October 11, 2011

61C In the News

GPUs Will Morph ORNL's Jaguar Into 20-Petaflop Titan

Michael Feldman

www.hpcwire.com/hpcwire/2011-10-11/gpus_will_morph_ornl_s_jaguar_into_20-petaflop_titan.html

The current Jaguar system … currently sits at number three on the TOP500 list...

Jaguar's days as a CPU-only supercomputer are numbered. Over the next year, the 2.3 petaflop machine at the Oak Ridge National Lab (ORNL) will be upgraded by Cray with the new NVIDIA "Kepler" GPUs, […] The transformed supercomputer will be renamed Titan and should deliver in the neighborhood of 20 peak petaflops sometime in late 2012.

"It's all about power efficiency"

CS 61C: Great Ideas in Computer Architecture (Machine Structures)

Lecture 22

Thread Level Parallelism III

Instructors:
Michael Franklin
Dan Garcia
http://inst.eecs.Berkeley.edu/~cs61c/Fa11

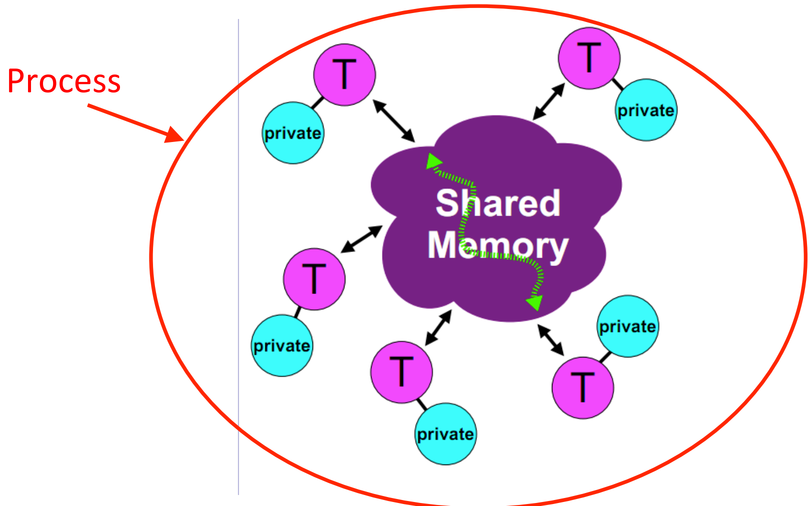
Review

- Sequential software is slow software
  - SIMD and MIMD only path to higher performance
- Multiprocessor (Multicore) uses Shared Memory (single address space)
- Cache coherency implements shared memory even with multiple copies in multiple caches
  - False sharing a concern
- MOESI Protocol ensures cache consistency and has optimizations for common cases.

Threads

- *thread of execution*: smallest unit of processing scheduled by operating system
- Threads have their own *state* or *context*:
  - Program counter, Register file, Stack pointer,
- Threads share: a memory address space
- Note: A "process" is a heavier-weight construct, which has its own address space. A process typically contains one or more threads.
  - Not to be confused with a processor, which is a physical device (i.e., a core)

Memory Model for Multi-threading



CAN BE SPECIFIED IN A LANGUAGE WITH MIMD SUPPORT – SUCH AS OPENMP

Multithreading

- On a single processor, multithreading occurs *by time-division multiplexing*:
  - Processor switched between different threads
    - may be "pre-emptive" or "non pre-emptive"
  - *Context switching* happens frequently enough that user perceives threads as running at the same time
- On a multiprocessor, threads run at the same time, with each processor running a thread

Multithreading vs. Multicore

- Basic idea: Processor resources are expensive and should not be left idle
- For example: Long latency to memory on cache miss?
  - Hardware switches threads to bring in other useful work while waiting for cache miss
  - Cost of thread context switch must be much less than cache miss latency
- Put in redundant hardware so don't have to save context on every thread switch:
  - PC, Registers, …
- Attractive for apps with abundant TLP

Data Races and Synchronization

- Two memory accesses form a *data race* if from different threads, to same location, and at least one is a write, and they occur one after another
- If there is a data race, result of 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

