CIS 371
Computer Organization and Design

Unit 12: Multicore
(Shared Memory Multiprocessors)

Slides originally developed by Amir Roth with contributions by Milo Martin at University of Pennsylvania with sources that included University of Wisconsin slides by Mark Hill, Guri Sohi, Jim Smith, and David Wood.
This Unit: Shared Memory Multiprocessors

- Thread-level parallelism (TLP)
- Shared memory model
  - Multiplexed uniprocessor
  - Hardware multithreading
  - Multiprocessing
- Synchronization
  - Lock implementation
  - Locking gotchas
- Cache coherence
- Memory consistency models
Readings

- P&H
  - Chapter 7.1-7.3, 7.5
  - Chapter 5.8, 5.10
Beyond Implicit Parallelism

- Consider “daxpy”:
  ```c
  double a, x[SIZE], y[SIZE], z[SIZE];
  void daxpy():
    for (i = 0; i < SIZE; i++)
      z[i] = a*x[i] + y[i];
  ```

- Lots of instruction-level parallelism (ILP)
  - Great!
  - But how much can we really exploit? 4 wide? 8 wide?
    - Limits to (efficient) super-scalar execution

- But, if SIZE is 10,000, the loop has 10,000-way parallelism!
  - How do we exploit it?
Explicit Parallelism

• Consider “daxpy”:
  ```c
  double a, x[SIZE], y[SIZE], z[SIZE];
  void daxpy():
      for (i = 0; i < SIZE; i++)
          z[i] = a*x[i] + y[i];
  ```

• Break it up into N “chunks” on N cores!
  • Done by the programmer (or maybe a really smart compiler)
  ```c
  void daxpy(int chunk_id):
      chuck_size = SIZE / N
      my_start = chunk_id * chuck_size
      my_end = my_start + chuck_size
      for (i = my_start; i < my_end; i++)
          z[i] = a*x[i] + y[i]
  ```

• Assumes
  • Local variables are “private” and x, y, and z are “shared”
  • Assumes SIZE is a multiple of N (that is, SIZE % N == 0)

<table>
<thead>
<tr>
<th>Chunk ID</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>99</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>199</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>299</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>399</td>
</tr>
</tbody>
</table>
Explicit Parallelism

• Consider “daxpy”:
  
  ```c
  double a, x[SIZE], y[SIZE], z[SIZE];
  void daxpy(int chunk_id):
      chuck_size = SIZE / N
      my_start = chunk_id * chuck_size
      my_end = my_start + chuck_size
      for (i = my_start; i < my_end; i++)
          z[i] = a*x[i] + y[i]
  ```

• Main code then looks like:
  
  ```c
  parallel_daxpy():
      for (tid = 0; tid < CORES; tid++) {
          spawn_task(daxpy, tid);
      }
      wait_for_tasks(CORES);
  ```
Explicit (Loop-Level) Parallelism

• Another way: “OpenMP” annotations to inform the compiler

```c
double a, x[SIZE], y[SIZE], z[SIZE];
void daxpy() {
    #pragma omp parallel for
    for (i = 0; i < SIZE; i++) {
        z[i] = a*x[i] + y[i];
    }
}
```

• Look familiar?
  • Hint: homework #1

• But only works if loop is actually parallel
  • If not parallel, incorrect behavior may result in unpredictable ways
Multicore & Multiprocessor Hardware
Multiplying Performance

- A single processor can only be so fast
  - Limited clock frequency
  - Limited instruction-level parallelism
  - Limited cache hierarchy

- What if we need even more computing power?
  - Use multiple processors!
  - But how?

- High-end example: Sun Ultra Enterprise 25k
  - 72 UltraSPARC IV+ processors, 1.5Ghz
  - 1024 GBs of memory
  - Niche: large database servers
  - $$$
Multicore: Mainstream Multiprocessors

• **Multicore chips**

  • IBM Power5
    • Two 2+GHz PowerPC cores
    • Shared 1.5 MB L2, L3 tags

  • AMD Quad Phenom
    • Four 2+ GHz cores
    • Per-core 512KB L2 cache
    • Shared 2MB L3 cache

  • Intel Core i7 Quad
    • Four cores, private L2s
    • Shared 6 MB L3

  • Sun Niagara
    • 8 cores, each 4-way threaded
    • Shared 2MB L2, shared FP
    • For servers, not desktop

Why multicore? What else would you do with 1 billion transistors?
Sun Niagara II
Intel Quad-Core “Core i7”
Application Domains for Multiprocessors

- **Scientific computing/supercomputing**
  - Examples: weather simulation, aerodynamics, protein folding
  - Large grids, integrating changes over time
  - Each processor computes for a part of the grid

- **Server workloads**
  - Example: airline reservation database
  - Many concurrent updates, searches, lookups, queries
  - Processors handle different requests

- **Media workloads**
  - Processors compress/decompress different parts of image/frames

- **Desktop workloads...**
- **Gaming workloads...**

  *But software must be written to expose parallelism*
“Threading” & The Shared Memory Execution Model
First, Uniprocessor Concurrency

