A Journey Through the World of OpenMP

Mission-Critical Computing
NSF CENTER FOR SPACE, HIGH-PERFORMANCE, AND RESILIENT COMPUTING (SHREC)

PCA Lecture

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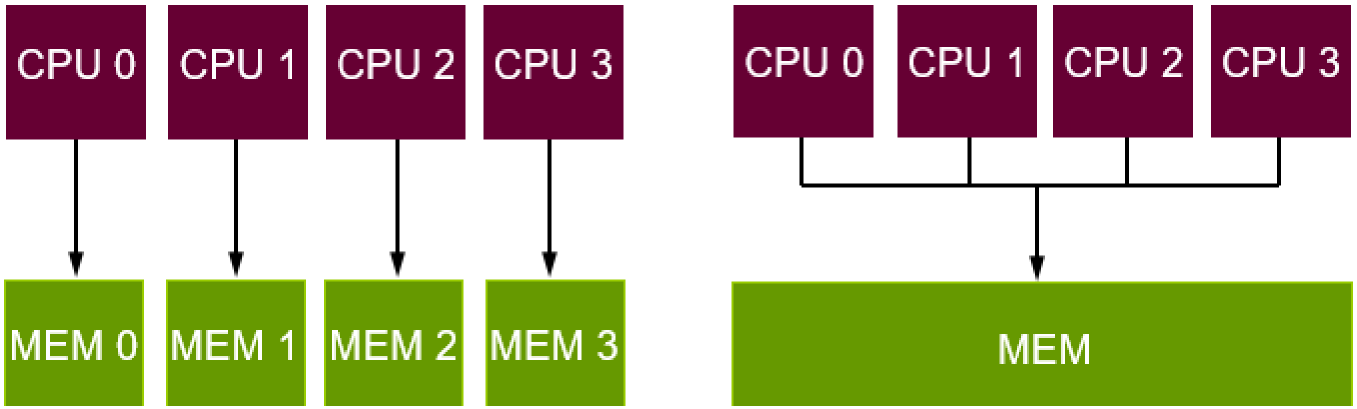
Overview

- Introduction to OpenMP
- Division of Work
- Serial Considerations
- Granularity and Scheduling
- Extra Fun

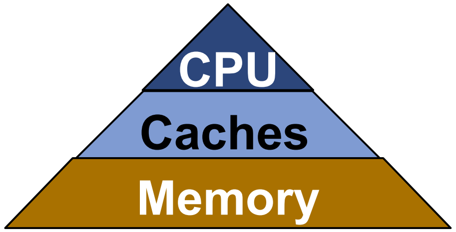
Shared Memory

- **Distributed Memory Programming**
  - Start multiple processes on multiple networked systems
  - Processes carry out work and communicate through message-passing
  - Processes coordinate through message-passing or synchronization
- **Shared Memory Programming**
  - Start a single process on one system and fork threads
  - Threads each carry out work and communicate through shared memory
  - Threads coordinate through synchronization

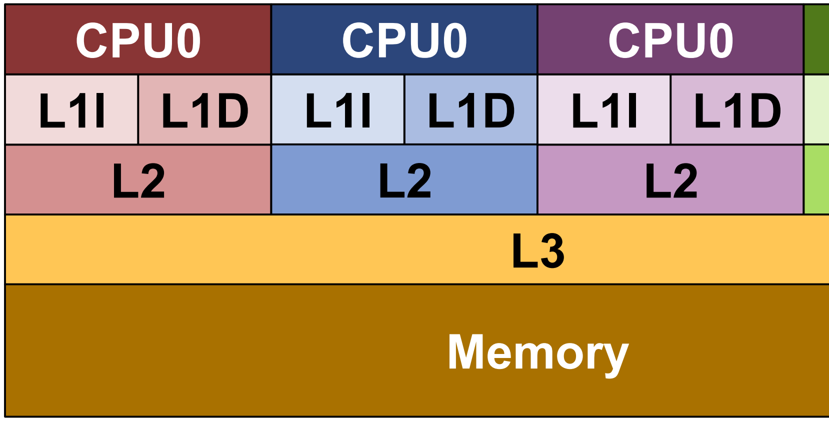


Distributed Memory **Shared Memory**

Memory Hierarchy



- **Cache Pyramid**
  - Simple illustration of concept
  - Higher is smaller and faster
- **Reality**
  - Multicore processors share uniquely
    - Shared L3 cache
    - Shared main memory space
    - Hyperthreading may share L2



- **(A)symmetric Multiprocessing**
  - Multiple cores in one or both states
    - Symmetric runs same operating system/programs on multiple cores
    - Asymmetric may run entirely different operating systems on each core
- **A little too local for Marco Polo…**

OpenMassivePastry

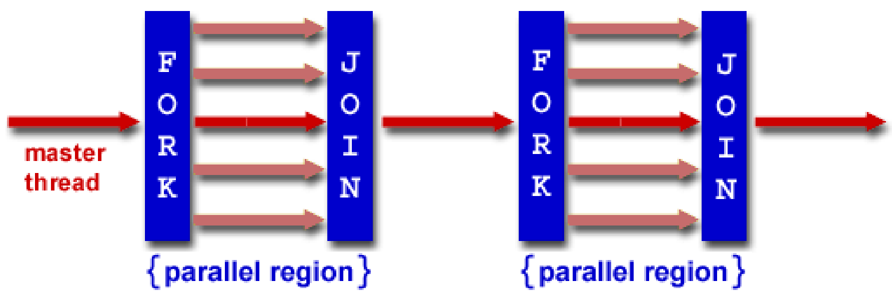
OpenMassivePasture

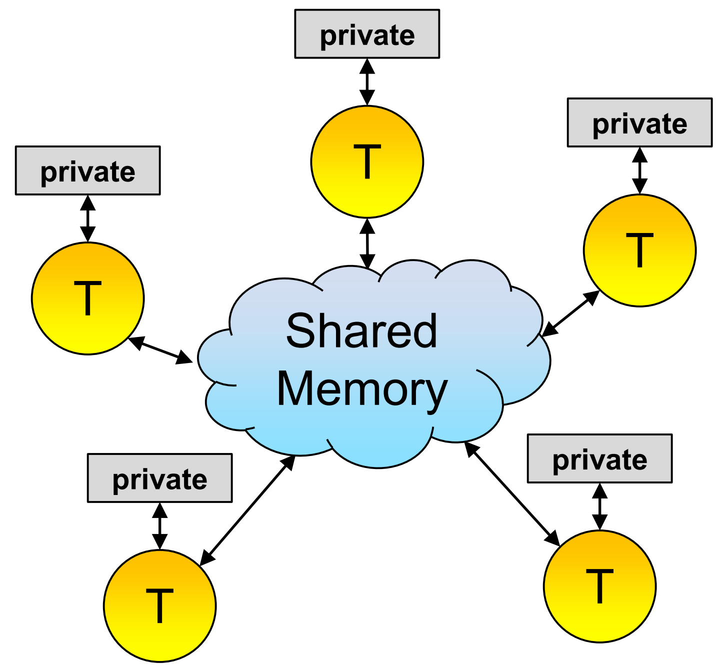
OpenMP Introduction

- **What does OpenMP stand for?**
  - **Open** specifications for **Multi-Processing** via collaborative work between interested parties from the hardware and software industry, government, and academia
- **OpenMP is an Application Programming Interface (API)**
  - Used to explicitly direct ***multi-threaded, shared-memory parallelism***
  - Components: compiler directives, library routines, environment variables
- **OpenMP is directive-based**
  - Directives invoke parallel computations on shared-memory multiprocessors
- **OpenMP API specified for C/C++ and Fortran**
- **Portable: supported by HP, IBM, Intel, SGI, SUN, and others**
- **De facto standard for writing shared memory programs**