Lock and Unlock Synchronization

- Lock used to create region (*critical section*) where only one thread can operate
- Given shared memory, use memory location as synchronization point: *lock* or *semaphore*
- Thread reads lock to see if it must wait, or OK to go into critical section (and set to locked)
  - 0 => lock is free / open / unlocked / lock off
  - 1 => lock is set / closed / locked / lock on

```
Set the lock
Critical section
  (only one thread
  gets to execute
  this section of
  code at a time)
e.g., change shared
  variables
Unset the lock
```


Possible Lock/Unlock Implementation

- Lock (aka busy wait):

```
         addiu $t1,$zero,1   ; t1 = 1 means Locked
Loop:    lw $t0,lock($s0)    ; load lock
         bne $t0,$zero,Loop  ; loop if locked
Lock:    sw $t1,lock($s0)    ; Unlocked, so lock
```

- Unlock:

```
         sw $zero,lock($s0)
```

- Any problems with this?

Peer Instruction: What Happens?

```
        addiu $t1,$zero, 1        ; t1 = 1 means locked
Loop:   lw $t0, lock($s0)         ; load lock
        bne $t0, $zero, Loop      ; loop if lock <> 0
Lock:   sw $t1, lock($s0)         ; set lock and continue
                                  ; to critical section
```

I. It works great! Ensures that at most one thread enters the critical section at a time.

II. Infinite Loop, since no change to lock before bne

III. Doesn't work because a different thread on another core could see lock == 0 before sw changes it to 1; so both go to critical section

IV. Doesn't work because a different thread on this same core could see lock == 0 before sw changes it to 1; so both go to critical section

(A) I only (B) II only (C) III only (D) IV only (E) III and IV

Possible Lock Problem

- Thread 1

```
      addiu $t1,$zero,1
Loop: lw $t0,lock($s0)

      bne $t0,$zero,Loop

Lock: sw $t1,lock($s0)
```

- Thread 2

```
      addiu $t1,$zero,1
Loop: lw $t0,lock($s0)

      bne $t0,$zero,Loop

Lock: sw $t1,lock($s0)
```

Time

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

Help! Hardware Synchronization

- Hardware support required to prevent interloper (either thread on other core or thread on same core) from changing the value
  - *Atomic* read/write memory operation
  - No other access to the location allowed between the read and write
- Could be a single instruction
  - E.g., atomic swap of register ↔ memory
  - Or an atomic pair of instructions

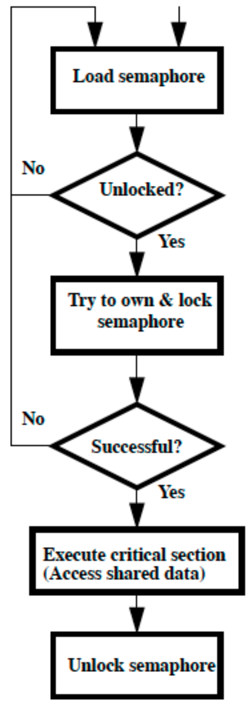
Synchronization in MIPS

- Load linked: `ll rt,offset(rs)`
- Store conditional: `sc rt,offset(rs)`
  - Succeeds if location not changed since the `ll`
    - Returns 1 in rt (clobbers register value being stored)
  - Fails if location has changed
    - Returns 0 in rt (clobbers register value being stored)
- Example: atomic swap (to test/set lock variable)
  Exchange contents of reg and mem: $s4 ←→ ($s1)

```
try: add $t0,$zero,$s4 ;copy exchange value
     ll  $t1,0($s1)    ;load linked
     sc  $t0,0($s1)    ;store conditional
     beq $t0,$zero,try ;branch store fails
     add $s4,$zero,$t1 ;put load value in $s4
```