- **Software “thread”:** Independent flows of execution
  - “private” per-thread state
    - Context state: PC, registers
    - Stack (per-thread local variables)
  - “shared” state: Globals, heap, etc.
  - Threads generally share the same memory space
    - “Process” like a thread, but different memory space
  - Java has thread support built in, C/C++ using a thread library
- Generally, system software (the O.S.) manages threads
  - “Thread scheduling”, “context switching”
  - In single-core system, all threads share the one processor
    - Hardware timer interrupt occasionally triggers O.S.
    - Quickly swapping threads gives illusion of concurrent execution
  - Much more in an operating systems course
Multithreaded Programming Model

- Programmer explicitly creates multiple threads

- All loads & stores to a single **shared memory** space
  - Each thread has a private stack frame for local variables

- A “thread switch” can occur at any time
  - Pre-emptive multithreading by OS

- Common uses:
  - Handling user interaction (GUI programming)
  - Handling I/O latency (send network message, wait for response)
  - **Expressing parallel work via Thread-Level Parallelism (TLP)**
    - This is our focus!
Simplest Multiprocessor

- Replicate entire processor pipeline!
  - Instead of replicating just register file & PC
  - Exception: share the caches (we’ll address this bottleneck later)
- Multiple threads execute
  - “Shared memory” programming model
  - Operations (loads and stores) are interleaved at random
  - Loads returns the value written by most recent store to location
Alternative: Hardware Multithreading

- **Hardware Multithreading (MT)**
  - Multiple threads dynamically share a single pipeline
  - Replicate only per-thread structures: program counter & registers
  - Hardware interleaves instructions
  + **Multithreading improves utilization and throughput**
    - Single programs utilize <50% of pipeline (branch, cache miss)
  + **Multithreading does not improve single-thread performance**
    - Individual threads run as fast or even slower
  - **Coarse-grain MT**: switch on L2 misses Why?
  - **Simultaneous MT**: no explicit switching, fine-grain interleaving
Shared Memory Implementations

- **Multiplexed uniprocessor**
  - Runtime system and/or OS occasionally pre-empt & swap threads
  - Interleaved, but no parallelism

- **Multiprocessing**
  - Multiply execution resources, higher peak performance
  - Same interleaved shared-memory model
  - Foreshadowing: allow private caches, further disentangle cores

- **Hardware multithreading**
  - Tolerate pipeline latencies, higher efficiency
  - Same interleaved shared-memory model

- **All support the shared memory programming model**
Four Shared Memory Issues

1. Parallel programming
   • How does the programmer express the parallelism?

2. Synchronization
   • How to regulate access to shared data?
   • How to implement “locks”?

3. Cache coherence
   • If cores have private (non-shared) caches
   • How to make writes to one cache “show up” in others?

4. Memory consistency models
   • How to keep programmer sane while letting hardware optimize?
   • How to reconcile shared memory with store buffers?
Parallel Programming
Parallel Programming

• One use of multiprocessors: **multiprogramming**
  • Running multiple programs with no interaction between them
  • Works great for a few cores, but what next?

• Or, programmers must **explicitly** express parallelism
  • “Coarse” parallelism beyond what the hardware can extract **implicitly**
  • Even the compiler can’t extract it in most cases

• How? Several options:
  • Call libraries that perform well-known computations in parallel
    • Example: a matrix multiply routine, etc.
  • Parallel “for” loops, task-based parallelism, ...
  • Add code annotations (“this loop is parallel”), OpenMP
  • Explicitly spawn “tasks”, OS thread schedules them on the cores

• Parallel programming: key challenge in multicore revolution
Example: Parallelizing Matrix Multiply

```
for (I = 0; I < SIZE; I++)
    for (J = 0; J < SIZE; J++)
        for (K = 0; K < SIZE; K++)
```

- How to parallelize matrix multiply?
  - Replace outer “for” loop with “parallel_for” or OpenMP annotation
  - Supported by many parallel programming environments

- Implementation: give each of N processors loop iterations
  ```
  int start = (SIZE/N) * my_id();
  for (I = start; I < start + SIZE/N; I++)
      for (J = 0; J < SIZE; J++)
          for (K = 0; K < SIZE; K++)
  ```

- Each processor runs copy of loop above
  - Library provides `my_id()` function
Example: Bank Accounts

• Consider

```c
struct acct_t { int balance; ... };  
struct acct_t accounts[MAX_ACCT];    // current balances 

struct trans_t { int id; int amount; };   
struct trans_t transactions[MAX_TRANS];  // debit amounts 

for (i = 0; i < MAX_TRANS; i++) {
    debit(transactions[i].id, transactions[i].amount);
}

void debit(int id, int amount) {
    if (accounts[id].balance >= amount) {
        accounts[id].balance -= amount;
    }
}
```