OpenMP Basics

- **OpenMP uses fork-join model of parallel execution**
  - OpenMP program begins with single **master thread**
  - Master thread executes sequentially until a **parallel region** is encountered
  - Creates **team of parallel threads** (**FORK**) when parallel region is encountered
  - When parallel region ends the threads synchronize and terminate (**JOIN**)
  - This leaves only the master thread





- **Thread-based programming model**
  - All threads have access to **shared memory**
  - Each thread has access to its own **private memory**
- **Synchronization mostly implicit**
  - More on synchronization later

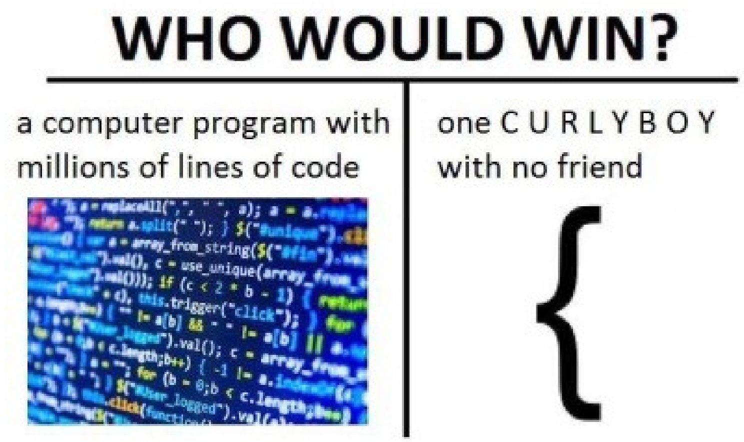
OpenMP Compilation/Execution

- **Compile the Program**
  - Terminal command: “gcc -fopenmp <filename>.c –o <executable_name>”
  - Compiles <filename>.c and outputs <executable_name>
  - Be sure to add the –fopenmp compiler flag
    - Everything needed for OpenMP is already in gcc, just waiting to be turned on

- **Execute the Program**
  - Terminal command: “./<executable_name> <arguments>”
  - Can pass in number of cores among other arguments

Basic OpenMP Pragmas

- **Pragma OMP Parallel**
  - OpenMP operates through "#pragma omp" compiler directives
  - "pragma omp parallel" is used to specify the start of a parallel region
  - Each thread will execute given code inside of given scope



Code Example

```c
#include <omp.h>

int main( int argc, char **argv ) {

  #pragma omp parallel
  {
    printf( "Hello from a random thread!\n" );
  }

  return 0;
}
```

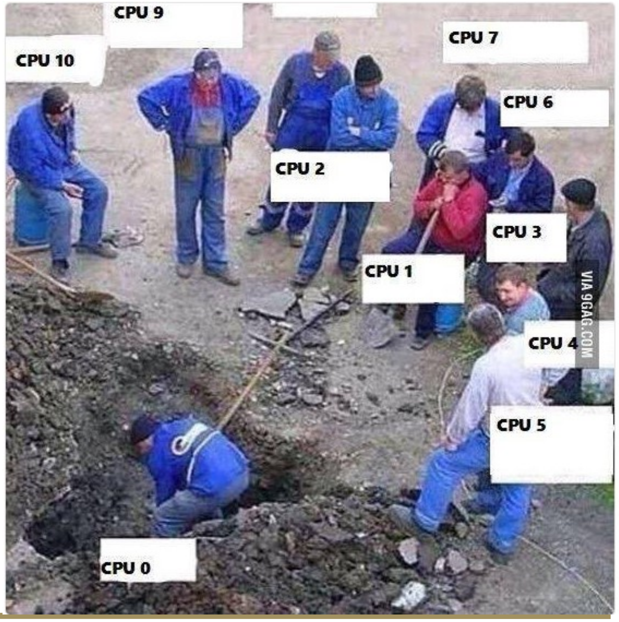
Output (4 Cores)

```
$ gcc -fopenmp ...
(builds)
$ ./example
Hello from a random thread!
Hello from a random thread!
Hello from a random thread!
Hello from a random thread!
$
```

Pragma OMP Parallel Parameters

- **private(…)**
  - List of variables to keep private, accessible to one thread
- **shared(…)**
  - List of variables to make shared, accessible to each and every thread
- **default(none | shared)**
  - Makes variables private or shared by default if not specified
- **num_threads(#)**
  - Best way to set number to cores to be utilized

- **All variables called out must be previously declared!**



OpenMP Functions

- **int omp_get_num_threads( )**
  - Returns number of threads being used in parallel regions
- **int omp_get_max_threads( )**
  - Returns maximum number of threads this system can process in parallel
- **int omp_get_thread_num( )**
  - Returns the thread number of the thread
  - Thread numbers of indexed starting with 0 up to (omp_get_num_threads()-1)
- **void omp_set_num_threads(int num_threads)**
  - Sets the number of threads (cores) to use in subsequent parallel regions
  - Can cause unexpected results; best to use "num_threads( )" in pragma
- **And more!**

OpenMP Hello World Program

Code Example

```c
#include <omp.h>

int main( int argc, char **argv ) {
  int num_threads = 0;  // Number of Threads
  int thread_id   = 0;  // ID Number of Running Thread

  // Fork the threads, giving each one a private copy of:
  #pragma omp parallel private( num_threads, thread_id )
  {
    // Get the thread number
    thread_id     = omp_get_thread_num( );
    printf( "Hello World from Thread %d\n", thread_id );

    // Have master print the total number of threads used.
    if( thread_id == 0 ) {
      num_threads = omp_get_num_threads( );
      printf( "Number of Threads = %d\n", num_threads );
    }
  }  // All of the threads rejoin the master thread.
  return 0;
}
```

Output (4 Cores)

```
$ gcc -fopenmp...
(builds)
$ ./example
Hello World from Thread 0
Hello World from Thread 1
Hello World from Thread 2
Hello World from Thread 3
Number of Threads = 4
$
```

Note that order is never guaranteed.

Shared/Private/Default Example

Code Example

```
#include <omp.h>

int main( int argc, char **argv ) {

  int id = 0; // Variables declared before pragma.
  int i  = 0;
  int m  = 0;
  int x  = 2;

  #pragma omp parallel private( id, i ) shared ( m ) \
                       default( shared )
  {
    id = omp_get_thread_num( );
    if( id == 0 ) {  // Only id = 0 master makes changes.
      i = 3;    // Change i, private, just this thread.
      m = 17;   // Change m, shared, all threads.
      x++;      // Change x, default shared, all.
    }
    printf( "Thread %d: %d %d %d\n", id, i, m, x );
  }

  return 0;
}
```

Output (4 Cores)

```
$ gcc -fopenmp ...
(builds)
$ ./example
Thread 0: 3 17 3
Thread 1: 0 17 3
Thread 2: 0 17 3
Thread 3: 0 17 3
$
```

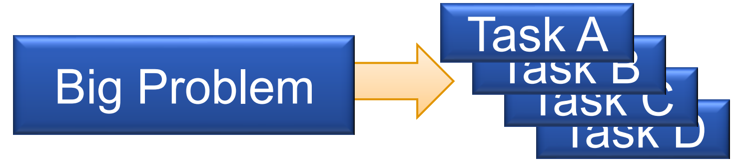
Note that order of threads is never guaranteed.