Test-and-Set

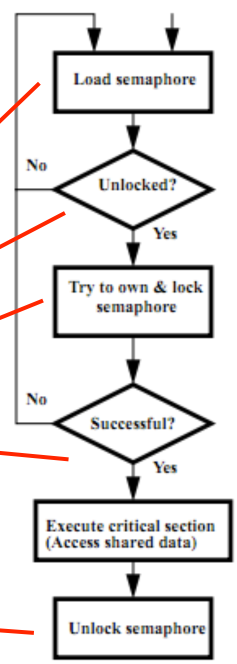
- In a single atomic operation:
  - *Test* to see if a memory location is set (contains a 1)
  - *Set* it (to 1) If it isn't (it contained a zero when tested)
  - Otherwise indicate that the Set failed, so the program can try again
  - No other instruction can modify the memory location, including another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



Test-and-Set in MIPS

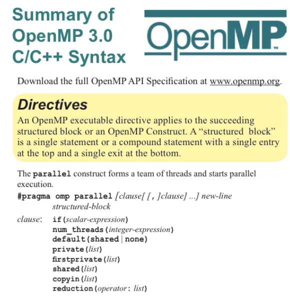
- Single atomic operation
- Example: MIPS sequence for implementing a T&S at ($s1)

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

     critical section

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



What is OpenMP?

- API used for multi-threaded, shared memory parallelism
  - Compiler Directives
  - Runtime Library Routines
  - Environment Variables
- Portable
- Standardized
- See http://www.openmp.org/, 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.

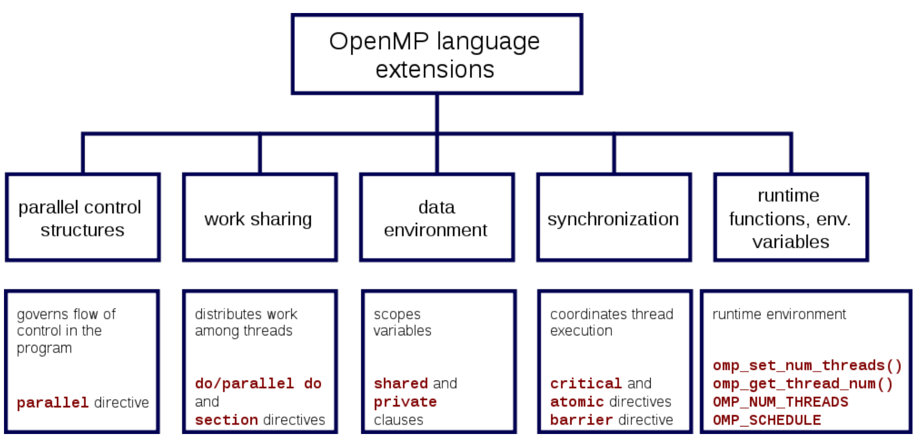
Directives

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

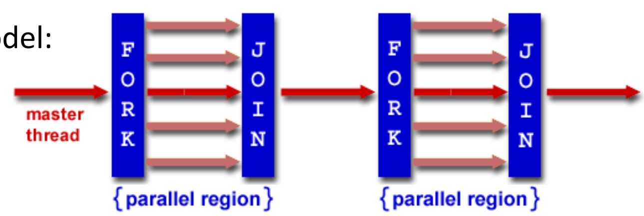


Shared Memory Model with Explicit Thread-based Parallelism

- Shared memory process consists of multiple threads, explicit programming model with full programmer control over parallelization
- Pros:
  - Takes advantage of shared memory, programmer need not worry (that much) about data placement
  - Programming model is "serial-like" and thus conceptually simpler than alternatives (e.g., message passing/MPI)
  - Compiler directives are generally simple and easy to use
  - Legacy serial code does not need to be rewritten
- Cons:
  - Codes can only be run in shared memory environments!
  - Compiler must support OpenMP (e.g., gcc 4.2)

