Great Ideas in Computer Architecture

Multithreading Issues, Cache Coherency

Instructor: Sean Farhat
Review of Last Lecture (1/3)

• Sequential software is slow software
  – SIMD and MIMD only path to higher performance
• Multithreading increases utilization, Multicore more processors (MIMD)
• OpenMP as simple parallel extension to C
  – Small, so easy to learn, but not very high level
  – It’s easy to get into trouble (more today!)
Review of Last Lecture (2/3)

• Synchronization in RISC-V:

• Atomic Swap:
  
amoswap.w.aq rd,rs2,(rs1)
amoswap.w.rl rd,rs2,(rs1)

  – swaps the memory value at M[R[rs1]] with the register value in R[rs2]

  – **atomic** because this is done in one instruction
• 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
#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

• OpenMP Directives
  – Workshare for Matrix Multiplication
  – Synchronization
• Common OpenMP Pitfalls
• Multiprocessor Cache Coherence
• Coherence Protocol: MOESI
Matrix Multiplication

\[ C_{ij} = \sum_{k=1}^{n} a_{ik} \cdot b_{kj} \]
Naïve Matrix Multiply

for (i=0; i<N; i++)
    for (j=0; j<N; j++)
        for (k=0; k<N; k++)
            C[i][j] += A[i][k] * B[k][j];
    C[i*N+j] += A[i*N+k] * B[k*N+j];

**Advantage:** Code simplicity

**Disadvantage:** Blindly marches through memory (how does this affect the cache?)
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;

Why is there no data race here?
● Different threads only work on different ranges of i -- inside writing memory access
● Each thread works on writing to different rows
● Never reducing to a single value (because every write is unique).
Naïve Matrix Multiply

for (i=0; i<N; i++)
    for (j=0; j<N; j++)
        for (k=0; k<N; k++)
            C[i*N+j] += A[i*N+k] * B[N*k+j];

**Question**: What if cache block size > N?
Block Size > N

Won’t use last half of the block!

\[ c_{ij} = \sum_{k=1}^{n} a_{ik} \cdot b_{kj} \]

Cache Block
Question: What if cache block size > N?

—We wouldn’t be using all the data in the blocks that were put in the cache for matrix C and A!

What about if cache block size < N?
Block Size < N

\[
c_{ij} = \sum_{k=1}^{n} a_{ik} \cdot b_{kj}
\]

Must pull in two blocks instead of one!
Cache Blocking

• Increase the number of cache hits you get by using up as much of the cache block as possible
  – For an N x N matrix multiplication:
    • Instead of striding by the dimensions of the matrix, stride by the blocksize
    • When N is not perfect divisible by the blocksize, chunk up data as much as possible into block sizes and handle the remainder as a tailcase
• You’ve already done this in the cache lab — really try to understand it!
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  – Workshare for Matrix Multiplication
  – Synchronization
• **Common OpenMP Pitfalls**
• **Multiprocessor Cache Coherence**
• **Coherence Protocol: MOESI**
Synchronization Problems

double compute_sum(double *a, int a_len) {
    double sum = 0.0;
    #pragma omp parallel for
    for (int i = 0; i < a_len; i++) {
        sum += a[i];
    }
    return sum;
}

Problem: data race with sum!

Solution 1: Put body of loop in critical section

New Problem: Code is now serial! Each thread must wait its turn to add to sum

Solution 2: Separate “sum”s for each thread! Combine at the end
OpenMP Reduction

• **Reduction**: specifies that 1 or more variables that are private to each thread are subject of reduction operation at end of parallel region:

  reduction(operation:var)

  – **Operation**: perform on the variables (var) at the end of the parallel region
  – **Var**: variable(s) on which to perform scalar reduction

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

double compute_sum(double *a, int a_len) {
    double sum = 0.0;
    #pragma omp parallel for reduction(+ : sum)
    for (int i = 0; i < a_len; i++) {
        sum += a[i];
    }
    return sum;
}
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OpenMP Pitfalls

• We can’t just throw pragmas on everything and expect performance increase 😞
  – Might not change speed much or break code!
  – Must understand application and use wisely

• Discussed here:
  1) Data dependencies
  2) Sharing issues (private/non-private variables)
  3) Updating shared values
  4) Parallel overhead
OpenMP Pitfall #1: Data Dependencies

• Consider the following code:
  
  ```c
  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:

```c
#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!**

```c
#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;
}
```

Each thread accesses different elements of a, b, and c, but the same temp
OpenMP Pitfall #3: Updating Shared Variables Simultaneously

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

Reads and writes to sum interleaved among threads

– 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

```c
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.
Agenda

- OpenMP Directives
  - Workshare for Matrix Multiplication
  - Synchronization
- Common OpenMP Pitfalls
- Multiprocessor Cache Coherence
- Coherence Protocol: MOESI
Where are the caches?

Recall: multithreading could be spread across multiple cores
Multiprocessor Caches

• Memory is a performance bottleneck
  – Even with just one processor
  – Caches reduce bandwidth demands on memory

• Each core has a *local* private cache
  – Cache misses access shared common memory
Shared Memory and Caches

• What if?
  – Processors 1 and 2 read Memory[1000] (value 20)