Strange things can happen.
O_O

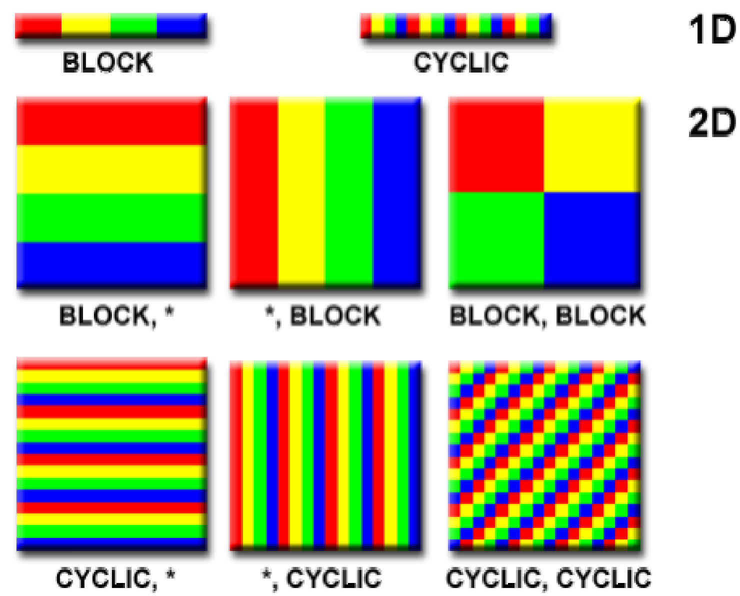
Division of Work

Smile and nod if you are paying attention.

Division of Work



- **Using OpenMP to divide work**
  - Creation of parallel region with additional directive of task to divide
  - Simplest is “pragma omp parallel for”
  - Will discuss “single” and “sections” later
- **Type of division depends on application, scheduling, and desires**
  - Vector addition may be best served by cyclic
  - Image processing often lends itself to even block division over an axis
- **Number of divisions depends on cores**
- **Partitioning methods**
  - In domain decomposition each task performs the same function and gets a portion of the data (our focus, for now)
  - In functional decomposition, each task performs a different function (cool, later)



Parallel For

- **Pragma OMP Parallel For**
  - Append “pragma omp for” before for loop inside “pragma omp parallel”
  - A work-sharing construct, divides iterations of a for loop between cores
  - Must ensure there are no “loop carry” dependencies between iterations
  - Implicit barrier at conclusion of for loop - “no thread gets left behind”

Code Example

```c
#include <omp.h>
int main( int argc, char **argv ) {
  int i = 0;   // Loop Iterator
  int n = 12;  // Number of Iterations
  #pragma omp parallel shared( n ) private( i )
  {
    #pragma omp for
    for( i = 0; i < n; i++ ) {
      printf( “Thread %d of %d – Iteration %d\n”,
              omp_get_thread_num( ),
              omp_get_max_threads( ), i         );
    }  // Note scopes – no “{}” with for.
  }
  return 0;
}
```

Output (4 Cores)

```
$ gcc -fopenmp ...
(builds)
$ ./basicFor
Thread 0 of 4 – Iteration 0
Thread 0 of 4 – Iteration 1
Thread 0 of 4 – Iteration 2
Thread 1 of 4 – Iteration 3
Thread 1 of 4 – Iteration 4
Thread 1 of 4 – Iteration 5
Thread 2 of 4 – Iteration 6
Thread 2 of 4 – Iteration 7
Thread 2 of 4 – Iteration 8
Thread 3 of 4 – Iteration 9
Thread 3 of 4 – Iteration 10
Thread 3 of 4 – Iteration 11
$
```

Parallel For – One Line

Code Example

```
#include <omp.h>

int main( int argc, char **argv ) {

  int i = 0;   // Loop Iterator
  int n = 12;  // Number of Iterations

  #pragma omp parallel for shared( n ) private( i )

    for( i = 0; i < n; i++ ) {
      printf( “Thread %d of %d – Iteration %d\n”,
              omp_get_thread_num( ),
              omp_get_max_threads( ), i           );
    }  // Note scopes – no “{}” at all!

  return 0;

}
```

Output (4 Cores)

```
$ gcc –fopenmp ...
(builds)
$ ./oneLineFor
Thread 0 of 4 – Iteration 0
Thread 0 of 4 – Iteration 1
Thread 0 of 4 – Iteration 2
Thread 1 of 4 – Iteration 3
Thread 1 of 4 – Iteration 4
Thread 1 of 4 – Iteration 5
Thread 2 of 4 – Iteration 6
Thread 2 of 4 – Iteration 7
Thread 2 of 4 – Iteration 8
Thread 3 of 4 – Iteration 9
Thread 3 of 4 – Iteration 10
Thread 3 of 4 – Iteration 11
$
```

Wall Clock Time

- **double omp_get_wtime( )**
  - Returns double-precision floating-point elapsed wall-clock time in seconds
  - Called before and after parallel code
  - Simple arithmetic to determine overall elapsed time

Code Example

```
#include <omp.h>
int main( int argc, char **argv ) {

   double start = 0.0;   // Start Time
   double end   = 0.0;   // End Time
   double total = 0.0;   // Total Execution Time

   start        = omp_get_wtime( );   // Get Start Measure
   #pragma omp parallel               // Perform Task
   {
     printf( "Hello from a random thread!\n" );
   }
   end          = omp_get_wtime( );   // Get End Measure
   total        = end - start;        // Calculate Total
   printf( "Execution Time: %lf", total );
   return 0;
}
```

Output (4 Cores)

```
$ gcc -fopenmp ...
(builds)
$ ./ompTime
Hello from a random thread!
Hello from a random thread!
Hello from a random thread!
Hello from a random thread!
Execution Time: 0.00023
$
```

Varying Cores

- **Varying number of cores per run**
  - Pass in number of cores as an argument when invoking the program
  - Parse that input argument within the code and convert the string to integer
  - Use the num_threads(x) parameter discussed before to set for the region

Code Example

```
#include <omp.h>
int main( int argc, char **argv ) {
  int    cores = 0;    // Number of Cores
  double start = 0.0;  // Start Time
  double end   = 0.0;  // End Time
  double total = 0.0;  // Total Execution Time
  cores        = atoi( argv[1] );
  start        = omp_get_wtime( );  // Get Start Measure
  #pragma omp parallel num_threads( cores )
  {
    printf( “Hello from a random thread!\n” );
  }
  end          = omp_get_wtime( );  // Get End Measure
  total        = end - start;       // Calculate Total
  printf( “Execution Time: %lf”, total );
  return 0;
}
```

Output (4 Cores)

