CS 61C: Great Ideas in Computer Architecture

Synchronization, OpenMP

Guest Lecturer: Justin Hsia

Review of Last Lecture

- Multiprocessor systems uses shared memory (single address space)
- Cache coherence implements shared memory even with multiple copies in multiple caches
  - Track state of blocks relative to other caches (e.g. MOESI protocol)
  - False sharing a concern

Great Idea #4: Parallelism

Software

- Parallel Requests
  Assigned to computer
  e.g. search "Garcia"
- Parallel Threads
  Assigned to core
  e.g. lookup, ads
- Parallel Instructions
  > 1 instruction @ one time
  e.g. 5 pipelined instructions
- Parallel Data
  > 1 data item @ one time
  e.g. add of 4 pairs of words
- Hardware descriptions
  All gates functioning in
  parallel at same time

Leverage Parallelism & Achieve High Performance

Hardware

Warehouse Scale Computer

Smart Phone

Computer

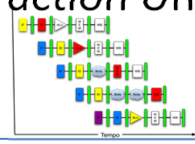
Core … Core

Memory

Input/Output

Core

Instruction Unit(s)

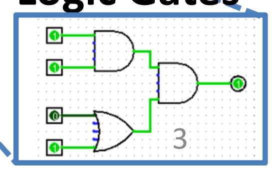


Functional Unit(s)

A_0+B_0	A_1+B_1	A_2+B_2	A_3+B_3

Cache Memory

Logic Gates



Agenda

- Synchronization - A Crash Course
- Administrivia
- OpenMP Introduction
- OpenMP Directives
  - Workshare
  - Synchronization
- Bonus: Common OpenMP Pitfalls

Data Races and Synchronization

- Two memory accesses form a *data race* if different threads access the same location, and at least one is a write, and they occur one after another
  - Means that the result of a program can vary depending on chance (which thread ran first?)
  - Avoid data races by *synchronizing* writing and reading to get deterministic behavior
- Synchronization done by user-level routines that rely on hardware synchronization instructions

Analogy: Buying Milk

- Your fridge has no milk. You and your roommate will return from classes at some point and check the fridge
- Whoever gets home first will check the fridge, go and buy milk, and return
- What if the other person gets back while the first person is buying milk?
  - You've just bought twice as much milk as you need!
- It would've helped to have left a note…

Lock Synchronization (1/2)

- Use a "Lock" to grant access to a region (*critical section*) so that only one thread can operate at a time
  - Need all processors to be able to access the lock, so use a location in shared memory as *the lock*
- Processors read lock and either wait (if locked) or set lock and go into critical section
  - **0** means lock is free / open / unlocked / lock off
  - **1** means lock is set / closed / locked / lock on

Lock Synchronization (2/2)

- Pseudocode:

```
Check lock
Set the lock
Critical section
(e.g. change shared variables)
Unset the lock
```

Can loop/idle here if locked

Possible Lock Implementation

- Lock (a.k.a. busy wait)

```
Get_lock:                          # $s0 -> addr of lock
       addiu $t1,$zero,1           # t1 = Locked value
Loop:  lw $t0,0($s0)               # load lock
       bne $t0,$zero,Loop          # loop if locked
Lock:  sw $t1,0($s0)               # Unlocked, so lock
```

- Unlock

```
Unlock:
       sw $zero,0($s0)
```

- Any problems with this?

Possible Lock Problem

• Thread 1	• Thread 2
`      addiu $t1,$zero,1`	
`Loop: lw $t0,0($s0)`	
	`      addiu $t1,$zero,1`
	`Loop: lw $t0,0($s0)`
`      bne $t0,$zero,Loop`	
	`      bne $t0,$zero,Loop`
`Lock: sw $t1,0($s0)`	
	`Lock: sw $t1,0($s0)`

Time

Both threads think they have set the lock!
Exclusive access not guaranteed!