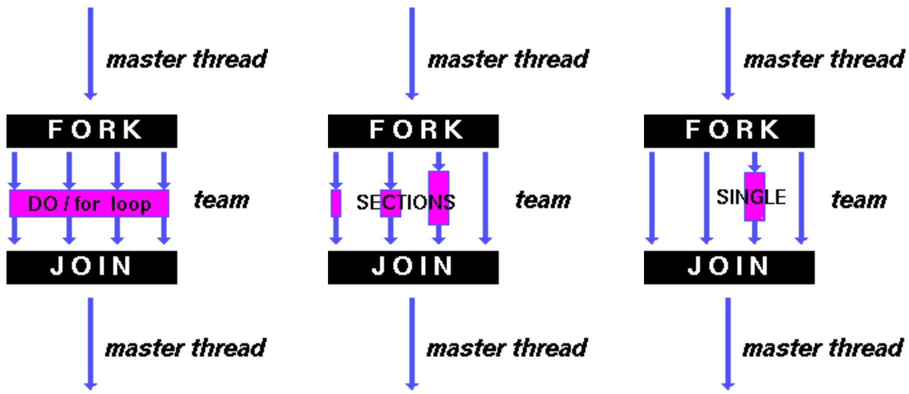
OpenMP Programming Model

- Fork - Join Model:



- OpenMP programs begin as single process: *master thread*; Executes sequentially until the first parallel region construct is encountered
  - FORK: the 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 team threads
  - JOIN: When the team threads complete the statements in the parallel region construct, they synchronize and terminate, leaving only the master thread

OpenMP Directives



shares iterations of a loop across the team

each section executed by a separate thread

serializes the execution of a thread

Building Block: C `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 two threads, assign 0-49 to thread 0, 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

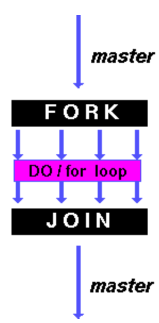
OpenMP Extends C with Pragmas

- Pragmas are a mechanism C provides for language extensions
- Commonly implemented pragmas:
  structure packing, symbol aliasing, floating point exception modes
- 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

OpenMP: 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?



Thread Creation

- How many threads will OpenMP create?
- Defined by OMP_NUM_THREADS environment variable (or in 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 HW on which the program is run

OMP_NUM_THREADS

- Shell command to set number threads:
  `export OMP_NUM_THREADS=x`
- Shell command check number threads:
  `echo $OMP_NUM_THREADS`
- OpenMP intrinsic to set number of threads:
  `omp_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 Threads and Scope

Each thread executes a copy of the code within the structured block

```
#include <omp.h>
main ()  {

int nthreads, tid;

/* Fork a team of threads with each thread having a private tid variable */
#pragma omp parallel private(tid)
  {
  /* Obtain and print thread id */
  tid = omp_get_thread_num();
  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 thread and terminate */
}
```


Matrix Multiply in OpenMP

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

Note: Outer loop spread across N threads; inner loops inside a 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 SSE3 Instructions to raise floating point computation rate

And in Conclusion, …

- Sequential software is slow software
  - SIMD and MIMD only path to higher performance
- Multiprocessor/Multicore uses Shared Memory
  - Cache coherency implements shared memory even with multiple copies in multiple caches
  - False sharing a concern; watch block size!
- Data races lead to subtle parallel bugs
- Synchronization via atomic operations:
  - MIPS does it with Load Linked + Store Conditional
- OpenMP as simple parallel extension to C
  - Threads, Parallel for, private, critical sections, …

Bonus Slides

OpenMP Pitfall #1: Data Dependencies

- Consider the following code:

```
a[0] = 1;
for(i=1; i<5; i++)
a[i] = i + a[i-1];
```

- There are dependencies between loop iterations
- Sections of loops split between threads will not necessarily execute in order
- Out of order loop execution will result in undefined behavior

Open MP Pitfall #2: Avoiding Dependencies by Using Private Variables

- 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;
        }
}
```

- Threads share common address space: will be modifying temp simultaneously; solution:

```
#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 section, but for convenience, OpenMP also provides the 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 #3: Parallel Overhead

- Spawning and releasing threads results in significant overhead
- Therefore, you want to make your parallel regions as large as possible
  - 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)
  - Coarse granularity is your friend!