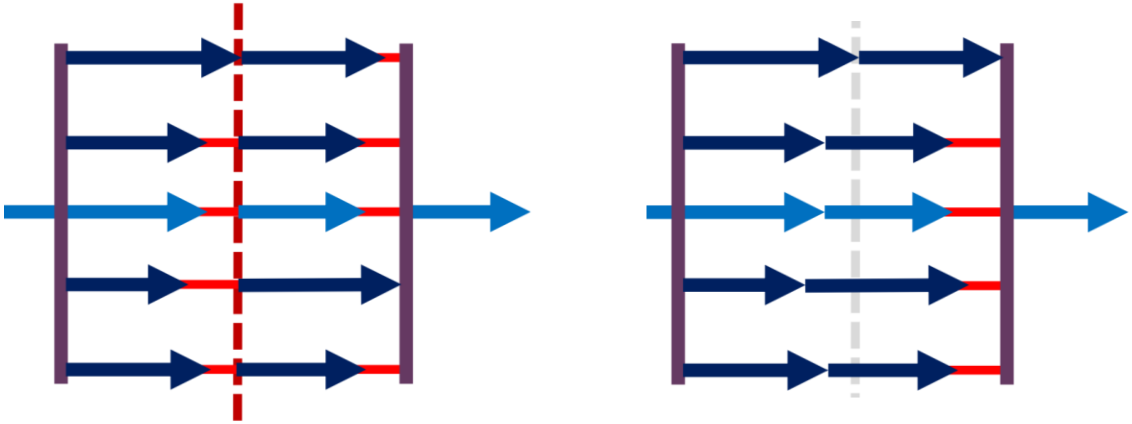
```
$ gcc -fopenmp ...
(builds)
$ ./howMany 4
Hello from a random thread!
Hello from a random thread!
Hello from a random thread!
Hello from a random thread!
Execution Time: 0.000460
$ ./howMany 2
Hello from a random thread!
Hello from a random thread!
Execution Time: 0.000312
$ ./howMany 206

  ???
```

What Time Really Means

- **Serial Baseline**
  - Execution time of serial application implemented without OpenMP
- **Execution Time**
  - Per-core execution time measured with OpenMP for each number of cores
- **Speedup = $Time_{Serial}$ / $Time_{Parallel}$**
  - Unitless ratio of serial execution time over parallel execution time
  - Goal is to realize best possible speedup doing useful work
- **Parallel Efficiency = Speedup / Cores**
  - Percentage measure of how efficiently additional cores are being used
- **Useful Work**
  - Operations and functions that would have been conducted in serial program
- **Parallel Overhead**
  - Additional operations for OpenMP, sharing, timing - minimize

Barriers

- **Concept**
  - All threads wait at barrier until all others reach it
  - Helps ensure operations are complete before moving on
- **Implicit Barriers**
  - Using a parallel for pragma implies a barrier at the end
  - This is used to ensure the whole loop is complete before moving on
  - Can append a "nowait" to remove this implied barrier
  - May improve speed, but must watch out for dependencies



Parallel For

Code Example

```
#include <omp.h>
int main( int argc, char **argv ) {
  int i = 0;   // Loop Iterator
  int n = 12;  // Number of Iterations
  #pragma omp parallel shared( n ) private( i )
  {
    #pragma omp for
    for( i = 0; i < n; i++ ) {
      printf( "Thread %d of %d – Iteration %d\n",
              omp_get_thread_num( ),
              omp_get_max_threads( ), i          );
    }

    #pragma omp for
    for( i = 0; i < n; i++ ) {
      printf( "Thread %d of %d – Iteration %d\n",
              omp_get_thread_num( ),
              omp_get_max_threads( ), i          );
    }

  }
  return 0;
}
```

Output (4 Cores)

```
$ gcc –fopenmp ...
(builds)
$ ./noWait
Thread 0 of 4 – Iteration 0
Thread 0 of 4 – Iteration 1
Thread 0 of 4 – Iteration 2
Thread 1 of 4 – Iteration 3
Thread 1 of 4 – Iteration 4
Thread 1 of 4 – Iteration 5
Thread 2 of 4 – Iteration 6
Thread 2 of 4 – Iteration 7
Thread 2 of 4 – Iteration 8
Thread 3 of 4 – Iteration 9
Thread 3 of 4 – Iteration 10
Thread 3 of 4 – Iteration 11
Thread 0 of 4 – Iteration 0
Thread 0 of 4 – Iteration 1
Thread 0 of 4 – Iteration 2
Thread 1 of 4 – Iteration 3
Thread 1 of 4 – Iteration 4
Thread 1 of 4 – Iteration 5
Thread 2 of 4 – Iteration 6
Thread 2 of 4 – Iteration 7
...
$
```

Parallel For Nowait

Code Example

```
#include <omp.h>
int main( int argc, char **argv ) {
  int i = 0;   // Loop Iterator
  int n = 12;  // Number of Iterations
  #pragma omp parallel shared( n ) private( i )
  {
    #pragma omp for nowait
    for( i = 0; i < n; i++ ) {
      printf( "Thread %d of %d - Iteration %d\n",
              omp_get_thread_num( ),
              omp_get_max_threads( ), i           );
    }

    #pragma omp for nowait
    for( i = 0; i < n; i++ ) {
      printf( "Thread %d of %d - Iteration %d\n",
              omp_get_thread_num( ),
              omp_get_max_threads( ), i           );
    }

  }
  return 0;
}
```

Output (4 Cores)

```
$ gcc -fopenmp ...
(builds)
$ ./noWait
(Similar to previous, but orders
merge and times overlap.  Please
explore!)
$

Significantly faster speeds!
```

Parallel For Nowait with Barrier

Code Example

```
#include <omp.h>
int main( int argc, char **argv ) {
  int i = 0;   // Loop Iterator
  int n = 12;  // Number of Iterations
  #pragma omp parallel shared( n ) private( i )
  {
    #pragma omp for nowait
    for( i = 0; i < n; i++ ) {
      printf( "Thread %d of %d - Iteration %d\n",
              omp_get_thread_num( ),
              omp_get_max_threads( ), i           );
    }

    #pragma omp barrier

    #pragma omp for nowait
    for( i = 0; i < n; i++ ) {
      printf( "Thread %d of %d - Iteration %d\n",
              omp_get_thread_num( ),
              omp_get_max_threads( ), i           );
    }

  }
  return 0;
}
```

Output (4 Cores)

```
$ gcc -fopenmp ...
(builds)
$ ./noWait
(Barrier overrides noWait.
While order is not guaranteed,
there will be no overlap.)
$

Roughly the same performance as
standard parallel for with
implicit barrier.
```

Ordered

- **Guarantees proper execution order…but at what cost?**
  - Iterations executed serially, one thread at a time…no parallelism
  - Only applicable to parallel for and each iteration can have only one
  - Requires "ordered" clause on initial pragma and inside at specific function

Code Example

```
#include <omp.h>
int main( int argc, char **argv ) {
  int i = 0;   // Loop Iterator
  int n = 12;  // Number of Iterations
  #pragma omp parallel for ordered \
              shared( n ) private( i )
  for( i = 0; i < n; i++ ) {
    #pragma omp ordered
    printf( "Thread %d of %d – Iteration %d\n",
              omp_get_thread_num( ),
              omp_get_max_threads( ), i         );
    }
  }
  return 0;
}
```

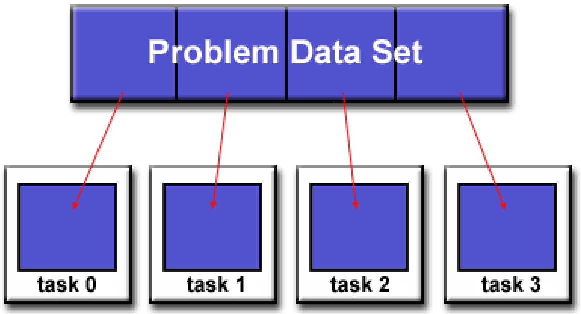
Output (4 Cores)

```
$ gcc ...
(builds)
$ ./ordered
Thread 0 of 4 – Iteration 0
Thread 0 of 4 – Iteration 1
Thread 0 of 4 – Iteration 2
Thread 1 of 4 – Iteration 3
Thread 1 of 4 – Iteration 4
Thread 1 of 4 – Iteration 5
Thread 2 of 4 – Iteration 6
Thread 2 of 4 – Iteration 7
Thread 2 of 4 – Iteration 8
Thread 3 of 4 – Iteration 9
Thread 3 of 4 – Iteration 10
Thread 3 of 4 – Iteration 11…
$
```