Hardware Synchronization

- Hardware support required to prevent an interloper (another thread) from changing the value
  - *Atomic* read/write memory operation
  - No other access to the location allowed between the read and write
- How best to implement in software?
  - Single instr? Atomic swap of register ↔ memory
  - Pair of instr? One for read, one for write

Synchronization in MIPS

- *Load linked:* `ll rt,off(rs)`
- *Store conditional:* `sc rt,off(rs)`
  - Returns **1** (success) if location has not changed since the `ll`
  - Returns **0** (failure) if location has changed
- Note that `sc` *clobbers* the register value being stored (`rt`)!
  - Need to have a copy elsewhere if you plan on repeating on failure or using value later

Synchronization in MIPS Example

- Atomic swap (to test/set lock variable)

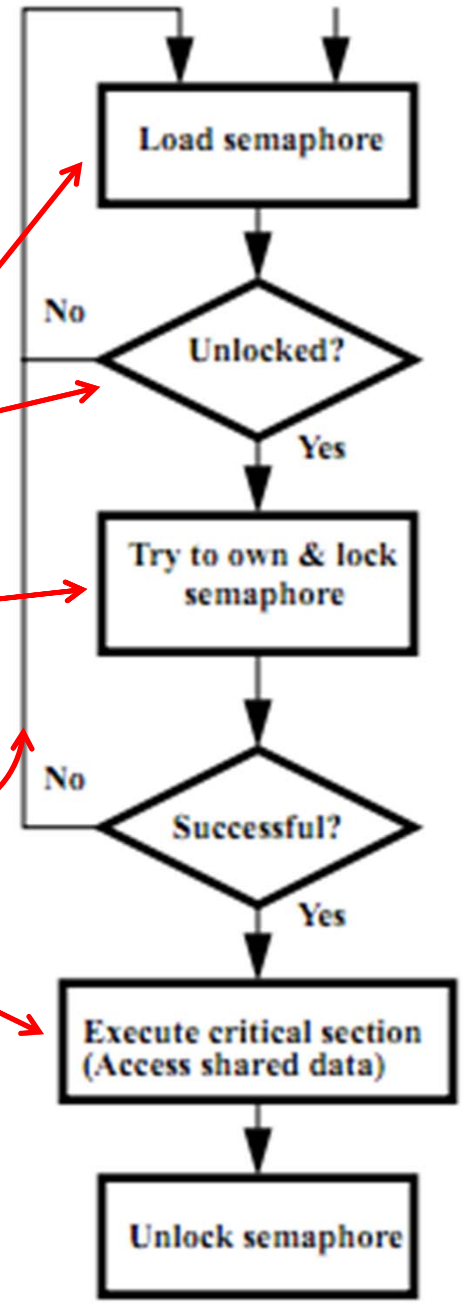
  Exchange contents of register and memory:
  \$s4 ↔ Mem(\$s1)

```
try: add $t0,$zero,$s4 #copy value
     ll  $t1,0($s1)    #load linked
     sc  $t0,0($s1)    #store conditional
     beq $t0,$zero,try #loop if sc fails
     add $s4,$zero,$t1 #load value in $s4
```

sc would fail if another threads executes sc here

Test-and-Set

- In a single atomic operation:
  - *Test* to see if a memory location is set (contains a 1)
  - *Set* it (to 1) if it isn't (it contained a zero when tested)
  - Otherwise indicate that the Set failed, so the program can try again
  - While accessing, no other instruction can modify the memory location, including other Test-and-Set instructions
- Useful for implementing lock operations



