallelism can be enabled using the `OMP_NESTED` environment variable.
- If the `OMP_NESTED` environment variable is set to `TRUE`, nested parallelism is enabled.
- In this case, each parallel directive creates a new team of threads.

OpenMP Library Functions

- In addition to directives, OpenMP also supports a number of functions that allow a programmer to control the execution of threaded programs.

```
/* thread and processor count */  
void omp_set_num_threads (int num_threads);  
int omp_get_num_threads ();  
int omp_get_max_threads ();  
int omp_get_thread_num ();  
int omp_get_num_procs ();  
int omp_in_parallel();
```

OpenMP Library Functions

```
/* controlling and monitoring thread creation */  
void omp_set_dynamic (int dynamic_threads);  
int omp_get_dynamic ();  
void omp_set_nested (int nested);  
int omp_get_nested ();  
/* mutual exclusion */  
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);
```

- In addition, all lock routines also have a nested lock counterpart for recursive mutexes.

Environment Variables in OpenMP

- OMP_NUM_THREADS: This environment variable specifies the default number of threads created upon entering a parallel region.
- OMP_SET_DYNAMIC: Determines if the number of threads can be dynamically changed.
- OMP_NESTED: Turns on nested parallelism.
- OMP_SCHEDULE: Scheduling of for-loops if the clause specifies runtime

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.

in OpenMP

Rohit Chandra

Examples

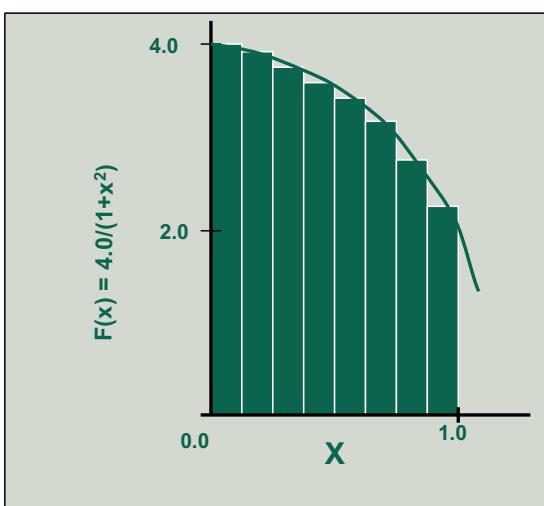
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Back to the PI Problem ...



Mathematically, we know that:

$$\int_0^1 \frac{4.0}{(1+x^2)} dx = \pi$$

We can approximate the integral as a sum of rectangles:

$$\sum_{i=0}^N F(x_i) \Delta x \approx \pi$$

Where each rectangle has width Δx and height $F(x_i)$ at the middle of interval i.

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Back to the PI Problem: Serial Code

```
static long num_steps = 100000;
double step;
void main ()
{
    int i;
    double x, pi, sum = 0.0;

    step = 1.0/(double) num_steps;

    for (i=0;i< num_steps; i++){
        x = (i+0.5)*step;
        sum = sum + 4.0/(1.0+x*x);
    }
    pi = step * sum;
}
```

Calculate Pi by integration

$$\Pi = \int_0^1 \frac{4}{(1+x^2)} dx$$

```
double f(double x) {
    return (double)4.0 / ((double)1.0 + (x*x));
}
void computePi() {
    double h = (double)1.0 / (double)iNumIntervals;
    double sum = 0, x;

    ...
    for (int i = 1; i <= iNumIntervals; i++) {
        x = h * ((double)i - (double)0.5);
        sum += f(x);
    }
    myPi = h * sum;
}
```

$$\Pi = \int_0^1 \frac{4}{(1+x^2)} dx$$

Calculate Pi by integration

```

double f(double x) {
    return (double)4.0 / ((double)1.0 + (x*x));
}
void computePi() {
    double h = (double)1.0 / (double)iNumIntervals;
    double sum = 0, x;

#pragma omp parallel for private(x) reduction(+:sum)

    for (int i = 1; i <= iNumIntervals; i++) {
        x = h * ((double)i - (double)0.5);
        sum += f(x);
    }

    myPi = h * sum;
}

```

Reduction Example: Computing Pi

```

long num_steps=100000; double step;

void main()
{ int i;
  double x, sum = 0.0, pi;

  step = 1.0/(double)num_steps;
  start = clock();
  #pragma omp parallel for private(x) reduction (+:sum)
  for (i=0; i<num_steps; i++)
  {
    x = (i + .5)*step;
    sum = sum + 4.0/(1.0 + x*x);
  }

  pi = sum*step;
  stop = clock();

  printf("The value of PI is %15.12f\n",pi);
  printf("Time to calculate PI was %f seconds\n",((double)(stop - start)/1000.0));
  return 0;
}