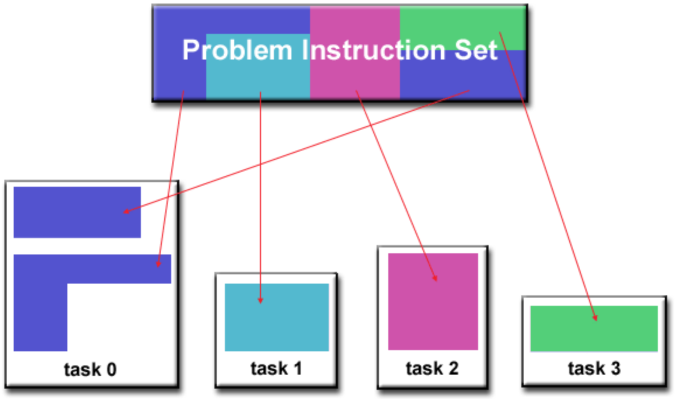
Serial Considerations

Raise your left hand if you are still paying attention.

Serial Considerations



- **Why back to serial?**
  - Overcome things that do not parallelize well
  - Divide functions between cores
  - Cases where file operations or output must be serial
- **One-for-all or all-for-one?**
  - Single core can perform some functions while other cores work together
  - Each core can work independently on its own function
  - Could pipeline cores so that data moves between them in series



Single

- **Pragma OMP Single**
  - Runs given code on a single core
  - Can be coupled with parallel for other tasks running on other cores
  - Like for, work-sharing construct with an implicit barrier at end

Code Example

```
#include <omp.h>
int main( int argc, char **argv ) {
  int i = 0;   // Loop Iterator
  int n = 12;  // Number of Iterations
  #pragma omp parallel
  {
    #pragma omp single
    {
      printf( "Thread %d of %d - Single\n",
              omp_get_thread_num( ),
              omp_get_max_threads( )        );
    }
  }
  return 0;
}
```

Output (4 Cores)

```
$ gcc -fopenmp ...
(builds)
$ ./single
Thread 0 of 4 - Single
$
```

Sections

- **Pragma OMP Sections**
  - Creates section to run on single thread
  - Can be used to break problems into separate functions that run in parallel
  - Like for, work-sharing construct with an implicit barrier at end

Code Example

```
#include <omp.h>
int main( int argc, char **argv ) {
  int i = 0;   // Loop Iterator
  int n = 12;  // Number of Iterations
  #pragma omp parallel
  {
    #pragma omp sections
    {
      #pragma omp section
      functionA( );

      #pragma omp section
      functionB( );
    }
  }
  return 0;
}
```

Output (4 Cores)

```
$ gcc -fopenmp ...
(builds)
$ ./sections
(Words from Function A)
(Words from Function B)
$
```

Master

- **Only the master thread does this**
  - Can also accomplish with if(omp_get_thread_num( ) == 0)
  - Reduces amount of code, more tidy
  - No implicit barrier for the other threads

Code Example

```c
#include <omp.h>
int main( int argc, char **argv )  {
  int num_threads = 0;  // Number of Threads
  int thread_id   = 0;  // ID Number of Running Thread
  #pragma omp parallel private( num_threads, thread_id )
  {
    thread_id = omp_get_thread_num( );
    printf( "Hello World from Thread = %d\n", thread_id );
    #pragma omp master
    {
      num_threads = omp_get_num_threads( );
      printf( "Number of Threads = %d\n", num_threads );
    }
  }
  return 0;
}
```

Output (4 Cores)

```
$ gcc -fopenmp ...
(builds)
$ ./example
Hello World from Thread = 0
Hello World from Thread = 1
Hello World from Thread = 2
Hello World from Thread = 3
Number of Threads = 4
$
```

Note that order is never guaranteed.

Critical

- **Concept**
  - Ensures only one core can access shared variable at a time
  - Helps avoid race conditions where value is incorrectly altered
- **Race Condition**
  - Thread one gets data and changes it
  - Thread two gets data
  - Thread one stores data
  - Thread two performs operation on old data and overwrites thread one’s store

Thread A		Thread B		
Instruction	Register	Instruction	Register	Count
		LOAD Count	10	10
LOAD Count	10			10
ADD #1	11			10
STORE Count	11			11
		SUB #1	9	11
		STORE Count	9	9

Critical

Code Example

```
#include <omp.h>
int main( int argc, char **argv ) {
  int *a        = malloc( 25 * sizeof( int ) );
  int  i        = 0;   // Loop Iterator
  int  n        = 25;  // Number of Iterations
  int  localSum = 0;   // Private Local Sum
  int  totalSum = 0;   // Shared Total Sum
  int  thread   = 0;   // Thread Number
  // Fill Array with Values 1 to 25
  for( i = 0; i < n; i++ ) {
    a[i] = i + 1;
  }
  #pragma omp parallel                 \
              shared( n, a, totalSum ) \
              private( thread, localSum )
  {
    thread   = omp_get_thread_num( );
    localSum = 0;
    #pragma omp for
    for( i = 0; i < n; i++ ) {
      localSum += a[i];
    }
    #pragma omp critical( totalSum )
    {
      totalSum += localSum;
      printf( "Thread %d has local sum %d and adds
               to total sum %d.\n",
               thread, localSum, totalSum );
    }
  }
```

Output (4 Cores)

```
$ gcc ...
(builds)
$ ./noWait
Thread 0 has local sum 99 and
adds to total sum 99.
Thread 1 has local sum 135 and
adds to total sum 234.
Thread 2 has local sum 28 and
adds to total sum 262.
Thread 3 has local sum 63 and
adds to total sum 325.
Total sum at end is 325.
$
```

Problem?

Atomic

- **Specifies a specific memory location to update atomically**
  - Does not need to worry about overhead to lock for multiple threads
  - Operation in hardware guarantees no interference
  - Consider machine code that allows immediate incrementation, assignment
- **A number of operations allowed**
  - Arithmetic increment (++, +=), decrement (--, -=)
  - Arithmetic assignment (+=, -=, *=, /=)
  - Bit shifting assignment (<<=, >>=)
  - Bitwise logical assignment (&=, |=, ^=)
- **Watch out**
  - Specific syntax
  - Small set of operations
  - Single statement

Expr1++	++expr1
Expr1--	--Expr1
Expr1 += expr2	Expr1 -= expr2
Expr1 *= expr2	Expr1 /= expr2
Expr1 <<= expr2	Expr1 >>= expr2
Expr1 &= expr2	Expr1 ^=expr2
Expr1 |= expr2	