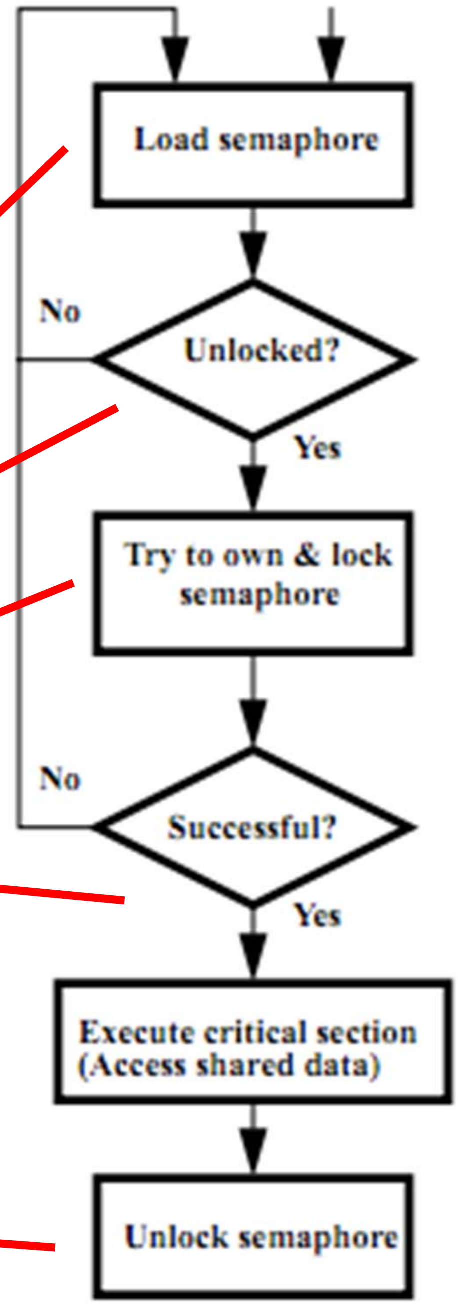
Test-and-Set in MIPS

- Example: MIPS sequence for implementing a T&S at ($s1)

```
Try: addiu $t0,$zero,1
     ll  $t1,0($s1)
     bne $t1,$zero,Try
     sc  $t0,0($s1)
     beq $t0,$zero,try
Locked:

     # critical section

Unlock:
     sw $zero,0($s1)
```



Question: Consider the following code when executed *concurrently* by two threads.

What possible values can result in *($s0)?

```
# *($s0) = 100
lw   $t0,0($s0)
addi $t0,$t0,1
sw   $t0,0($s0)
```

- ☐ 101 or 102
- ☐ 100, 101, or 102
- ☐ 100 or 101
- ☐ 102

Agenda

- Synchronization - A Crash Course
- Administrivia
- OpenMP Introduction
- OpenMP Directives
  - Workshare
  - Synchronization
- Bonus: Common OpenMP Pitfalls

Administrivia

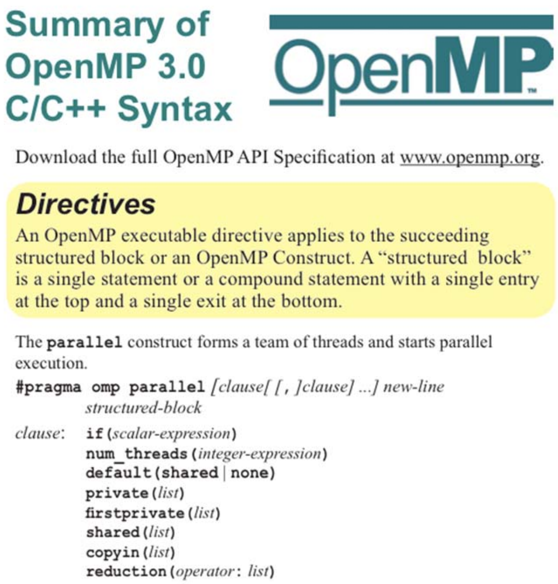
- Midterm re-grade requests due Tuesday (3/19)
- Project 2: MapReduce
  - Work in groups of two!
  - Part 1: Due March 17 (this Sunday)
  - Part 2: Due March 24 (part of Spring Break)
- Homework 4 will be posted before Spring Break
  - If you want to get a head start

Agenda

- Synchronization - A Crash Course
- Administrivia
- OpenMP Introduction
- OpenMP Directives
  - Workshare
  - Synchronization
- Bonus: Common OpenMP Pitfalls

What is OpenMP?

- API used for multi-threaded, shared memory parallelism
  - Compiler Directives
  - Runtime Library Routines
  - Environment Variables
- Portable
- Standardized
- **Resources:** http://www.openmp.org/ and http://computing.llnl.gov/tutorials/openMP/


Summary of OpenMP 3.0 C/C++ Syntax

OpenMP™

Download the full OpenMP API Specification at www.openmp.org.