```

$$\Pi = \int_0^1 \frac{4}{(1+x^2)} dx$$

Calculate Pi by integration

#Threads	Runtime [sec.]	Speedup
1	0.002877	1.00
2	0.001777	1.62
4	0.002988	0.96
8	0.002050	1.40
16	0.105787	1.26

Number of Iterations: 1000,000

PI value: 3.141593

Architecture: Intel i7, 3 GHz, running Mac OS 10.11.3 with 16GB RAM

Useful MacOS/Linux Commands

To compile

```
gcc -Wall -fopenmp -o pi pi.c
```

To set the number of threads to 4 using OMP_NUM_THREADS:

```
In the bash shell, type: export OMP_NUM_THREADS=4
in the c shell, type: setenv OMP_NUM_THREADS 4
```

You can set the number of threads to different values (2, 8, etc) using the same command
To run the OpenMP example code, simply type ./pi

You can use the time command to evaluate the program's runtime:

Not very accurate but will do!

```
voyager-2:~ haidar$ export OMP_NUM_THREADS=4
voyager-2:~ haidar$ /usr/bin/time -p ./pi
The value of PI is 3.141592653590
The time to calculate PI was 18037.175000 seconds
real 6.52
user 17.97
sys 0.06
```

You can compare the running time of the OpenMP version with the serial version by compiling the serial version and repeating the above analysis

Parallel Tree Traversal

```
void traverse (Tree *tree)
{
    #pragma omp task
    if(tree->left)
        traverse(tree->left);

    #pragma omp task
    if(tree->right)
        traverse(tree->right);
    process(tree);
}
```

Useful MacOS/Linux Commands

- From within a shell, global adjustment of the number of threads:
 - export OMP_NUM_THREADS=4
 - ./pi
- From within a shell, one-time adjustment of the number of threads:
 - OMP_NUM_THREADS=4 ./pi
- Intel Compiler on Linux: asking for more information:
 - export KMP_AFFINITY=verbose
 - export OMP_NUM_THREADS=4
 - ./pi

Recursive Fibonacci

```
int main(int argc, char* argv[])
{
    [...]
    fib(input);
    [...]
```

```
int fib(int n)  {
    if (n < 2) return n;
    int x = fib(n - 1);
    int y = fib(n - 2);
    return
} x+y;
```

Recursive Fibonacci: Discussion

```
int main(int argc, char* argv[])
{
    [...]
    fib(input);
    [...]
```

```
int fib(int n)  {
    if (n < 2) return n;
    int x = fib(n - 1);
    int y = fib(n - 2);
    return
} x+y;
```

- Only one Task / Thread should enter `fib()` from `main()`, it is responsible for creating the two initial work tasks
- `taskwait` is required, as otherwise `x` and `y` would be lost

Recursive Fibonacci: Attempt 0

```
int main(int argc, char* argv[])
{
    [...]
#pragma omp parallel
{
#pragma omp single
{
    fib(input);
}
}
[...]
}
```

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

What's wrong here?

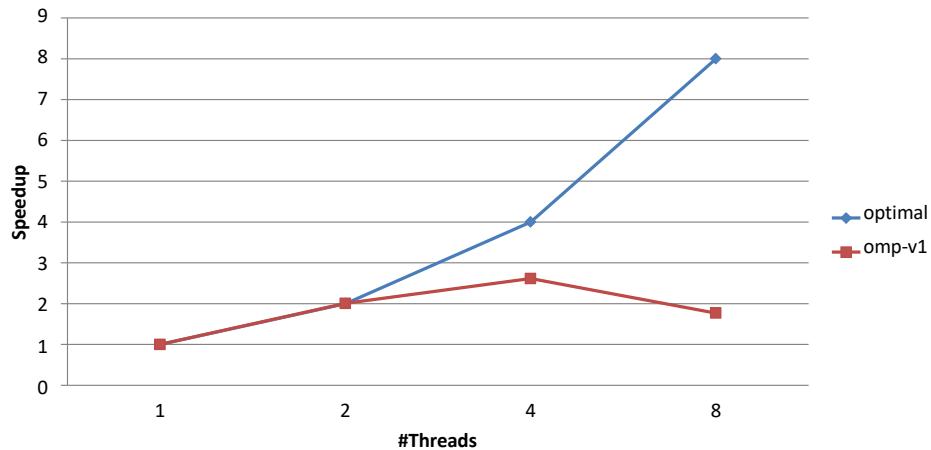
**x and y are private.
Can't use values of
private variables
outside of tasks**