Atomic Example

Code Example

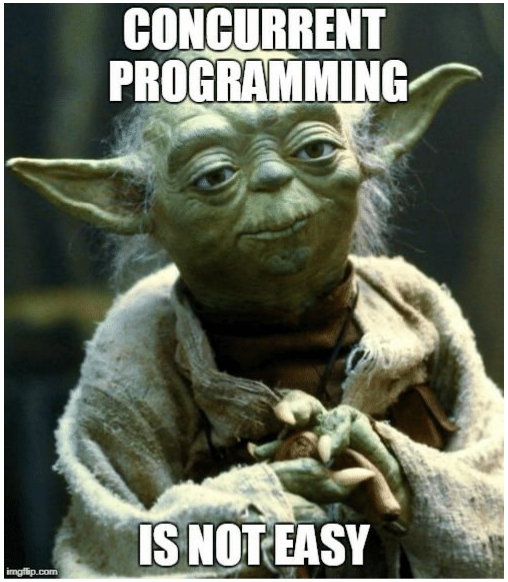
```
#include <omp.h>
int main( int argc, char **argv ) {
  int *a        = malloc( 25 * sizeof( int ) );
  int  i        = 0;   // Loop Iterator
  int  n        = 25;  // Number of Iterations
  int  localSum = 0;   // Private Local Sum
  int  totalSum = 0;   // Shared Total Sum
  // Fill Array with Values 1 to 25
  for( i = 0; i < n; i++ ) {
    a[i] = i + 1;
  }
  #pragma omp parallel                 \
              shared( n, a, totalSum ) \
              private( localSum )
  {
    localSum = 0;
    #pragma omp for
    for( i = 0; i < n; i++ ) {
      localSum += a[i];
    }
    #pragma omp atomic
    totalSum += localSum;
  }
  printf( "Total sum at end is %d.\n", totalSum )
  return 0;
}
```

Output (4 Cores)

```
$ gcc ...
(builds)
$ ./atomic
Total sum at end is 325.
Time:  0.000244141
$
```

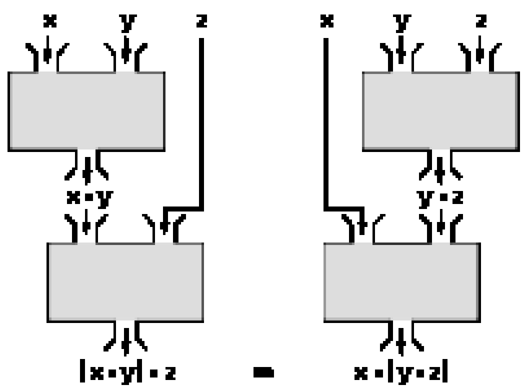
Critical vs. Atomic

- **Critical**
  - Surround any block of code, only one thread at a time can enter
  - Significant overhead entering and exiting, must block other threads
  - Can have names to group and categorize access restrictions
    - Unnamed criticals are considered the same across the entire program
    - May name critical sections to let each separate names to execute in parallel
    - Lets you do some pretty interesting things
      - Criticals with different names performing similar tasks
      - Criticals with the same name performing very different tasks
      - Must be sure you are protecting things appropriately and approaching options correctly
- **Atomic**
  - Significantly less overhead
  - Takes advantage of hardware if platform supports it
  - Does not block atomic operations on different variables
  - Small set of operations supported by atomic



Reduction

- **Handles combining values from parallel threads**
  - Private copy for each thread is operated on by each in parallel region
  - When complete, reduction applies operation to each of these private copies
  - Result ends up in specified global shared variable
- **A number of operations allowed**
  - Arithmetic addition (+), multiplication (*), subtraction (-)
  - Bitwise logic AND (&), OR (|), XOR (^)
  - Logical AND (&&), OR (||)
  - Initial conditions allow for first add from 0, mult from 1
- **Watch out**
  - Must be valid operation for this variable
  - Not shared or private
  - Associativity not guaranteed



Operator	Initial value
+	0
*	1
-	0

C/C++ only	
Operator	Initial value
&	~0
|	0
^	0
&&	1
||	0

Reduction Example

Code Example

```
#include <omp.h>
int main( int argc, char **argv ) {
  int *a   = malloc( 25 * sizeof( int ) );
  int  i   = 0;   // Loop Iterator
  int  n   = 25;  // Number of Iterations
  int  sum = 0;   // Only One Sum
  // Fill Array with Values 1 to 25
  for( i = 0; i < n; i++ ) {
    a[i]   = i + 1;
  }
  #pragma omp parallel for                    \
              shared( n, a ) private( thread ) \
              reduction( + : sum )
  {
    for( i = 0; i < n; i++ ) {
      sum += a[i];
    }
  }
  printf( "Total sum at end is %d.\n", totalSum )
  return 0;
}
```

Output (4 Cores)

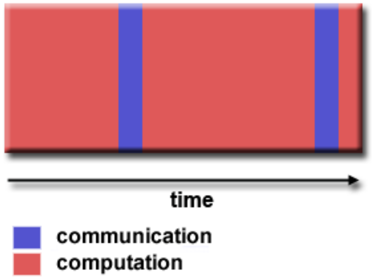
```
$ gcc -fopenmp ...
(builds)
$ ./reduction
Total sum at end is 325.
$
```

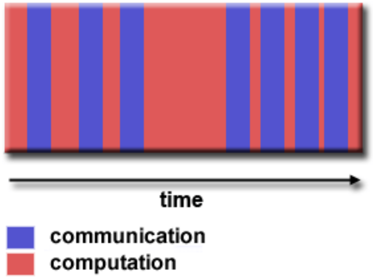
Granularity and Scheduling

Wave both hands if you are paying attention.

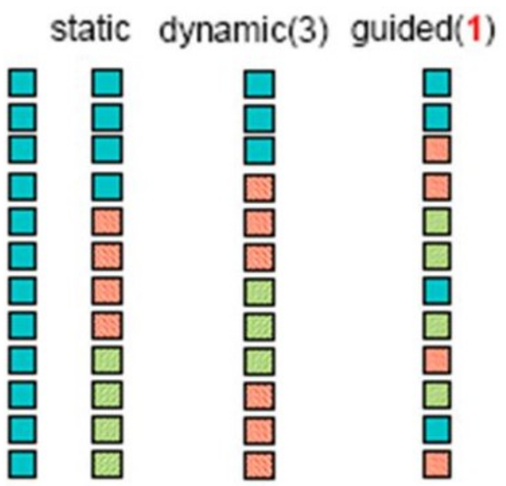
Granularity

- **What is granularity?**
  - Size of divided groups of data
  - Measure of computation to communication/synchronization
- **Why is it important?**
  - Want to maximize computation
  - Comm/sync time is not completing work
  - Applies differently to different applications/architectures
- **What kinds are there?**
  - Coarse granularity – a boulder
    - Large groups of data after division
    - Large amounts of work are done between communication
    - For OpenMP, not communication, more like “distribution” or “assignment”
  - Fine granularity – sand
    - Work split into very small pieces, maybe a single iteration
    - Only a small amount of work done before we must stop to get more





Scheduling



- **What is scheduling?**
  - Manages how iterations of a for loop are divided
  - Allows optimization for different program needs
  - Must balance granularity, overhead, performance
- **How do I use this?**
  - Append “schedule(type)” to pragma omp parallel for
- **What kinds are there?**
  - Static – iterations divided and assigned evenly at compile time
  - Static, Chunk – static, with size of divided chunks parameterizable
  - Dynamic – when core completes one, takes another from pile
  - Dynamic, Chunk – dynamic, but takes more than one to reduce overhead
  - Guided – dynamic, starts with big chunks, then they get smaller as it runs