Directives

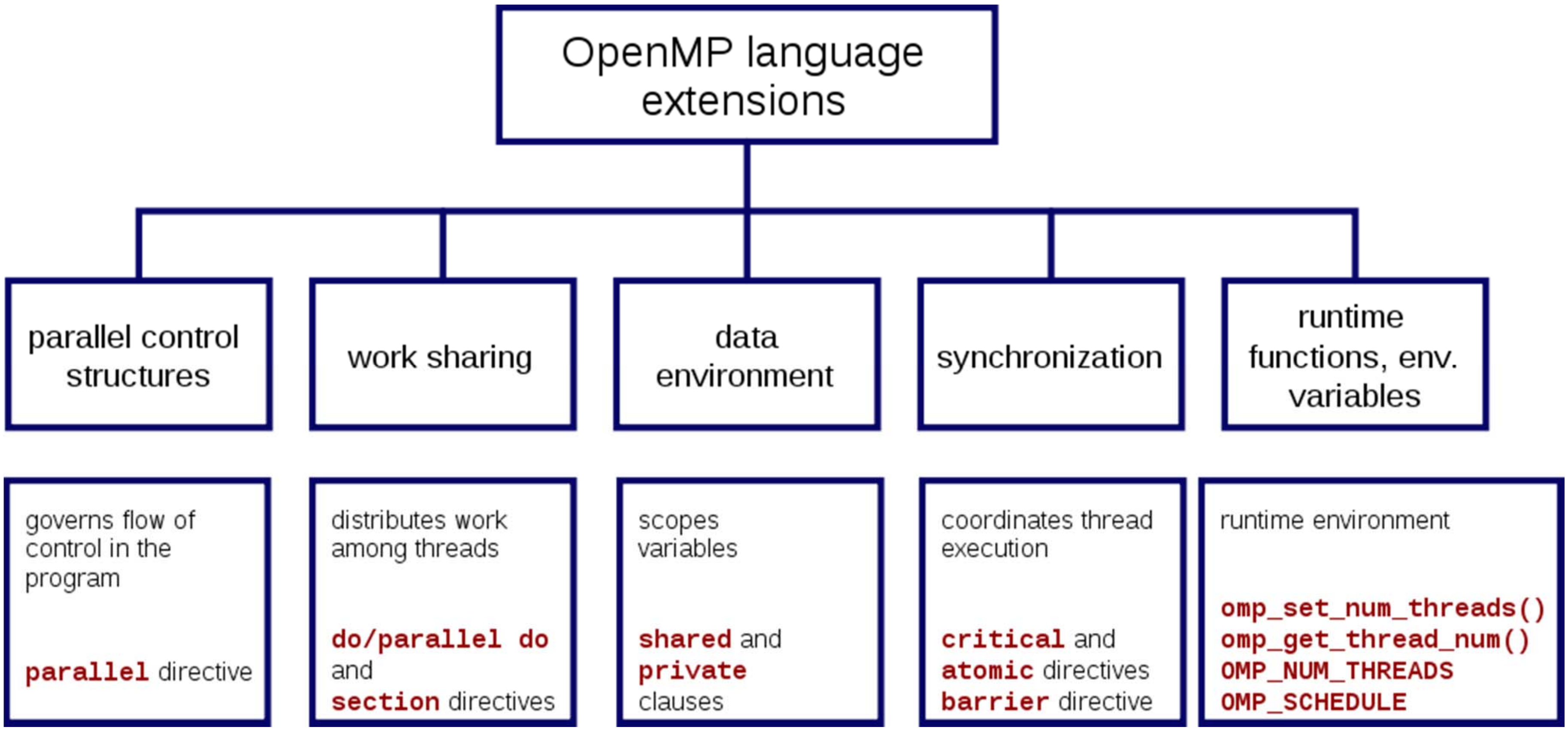
An OpenMP executable directive applies to the succeeding structured block or an OpenMP Construct. A "structured block" is a single statement or a compound statement with a single entry at the top and a single exit at the bottom.

The **parallel** construct forms a team of threads and starts parallel execution.