Recursive Fibonacci: Attempt 1

```
int main(int argc, char* argv[])
{
    [...]
#pragma omp parallel
{
#pragma omp single
{
    fib(input);
}
}
[...]
}
```

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

Recursive Fibonacci: Attempt 1



Task creation overhead prevents better scalability

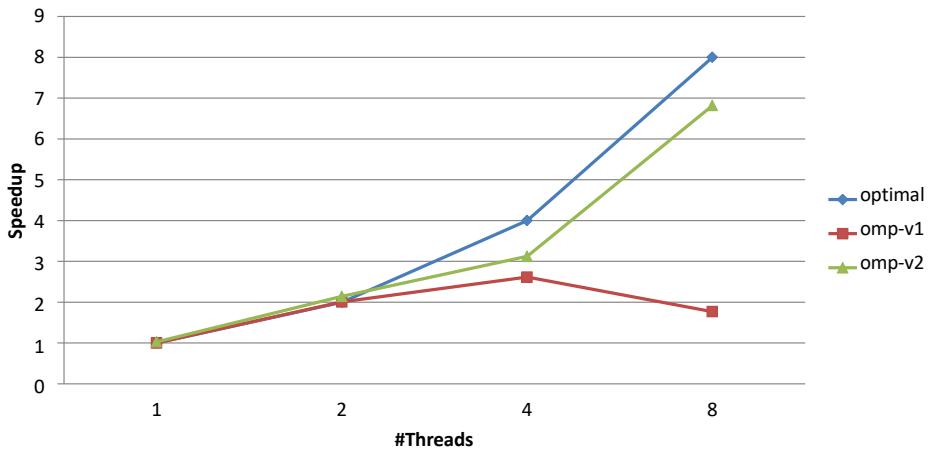
Recursive Fibonacci: Attempt 2

```
int main(int argc, char* argv[])
{
    [...]
#pragma omp parallel
{
#pragma omp single
{
    fib(input);
}
}
}

int fib(int n)
{
    if (n < 2) return n;
    int x, y;
#pragma omp task shared(x) if(n > 30)
{
    x = fib(n - 1);
}
#pragma omp task shared(y) if(n > 30)
{
    y = fib(n - 2);
}
#pragma omp taskwait
return x+y;
}
```

Don't create yet another task once a certain (small enough) n is reached

Recursive Fibonacci: Attempt 2



Overhead persists when running with 4 or 8 threads

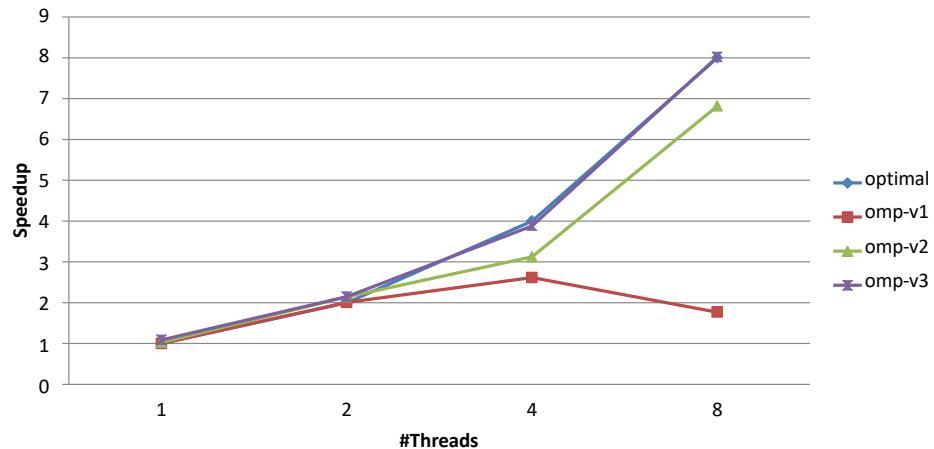
Recursive Fibonacci: Attempt 3

```
int main(int argc,  char* argv[])
{
    [...]
#pragma omp parallel
{
#pragma omp single
{
    fib(input);
}
}
[...]
}

int fib(int n)  {
    if (n < 2)  return n;
if (n <= 30)
    return serfib(n);
int x, y;
#pragma omp task shared(x)
{
    x = fib(n - 1);
}
#pragma omp task shared(y)
{
    y = fib(n - 2);
}
#pragma omp taskwait
return x+y;
```

Skip the OpenMP overhead once a certain n is reached (no issue w/ production compilers)

Recursive Fibonacci: Attempt 3



Example: Linked List using Tasks

- A typical C code that implements a linked list pointer chasing code is:

```
while(p != NULL) {
    do_work(p->data);
    p = p->next;
}
```

- Can we implement the above code using tasks in order to parallelize the application?