Scheduling Example

Code Example

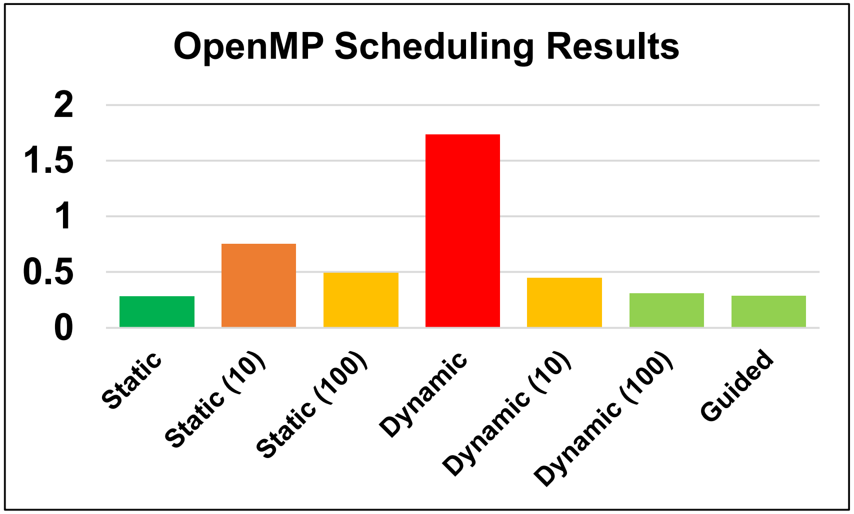
```c
#include <omp.h>
#define SIZE 100000000
int main( int argc, char **argv ) {
  srand( time( NULL ) );   // Seed Random
  int i              = 0;  // Loop Iterator
  // Initialize Vector Memory Spaces
  double *mainVector = malloc( SIZE * sizeof(double) );
  double *divVector  = malloc( SIZE * sizeof(double) );
  double *solVector  = malloc( SIZE * sizeof(double) );
  // Fill Vectors
  for( i = 0; i < SIZE; i++ ) {
    mainVector[i]    = ( rand( ) % 10000000 ) * 0.01;
    divVector[i]     = ( rand( ) % 1000 )     * 0.01;
    solVector[i]     = 0;
  }
  // Perform Processing
  double start       = omp_get_wtime( );
  #pragma omp parallel for num_threads( 4 )     \
     shared( mainVector, divVector, solVector ) \
     private( i ) schedule( static )
  for( i = 0; i < SIZE; i++ ) {
    solVector[i]     = mainVector[i] / divVector[i];
  }
  double end         = omp_get_wtime( );
  double solTime     = end - start;
  printf( "Complete - %lf Seconds\n", solTime );
  return 0;
}
```

Output (4 Cores)

```
$ gcc -fopenmp ...
(builds)
$ ./vectorOps
Complete - 0.282029 Seconds
$

Can tweak schedule to dynamic.

$ gcc -fopenmp ...
(builds)
$ ./vectorOps
Complete - 1.735515 Seconds
$

Wowza.  That's a lot of
overhead.  Can we alter the
chunk size?  Maybe try 1000?

$ gcc -fopenmp ...
(builds)
$ ./vectorOps
Complete - 0.286736 Seconds
$
```

Scheduling Results

- **Timings for Various Scheduling Methods**
  - Static 0.282029
  - Static, 10 0.753599
  - Static, 100 0.491518
  - Dynamic 1.735515
  - Dynamic, 10 0.445480
  - Dynamic, 100 0.307367
  - Guided 0.284483



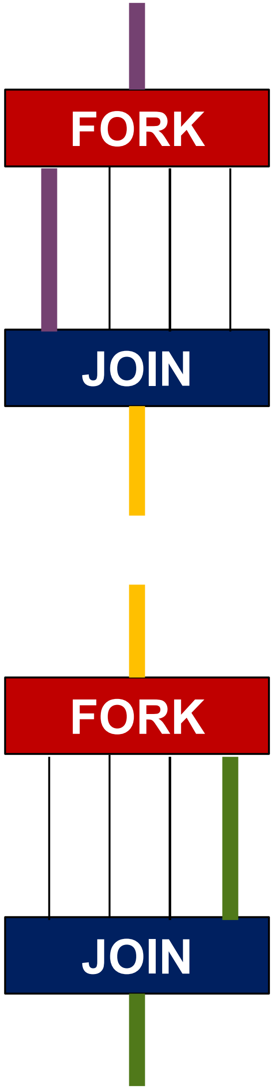
- **Visualizing the Balance**
  - Increasing chunk size of static division can induce overhead
  - Dynamic scheduling often induces significant overhead for small chunks
  - For some applications, division may cause load imbalance dynamic solves
  - Guided provides a suitable balance for many applications between the two

Extra Fun

You're doing so great! Almost there! WOOOO!

First/LastPrivate

- **Alters private behavior relating to first/last iteration**
- **Private**
  - Not initialized by default, just existing binary garbage
  - Order not guaranteed, may remain garbage
- **FirstPrivate**
  - Handled at start of parallel region
  - Automatically initializes values of variables in threads
  - Value of variable in master thread is carried into others
- **LastPrivate**
  - Handled at the end of a parallel region
  - Sets value of variable in master thread
  - Can be from for loop iterations or sections
  - Value taken from last iteration or section to execute
  - Sequential order implied, comes from highest thread index



FirstPrivate Example

Code Example

```
#include <omp.h>
int main( int argc, char **argv ) {
  int thread = 0;  // Thread Number
  int num    = 3;  // Number
  printf( "Master Thread\n  Num Value = %d\n", num );
  printf( "Parallel Region\n" );
  #pragma omp parallel private( thread ) \
                       firstprivate( num )
  {
    #pragma omp master
    {
      printf( "  Num Value = %d\n", num );
    }
    thread = omp_get_thread_num( );
    num    = thread * thread + num;
    printf( "  Thread %d - Value %d\n", thread, num );
  }
  printf( "Master Thread\n  Num Value = %d\n", num );
  return 0;
}
```

Output (4 Cores)

```
$ gcc ...
(builds)
$ ./firstprivate
Master Thread
  Num Value = 3
Parallel Region
  Num Value = 3
  Thread 0 – Value 3
  Thread 1 – Value 4
  Thread 2 – Value 7
  Thread 3 – Value 12
Master Thread
  Num Value = 3
$
```

LastPrivate Example

Code Example

```c
#include <omp.h>
int main( int argc, char **argv ) {
  int thread = 0;  // Thread Number
  int num    = 3;  // Number
  int i      = 0;  // Loop Iterator
  printf( "Master Thread\n  Num Value = %d\n", num );
  printf( "Parallel Region\n" );
  #pragma omp parallel private( thread )
  {
    #pragma omp master
    {
      printf( "  Num Value = %d\n", num );
    }
    #pragma omp for lastprivate( num )
    for( i = 0; i < 4; i++ ) {
      thread = omp_get_thread_num( );
      num    = thread * thread + num;
      printf( "  Thread %d - Value %d\n", thread, num );
    }
  }
  printf( "Master Thread\n  Num Value = %d\n", num );
  return 0;
}
```

Output (4 Cores)

```
$ gcc ...
(builds)
$ ./private
Master Thread
  Num Value = 3
Parallel Region
  Num Value = 3  (before for)
  Thread 0 - Value 0
  Thread 3 - Value 9
  Thread 2 - Value 4
  Thread 1 - Value 1
Master Thread
  Num Value = 9
$
```

Note that it still returns value from highest index even if order changes.