#pragma omp parallel *[clause[[,]clause] ...] new-line*
structured-block

clause:
if (*scalar-expression*)
num_threads (*integer-expression*)
default (**shared** | **none**)
private (*list*)
firstprivate (*list*)
shared (*list*)
copyin (*list*)
reduction (*operator*: *list*)

OpenMP Specification



Shared Memory Model with Explicit Thread-based Parallelism

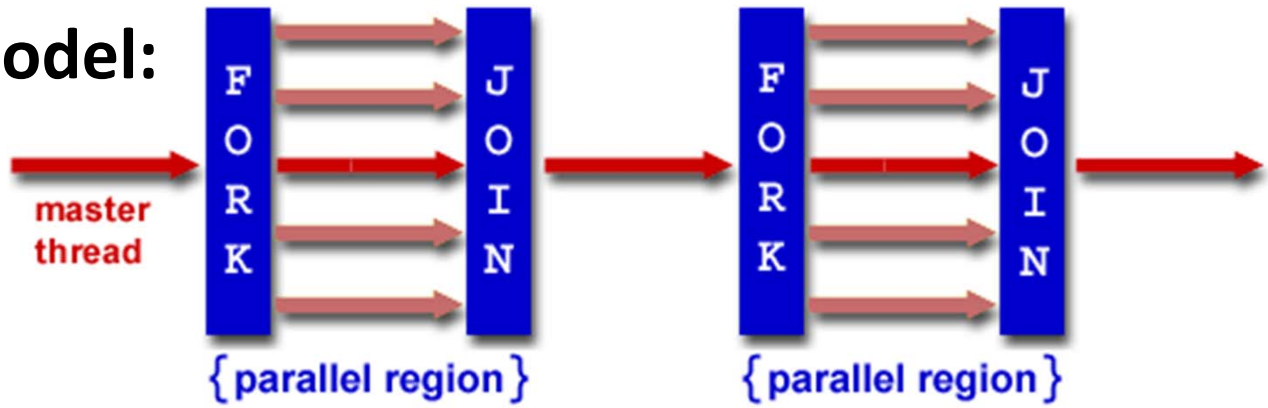
- Multiple threads in a shared memory environment, explicit programming model with full programmer control over parallelization
- **Pros:**
  - Takes advantage of shared memory, programmer need not worry (that much) about data placement
  - Compiler directives are simple and easy to use
  - Legacy serial code does not need to be rewritten
- **Cons:**
  - Code can only be run in shared memory environments
  - Compiler must support OpenMP (e.g. gcc 4.2)

OpenMP in CS61C

- OpenMP is built on top of C, so you don't have to learn a whole new programming language
  - Make sure to add `#include <omp.h>`
  - Compile with flag: `gcc -fopenmp`
  - Mostly just a few lines of code to learn
- You will NOT become experts at OpenMP
  - Use slides as reference, will learn to use in lab
- **Key ideas:**
  - Shared vs. Private variables
  - OpenMP directives for parallelization, work sharing, synchronization

OpenMP Programming Model

- **Fork - Join Model:**



- OpenMP programs begin as single process (*master thread*) and executes sequentially until the first parallel region construct is encountered
  - *FORK:* Master thread then creates a team of parallel threads
  - Statements in program that are enclosed by the parallel region construct are executed in parallel among the various threads
  - *JOIN:* When the team threads complete the statements in the parallel region construct, they synchronize and terminate, leaving only the master thread

OpenMP Extends C with Pragmas

- *Pragmas* are a preprocessor mechanism C provides for language extensions
- Commonly implemented pragmas: structure packing, symbol aliasing, floating point exception modes (not covered in 61C)
- Good mechanism for OpenMP because compilers that don't recognize a pragma are supposed to ignore them
  - Runs on sequential computer even with embedded pragmas

`parallel` Pragma and Scope

- Basic OpenMP construct for parallelization:

```
#pragma omp parallel
{
    /* code goes here */
}
```

This is annoying, but curly brace MUST go on separate line from #pragma

  - *Each* thread runs a copy of code within the block
  - Thread scheduling is *non-deterministic*
- OpenMP default is *shared* variables
  - To make private, need to declare with pragma:

```
#pragma omp parallel private (x)
```