```
Processor 0
    ▼
  Cache
    ▼
1000: 20
    ▼
Interconnection Network
    ▼
Memory 20
    ▼
Processor 1
    ▼
1000: 20
    ▼
Processor 2
    ▼
I/O
```

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Shared Memory and Caches

• Now:
  – Processor 0 writes Memory[1000] with 40

Problem?
Keeping Multiple Caches Coherent

• Architect’s job: keep cache values **coherent** with shared memory
• Idea: on cache miss or write, notify other processors via interconnection network
  – If **reading**, many processors can have copies
  – If **writing**, **invalidate** all other copies
• Write transactions from one processor “snoop” tags of other caches using common interconnect
  – Invalidate any “hits” to same address in other caches
Shared Memory and Caches

• Example, now with cache coherence
  – Processors 1 and 2 read Memory[1000]
  – Processor 0 writes Memory[1000] with 40
Using write-through caches removes the need for cache coherence

Every processor store instruction must check the contents of other caches

Most processor load and store accesses only need to check in the local private cache

Only one processor can cache any memory location at one time

Question
Which statement is TRUE about multiprocessor cache coherence?

(A) Using write-through caches removes the need for cache coherence

(B) Every processor store instruction must check the contents of other caches

(C) Most processor load and store accesses only need to check in the local private cache

(D) Only one processor can cache any memory location at one time
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How Does HW Keep $ Coherent?

- Simple protocol: **MSI**
- Each cache tracks state of each **block** in cache:
  - **Modified**: up-to-date, changed (**dirty**), OK to write
    - no other cache has a copy
    - copy in memory is out-of-date
    - must respond to read request by other processors by updating memory
  - **Shared**: up-to-date data, not allowed to write
    - other caches may have a copy
    - copy in memory is up-to-date
  - **Invalid**: data in this block is “garbage”
MSI Protocol: Current Processor

Invalid

Read Miss (get block from memory)

Shared

Write Miss (get block from memory) (WB/Write Alloc)

Modified

Write Hit

Read Hit

Write Hit

Read Hit Write Hit
MSI Protocol: Response to Other Processors

A probe is another processor

A probe hit means a probe finds its requested block in another cache

Invalid

Probe Write Hit

Probe Read Hit

Write Hit

Probe Read Hit (write back to memory)

Modified

Shared

Probe Write Hit

Probe Read Hit

Invalid

Probe Write Hit

Probe Read Hit

Write Hit

Probe Read Hit (write back to memory)

Modified

Shared

Probe Write Hit

Probe Read Hit

Write Hit

Probe Read Hit (write back to memory)
How to keep track of state block is in?

- Already have valid bit + dirty bit
- Introduce a new bit called “shared” bit

<table>
<thead>
<tr>
<th></th>
<th>Valid Bit</th>
<th>Dirty Bit</th>
<th>Shared Bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modified</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Shared</td>
<td>1</td>
<td>0</td>
<td>X (for now)</td>
</tr>
<tr>
<td>Invalid</td>
<td>0</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

X = doesn’t matter
MSI Example

Here there's only one other processor, but we would have to check & invalidate the data in "every" other processor.

Processor 0 -- Block 0 Read
Processor 1 -- Block 0 Read
Processor 0 -- Block 0 Write
Processor 1 -- Block 0 Read
Compatibility Matrix

- Each block in each cache is in one of the following states:
  - Modified (in cache)
  - Shared (in cache)
  - Invalid (not in cache)