ThreadPrivate

- **Let thread variables persist between parallel regions**
  - Same rules as private apply
    - Must specify variable after declaration
    - Each thread gets own copy, not visible to others
  - Undefined on first entry unless copyin is used
- **Watch out**
  - Must explicitly turn off dynamic threads
  - Number of threads must remain constant
- **CopyIn**
  - Allows assignment of value to all threads in team
  - Master thread is used as copy source for value
- **CopyPrivate**
  - Used with single directive
  - Copies value from single thread to all private instances in other threads

ThreadPrivate Example

Code Example

```c
#include <omp.h>
int num = 0;
int main( int argc, char **argv ) {
  // Disable Dynamic Threads
  omp_set_dynamic( 0 );
  // Set Num as ThreadPrivate
  #pragma omp threadprivate( num )
  int thread = 0;  // Thread Number
  num        = 6;  // Change Master Num Value
  printf( "First Parallel Region\n" );
  #pragma omp parallel private( thread ) copyin( num )
  {
    thread = omp_get_thread_num( );
    num    = thread * thread + num;
    printf( "  Thread %d - Value %d\n", thread, num );
  }

  printf( "Master Thread\n" );

  printf( "Second Parallel Region\n" );
  #pragma omp parallel
  {
    thread = omp_get_thread_num( );
    printf( "  Thread %d - Value Remains %d\n",
            thread, num                          );
  }
  return 0;
}
```

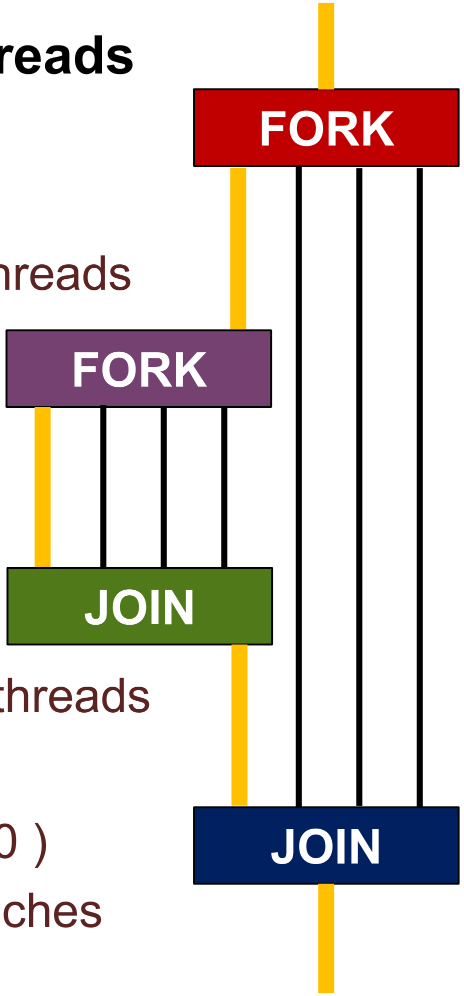
Output (4 Cores)

```
$ gcc ...
(builds)
$ ./threadprivate
First Parallel Region
  Thread 2 – Value 10
  Thread 1 – Value 7
  Thread 3 – Value 15
  Thread 0 – Value 6
Master Thread
Second Parallel Region
  Thread 0 – Value Remains 6
  Thread 1 – Value Remains 7
  Thread 2 – Value Remains 10
  Thread 3 – Value Remains 15
$
```

Note that values persist with thread number! No pesky dynamic reassignment!

Nested Parallelism

- **Thread within team forks again, creating more threads**
  - Original thread becomes master of created threads
- **Advantages**
  - Can quickly split functions more deeply to utilize more threads
  - May layer and combine functional and data parallelism
- **Disadvantages**
  - Requires more overhead – are we overdoing it?
  - Often less efficient – load balancing easier at low level
  - Additional complexity managing more thread teams
  - System may be "oversubscribed" by creating too many threads
- **Usage**
  - Must use omp_set_nested(1) and omp_set_dynamic(0)
  - Create parallel regions as before, assigning thread branches



Nested Parallelism On Example

Code Example

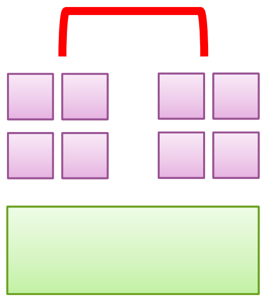
```
#include <omp.h>

int main( int argc, char **argv ) {

  omp_set_nested( 1 );    // Enable Nested Parallelism
  omp_set_dynamic( 0 );   // Disable Dynamic Threads

  // Outer Level Parallel Region - 2 Threads
  #pragma omp parallel num_threads( 2 )
  {

    printf( "Outer Level - See this twice.\n" );

    // Inner Level Parallel Region - 2 Threads Each
    #pragma omp parallel num_threads( 2 )
    {

      printf( "Inner Level - See this four times!\n" );

    }

  }

  return 0;
}
```

Output (4 Cores)

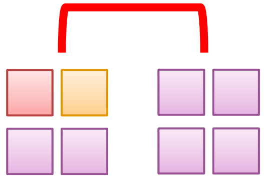
```
$ gcc ...
(builds)
$ ./nested
Outer Level – See this twice.
Outer Level – See this twice.
Inner Level – See this four
times!
Inner Level – See this four
times!
Inner Level – See this four
times!
Inner Level – See this four
times!
$
```

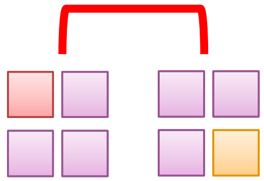
Thread Affinity (Binding)

- **Controls assignment of thread to specific core(s)**
  - Performed via environment variable assignment
  - Affects communication, memory use, performance
  - Helps group execution for NUMA architectures
    - Communication over bus may reduce performance
    - Lack of bandwidth for all cores in one socket may also impact performance
    - Just like everything else, a delicate balance



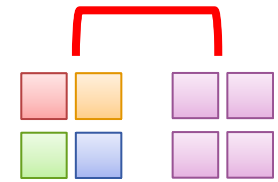
- **OMP_PROC_BIND = …**
  - False – no binding enforced
  - True – locks threads to one core throughout execution
    - Simple affinity for locked-to-core performance, similar to threadprivate
  - Master – collocates threads with the master thread
    - Convenient for recursive thread creation
  - Close – place threads close to the master
    - Minimize communication cost between each thread
  - Spread – spread threads out as much as possible
    - Maximize bandwidth available to each thread

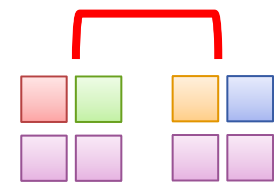


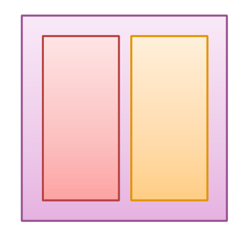


Thread Affinity (Binding)

- **OMP_PLACES = …**
  - Cores
    - Default setting, assigns to cores sequentially
    - May cause collisions that reduce performance
  - Sockets
    - Alternates assigning threads to cores of each socket
    - Helpful for bandwidth
  - Threads
    - Ties OpenMP execution to specific hardware thread
    - For processors with hardware multithreading
  - Manually – {location:number:stride}
    - OMP_PLACES="{0:8:1},{8:8:1}“
      - Two sockets, eight consecutive cores per socket
    - OMP_PLACES="{0},{1},{2},...,{15}“
      - Equivalent to setting individual cores
    - OMP_PLACES="{0:4:8}:4:1“
      - Four sockets; place 0, 8, 16, 24 repeated four times; core 0 of some socket, core 1 of another, etc.
  - Via GCC Compiler - GOMP_CPU_AFFINITY=0,1,8,9







Thank You! Any Questions?

You did it! I will be quiet now!