Thread Creation

- How many threads will OpenMP create?
- Defined by OMP_NUM_THREADS environment variable (or code procedure call)
  - Set this variable to the *maximum* number of threads you want OpenMP to use
  - Usually equals the number of cores in the underlying hardware on which the program is run

OMP_NUM_THREADS

- OpenMP intrinsic to set number of threads:
  `omp_set_num_threads(x);`
- OpenMP intrinsic to get number of threads:
  `num_th = omp_get_num_threads();`
- OpenMP intrinsic to get Thread ID number:
  `th_ID = omp_get_thread_num();`

Parallel Hello World

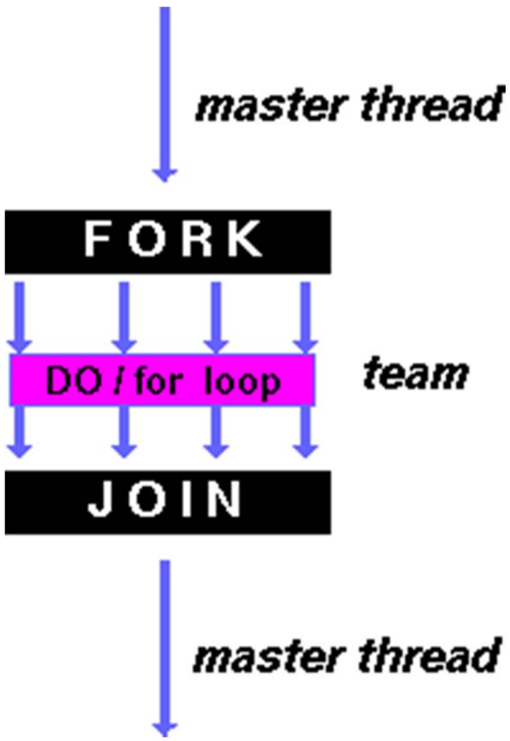
```
#include <stdio.h>
#include <omp.h>
int main () {
  int nthreads, tid;
  /* Fork team of threads with private var tid */
  #pragma omp parallel private(tid)
  {
    tid = omp_get_thread_num(); /* get thread id */
    printf("Hello World from thread = %d\n", tid);
    /* Only master thread does this */
    if (tid == 0) {
      nthreads = omp_get_num_threads();
      printf("Number of threads = %d\n", nthreads);
    }
  }  /* All threads join master and terminate */
}
```

Agenda

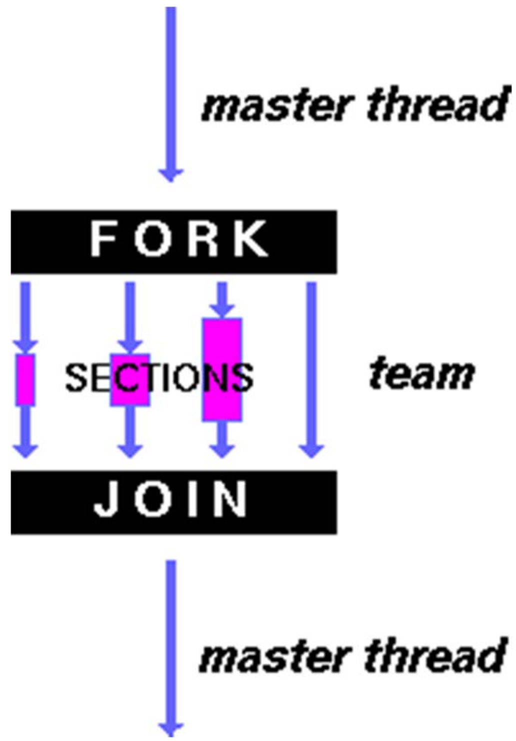
- Synchronization - A Crash Course
- Administrivia
- OpenMP Introduction
- OpenMP Directives
  – Workshare
  – Synchronization
- Bonus: Common OpenMP Pitfalls

OpenMP Directives (Work-Sharing)