Example: Linked List using Tasks

```
#pragma omp parallel
{
    #pragma omp single nowait
    {
        while (p != NULL) {
            #pragma omp task firstprivate(p)
            {
                processwork(p);
            }
            p = p->next;
        }
    }
}
```

List Traversal

```
List ml; //my_list
Element *e;
#pragma omp parallel
#pragma omp single
{
    for(e=ml->first;e;e=e->next)
        #pragma omp task
        process(e);
}
```

What's wrong here?

Possible data race !
Shared variable e
updated by multiple tasks

List Traversal

```
List ml; //my_list
Element *e;
#pragma omp parallel
#pragma omp single
{
    for(e=ml->first;e;e=e->next)
#pragma omp task firstprivate(e)
        process(e);
}
```

Good solution – e is firstprivate

List Traversal

```
List ml; //my_list
Element *e;
#pragma omp parallel
#pragma omp single private(e)
{
    for(e=ml->first;e;e=e->next)
#pragma omp task
        process(e);
}
```

Good solution – e is private

List Traversal

```
List ml; //my_list
#pragma omp parallel
{
    Element *e;
    for(e=ml->first;e;e=e->next)
#pragma omp task
    process(e);
}
```

Good solution – e is private

Sudoku for Lazy Computer Scientists

- Find an empty field
- Insert a number
- Check Sudoku
 - (4 a) If invalid:
 - Delete number,
 - Insert next number
 - (4 b) If valid:
 - Go to next field

	6					8	11		15	14		16
15	11				16	14			12		6	
13		9	12					3	16	14	15	11 10
2	16		11	15	10	1						
	15	11	10		16	2	13	8	9	12		
12	13		4	1	5	6	2	3				11 10
5	6	1	12	9		15	11	10	7	16		3
	2			10	11	6	5		13		9	
10	7	15	11	16			12	13				6
9					1		2		16	10		11
1	4	6	9	13			7	11		3	16	
16	14		7	10	15	4	6	1			13	8
11	10	15			16	9	12	13		1	5	4
		12		1	4	6	16			11	10	
		5		8	12	13	10		11	2		14
3	16		10		7		6			12		

Sudoku for Lazy Computer Scientists

(1) Search an empty field

(2) Insert a number

(3) Check Sudoku

(4 a) If invalid:

Delete number,

Insert next number

(4 b) If valid:

Go to next field

6															
15	11														
13		9	12												
2		16		11											
15	11	10													
12	13			4	1	5	6	2	3					11	10
5		6	1	12	9		15	11	10	7	16				3
	2				10	11	6		5		13				9
10	7	15	11	16											
9					#pragma omp task	needs to									
1	4	6	9	13			7		11		3	16			
16	14			7	10	15	4	6	1			13	8		
11	10		15			16	9	12	13			1	5	4	
	12		1	4	6	16						11	10		
	5		8	12		#pragma omp taskwait									
3	16			10											

|| Brute-force Sudoku: Pseudocode

► OpenMP parallel region creates a team of threads

```
#pragma omp parallel
{
    #pragma omp single
        solve_parallel(0, 0, sudoku2, false);
} // end omp parallel
    ► Single construct: One thread enters the execution of solve_parallel
    ► the other threads wait at the end of the single ...
        ► ... and are ready to pick up tasks „from the work queue“
```

► Syntactic sugar (either you like it or you donot)

```
#pragma omp parallel sections
{
    solve_parallel(0, 0, sudoku2, false);
} // end omp parallel
```

|| Brute-force Sudoku: Implementation

```
for (int i = 1; i <= sudoku->getFieldSize(); i++) {
    if (!sudoku->check(x, y, i)) {
        #pragma omp task firstprivate(i,x,y,sudoku)
        {
            // create from copy constructor
            CSudokuBoard new_sudoku(*sudoku);
            new_sudoku.set(y, x, i);
            if (solve_parallel(x+1, y, &new_sudoku)) {
                new_sudoku.printBoard();
            }
        } // end omp task
    }
} #pragma omp taskwait
# pragma omp task needs to
work on a new copy of the
Sudoku board
wait for all child tasks
```