```
+---+---+---+
|   | M  | S  | I  |
+---+---+---+
| M | x  | x  | ✓  |
+---+---+---+
| S | x  | ✓  | ✓  |
+---+---+---+
| I | ✓  | ✓  | ✓  |
+---+---+---+
```

Compatibility Matrix: Allowed states for a given cache block in any pair of caches
Problem: Writing to Shared is Expensive

• If block is in shared, need to check if other caches have data (so we can invalidate) if we want to write
• If block is in modified, don’t need to check other caches if we want to write.  
  – Why? Only one cache can have data if modified
Performance Enhancement 1: Exclusive State

• New state: exclusive
• Exclusive: up-to-date data, OK to write (change to modified)
  – no other cache has a copy
  – copy in memory up-to-date
  – no write to memory if block replaced
  – supplies data on read instead of going to memory

• Now, if block is in shared, at least 1 other cache must contain it:
  – Shared: up-to-date data, not allowed to write
    • other caches may definitely have a copy
    • copy in memory is up-to-date

• MESI also known as Illinois protocol (since it was developed at UIUC!)
MESI Protocol: Current Processor

- **Invalid**: Read Miss, first to cache data
- **Exclusive**: Read Hit, Write Hit
- **Shared**: Read Hit, Write Hit
- **Modified**: Read Hit, Write Hit

- **Write Miss (WB/Write Alloc)**: Write Hit
MESI Protocol: Response to Other Processors

- **Invalid**
  - Probe Write Hit
  - Probe Write Hit

- **Exclusive**
  - Probe Write Hit

- **Shared**
  - Probe Read Hit
  - Probe Read Hit (write back to memory)

- **Modified**
How to keep track of state block is in?

- New entry in truth table: Exclusive

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</tr>
</thead>
<tbody>
<tr>
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<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Exclusive</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Shared</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Invalid</td>
<td>0</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

\(X = \text{doesn't matter}\)
Problem: Expensive to Share Modified

• In MSI and MESI, if we want to share block in modified:
  1. Modified data written back to memory
  2. Modified block → shared
  3. Block that wants data → shared
• Writing to memory is expensive! Can we avoid it?
Performance Enhancement 2: Owned State

- **Owner**: up-to-date data, read-only (like shared, you can write if you invalidate shared copies first and your state changes to modified)
  - Other caches have a shared copy (Shared state)
  - Data in memory not up-to-date
  - Owner supplies data on probe read instead of going to memory
  - Combination of Modified and Shared

- **Shared**: up-to-date data, not allowed to write
  - other caches definitely have a copy
  - copy in memory is *may* be up-to-date
Common Cache Coherency Protocol: MOESI (snoopy protocol)

- Each block in each cache is in one of the following states:
  - **Modified** (in cache)
  - **Owned** (in cache)
  - **Exclusive** (in cache)
  - **Shared** (in cache)
  - **Invalid** (not in cache)

<table>
<thead>
<tr>
<th></th>
<th>M</th>
<th>O</th>
<th>E</th>
<th>S</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>✅</td>
</tr>
<tr>
<td>O</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>✅</td>
<td>✅</td>
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<td>E</td>
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<td>I</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
<td>✅</td>
</tr>
</tbody>
</table>

**Compatibility Matrix**: Allowed states for a given cache block in any pair of caches
MOESI Protocol: Current Processor

- **Invalid**
  - Read Miss
  - Read Miss Exclusive

- **Shared**
  - Read Miss
  - Shared
  - Write Hit
  - Write Hit

- **Exclusive**
  - Read Miss Exclusive
  - Write Hit

- **Modified**
  - Write Hit
  - Write Hit
  - Read Hit

- **Owned**
  - Read Hit
MOESI Protocol: Response to Other Processors

- **Invalid**
  - Probe Write Hit
  - Probe Write Hit

- **Shared**
  - Probe Read Hit
  - Probe Read Hit

- **Owned**
  - Probe Read Hit

- **Exclusive**
  - Probe Write Hit
  - Probe Read Hit
  - Probe Write Hit

- **Modified**
  - Probe Read Hit
How to keep track of state block is in?

- New entry in truth table: Owned

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<td>Modified</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><strong>Owned</strong></td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Exclusive</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Shared</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Invalid</td>
<td>0</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

\[X = \text{doesn’t matter}\]
Block 0 is in the exclusive state, so we don’t have to check if the block is in other caches and needs to be invalidated.

Block 0 is never unnecessarily evicted & we don’t waste bandwidth writing to memory.

Processor 0 -- Block 0 Read
Processor 0 -- Block 0 Write
Processor 1 -- Block 0 Read
Processor 0 -- Block 0 Write
Processor 1 -- Block 0 Read
Suppose:
- Block size is 32 bytes
- P0 reading and writing variable X, P1 reading and writing variable Y
- X in location 4000, Y in 4012

What will happen?
False Sharing

• Block ping-pongs between two caches even though processors are accessing disjoint variables
  – Effect called false sharing
• How can you prevent it?
  – Want to “place” data on different blocks
  – Reduce block size
False Sharing vs. Real Sharing

- If same piece of data being used by 2 caches, ping-ponging is inevitable
- This is **not** false sharing
- Would cache invalidation occur if block size was only 1 word?
  - Yes: true sharing
  - No: false sharing
Understanding Cache Misses: The 3Cs

- **Compulsory** (cold start or process migration, 1st reference):
  - First access to a block in memory impossible to avoid
  - Solution: block size ↑ (MP ↑)

- **Capacity**:
  - Cache cannot hold all blocks accessed by the program
  - Solution: cache size ↑ (may cause access/HT ↑)

- **Conflict (collision)**:
  - Multiple memory locations map to same cache location
  - Solutions: cache size ↑, associativity ↑ (may cause access/HT ↑)
“Fourth C”: Coherence Misses

• Misses caused by *coherence* traffic with other processor
• Also known as *communication misses* because represents data moving between processors working together on a parallel program
• For some parallel programs, coherence misses can dominate total misses
Summary

• **OpenMP** as simple parallel extension to C
  – Synchronization accomplished with critical/atomic/reduction
  – Pitfalls can reduce speedup or break program logic

• **Cache coherence** implements shared memory even with multiple copies in multiple caches
  – **False sharing** a concern