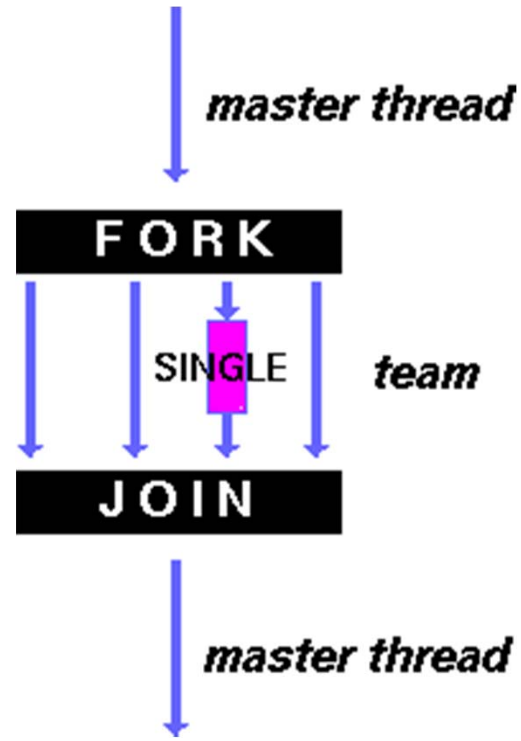
- These are defined *within* a `parallel` section



Shares iterations of a loop across the threads



Each section is executed by a separate thread



Serializes the execution of a thread

`Parallel` Statement Shorthand

```
#pragma omp parallel
{
  #pragma omp for
  for(i=0;i<len;i++) { … }
}
```

This is the only directive in the parallel section

can be shortened to:

```
#pragma omp parallel for
  for(i=0;i<len;i++) { … }
```

- Also works for `sections`

Building Block: `for` loop

```
for (i=0; i<max; i++) zero[i] = 0;
```

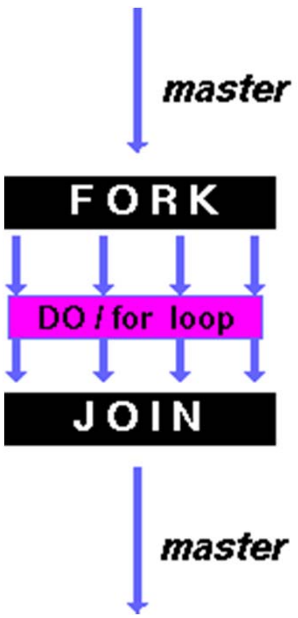
- Break *for loop* into chunks, and allocate each to a separate thread
  - e.g. if `max` = 100 with 2 threads:
    assign 0-49 to thread 0, and 50-99 to thread 1
- Must have relatively simple "shape" for an OpenMP-aware compiler to be able to parallelize it
  - Necessary for the run-time system to be able to determine how many of the loop iterations to assign to each thread
- No premature exits from the loop allowed
  - i.e. No `break`, `return`, `exit`, `goto` statements

In general, don't jump outside of any pragma block

Parallel `for` *pragma*

```
#pragma omp parallel for
  for (i=0; i<max; i++) zero[i] = 0;
```

- Master thread creates additional threads, each with a separate execution context
- All variables declared outside for loop are shared by default, except for loop index which is *private* per thread (Why?)
- Implicit synchronization at end of for loop
- Divide index regions sequentially per thread
  - Thread 0 gets 0, 1, …, (max/n)-1;
  - Thread 1 gets max/n, max/n+1, …, 2*(max/n)-1
  - Why?



OpenMP Timing

- Elapsed wall clock time:

  `double omp_get_wtime(void);`

  - Returns elapsed wall clock time in seconds
  - Time is measured per thread, no guarantee can be made that two distinct threads measure the same time
  - Time is measured from "some time in the past," so subtract results of two calls to `omp_get_wtime` to get elapsed time

Matrix Multiply in OpenMP

```
start_time = omp_get_wtime();
#pragma omp parallel for private(tmp, i, j, k)
  for (i=0; i<Mdim; i++){
    for (j=0; j<Ndim; j++){
      tmp = 0.0;
      for( k=0; k<Pdim; k++){
        /* C(i,j) = sum(over k) A(i,k) * B(k,j)*/
        tmp += *(A+(i*Pdim+k)) * *(B+(k*Ndim+j));
      }
      *(C+(i*Ndim+j)) = tmp;
    }
  }
run_time = omp_get_wtime() - start_time;
```

Outer loop spread across N threads; inner loops inside a single thread

Notes on Matrix Multiply Example

- More performance optimizations available:
  - Higher *compiler optimization* (-O2, -O3) to reduce number of instructions executed
  - *Cache blocking* to improve memory performance
  - Using SIMD SSE instructions to raise floating point computation rate (*DLP*)

OpenMP Directives (Synchronization)

- These are defined *within* a `parallel` section
- `master`
  - Code block executed only by the master thread (all other threads skip)
- `critical`
  - Code block executed by only one thread at a time
- `atomic`
  - Specific memory location must be updated atomically (like a mini-`critical` section for writing to memory)
  - Applies to single statement, not code block

OpenMP Reduction

- *Reduction* specifies that one or more private variables are the subject of a reduction operation at end of parallel region
  - Clause `reduction(operation:var)`
  - *Operation:* Operator to perform on the variables at the end of the parallel region
  - *Var:* One or more variables on which to perform scalar reduction

```
#pragma omp for reduction(+:nSum)
  for (i = START ; i <= END ; i++)
    nSum += i;
```

Summary

- Data races lead to subtle parallel bugs
- Synchronization via hardware primitives:
  - MIPS does it with Load Linked + Store Conditional
- OpenMP as simple parallel extension to C
  - During parallel fork, be aware of which variables should be shared vs. private among threads
  - Work-sharing accomplished with for/sections
  - Synchronization accomplished with critical/atomic/reduction

BONUS SLIDES

You are responsible for the material contained on the following slides, though we may not have enough time to get to them in lecture.

They have been prepared in a way that should be easily readable and the material will be touched upon in the following lecture.

Agenda

- Synchronization - A Crash Course
- Administrivia
- OpenMP Introduction
- OpenMP Directives
  - Workshare
  - Synchronization
- Bonus: Common OpenMP Pitfalls

OpenMP Pitfall #1: Data Dependencies

- Consider the following code:

```
a[0] = 1;
for(i=1; i<5000; i++)
  a[i] = i + a[i-1];
```

- There are dependencies between loop iterations!
  - Splitting this loop between threads does not guarantee in-order execution
  - Out of order loop execution will result in undefined behavior (i.e. likely wrong result)

Open MP Pitfall #2: Sharing Issues

- Consider the following loop:

```
#pragma omp parallel for
     for(i=0; i<n; i++){
          temp = 2.0*a[i];
          a[i] = temp;
          b[i] = c[i]/temp;
     }
```

- temp is a shared variable!

```
#pragma omp parallel for private(temp)
     for(i=0; i<n; i++){
          temp = 2.0*a[i];
          a[i] = temp;
          b[i] = c[i]/temp;
     }
```

OpenMP Pitfall #3: Updating Shared Variables Simultaneously

- Now consider a global sum:

```
for(i=0; i<n; i++)
     sum = sum + a[i];
```

- This can be done by surrounding the summation by a `critical`/`atomic` section or `reduction` clause:

```
#pragma omp parallel for reduction(+:sum)
{
   for(i=0; i<n; i++)
        sum = sum + a[i];
}
```

  – Compiler can generate highly efficient code for `reduction`

OpenMP Pitfall #4: Parallel Overhead

- Spawning and releasing threads results in significant overhead
- Better to have fewer but larger parallel regions
  - Parallelize over the largest loop that you can (even though it will involve more work to declare all of the private variables and eliminate dependencies)

OpenMP Pitfall #4: Parallel Overhead

```
start_time = omp_get_wtime();
for (i=0; i<Ndim; i++){
  for (j=0; j<Mdim; j++){
    tmp = 0.0;
    #pragma omp parallel for reduction(+:tmp)
      for( k=0; k<Pdim; k++){
        /* C(i,j) = sum(over k) A(i,k) * B(k,j)*/
        tmp += *(A+(i*Ndim+k)) * *(B+(k*Pdim+j));
      }
    *(C+(i*Ndim+j)) = tmp;
  }
}
run_time = omp_get_wtime() - start_time;
```

Too much overhead in thread generation to have this statement run this frequently.

Poor choice of loop to parallelize.