• Can we do these “debit” operations in parallel?
  • Does the order matter?
Example: Bank Accounts

```c
struct acct_t { int bal; ... };
shared struct acct_t accts[MAX_ACCT];
void debit(int id, int amt) {
    if (accts[id].bal >= amt) {
        accts[id].bal -= amt;
    }
}
```

- **Example of Thread-level parallelism (TLP)**
  - Collection of asynchronous tasks: not started and stopped together
  - Data shared “loosely” (sometimes yes, mostly no), dynamically
- **Example: database/web server** (each query is a thread)
  - `accts` is global and thus **shared**, can’t register allocate
  - `id` and `amt` are private variables, register allocated to `r1, r2`
- **Running example**
An Example Execution

- Two $100 withdrawals from account #241 at two ATMs
  - Each transaction executed on different processor
  - Track `accts[241].bal` (address is in `r3`)
A Problem Execution

Thread 0
0: addi r1,accts,r3
1: ld 0(r3),r4
2: blt r4,r2,done
3: sub r4,r2,r4

Thread 1
0: addi r1,accts,r3
1: ld 0(r3),r4
2: blt r4,r2,done
3: sub r4,r2,r4
4: st r4,0(r3)

<< Switch >>>

0: addi r1,accts,r3
1: ld 0(r3),r4
2: blt r4,r2,done
3: sub r4,r2,r4
4: st r4,0(r3)

• Problem: wrong account balance! Why?
  • Solution: synchronize access to account balance
Synchronization
Synchronization:

- **Synchronization**: a key issue for shared memory
- Regulate access to shared data (mutual exclusion)
- Low-level primitive: **lock** (higher-level: “semaphore” or “mutex”)
  - Operations: `acquire(lock)` and `release(lock)`
  - Region between `acquire` and `release` is a **critical section**
  - Must interleave `acquire` and `release`
  - Interfering `acquire` will block
- Another option: **Barrier synchronization**
  - Blocks until all threads reach barrier, used at end of “parallel_for”

```c
struct acct_t { int bal; ... }
shared struct acct_t accts[MAX_ACCT];
shared int lock;
void debit(int id, int amt):
    acquire(lock);
    if (accts[id].bal >= amt) {
        accts[id].bal -= amt;
    }
    release(lock);
```
A Synchronized Execution

Thread 0

0: addi r1,accts,r3
1: ld 0(r3),r4
2: blt r4,r2,done
3: sub r4,r2,r4
<<< Switch >>>
4: st r4,0(r3)
call release(lock)

Thread 1

call acquire(lock)

0: addi r1,accts,r3
1: ld 0(r3),r4
2: blt r4,r2,done
3: sub r4,r2,r4
<<< Switch >>>
4: st r4,0(r3)

Mem
500

Time

• Fixed, but how do we implement acquire & release?

CIS 371 (Martin): Multicore
**Strawman Lock (Incorrect)**

- **Spin lock**: software lock implementation
  - acquire(lock): while (lock != 0) {} lock = 1;
    - “Spin” while lock is 1, wait for it to turn 0
      ```assembly
      A0:  ld  0(&lock),r6
      A1:  bnez r6,A0
      A2:  addi r6,1,r6
      A3:  st  r6,0(&lock)
      ```
  - release(lock): lock = 0;
    ```assembly
    R0:  st r0,0(&lock) // r0 holds 0
    ```
**Strawman Lock (Incorrect)**

- Spin lock makes intuitive sense, but doesn’t actually work
  - Loads/stores of two *acquire* sequences can be interleaved
  - Lock *acquire* sequence also not atomic
  - Same problem as before!

- Note, *release* is trivially atomic
A Correct Implementation: SYSCALL Lock

ACQUIRE_LOCK:

A1: disable_interrupts
A2: ld r6,0(&lock)
A3: bnez r6,#A0
A4: addi r6,1,r6
A5: st r6,0(&lock)
A6: enable_interrupts
A7: return

- Implement lock in a SYSCALL
  - Only kernel can control interleaving by disabling interrupts
    + Works...
    - Large system call overhead
    - But not in a hardware multithreading or a multiprocessor...
Better Spin Lock: Use Atomic Swap

- ISA provides an atomic lock acquisition instruction
  - Example: **atomic swap**
    
    ```
    swap r1,0(&lock)
    ```
  - Atomically executes:
    ```
    mov r1->r2
    ld r1,0(&lock)
    st r2,0(&lock)
    ```

- New acquire sequence
  (value of r1 is 1)
  ```
  A0: swap r1,0(&lock)
  A1: bnez r1,A0
  ```
  - If lock was initially busy (1), doesn’t change it, **keep looping**
  - If lock was initially free (0), acquires it (sets it to 1), break loop

- Insures lock held by **at most one thread**
  - Other variants: **exchange, compare-and-swap, test-and-set (t&s), or fetch-and-add**
Atomic Update/Swap Implementation

- How is atomic swap implemented?
  - Need to ensure no intervening memory operations
  - Requires blocking access by other threads temporarily (yuck)

- How to pipeline it?
  - Both a load and a store (yuck)
  - Not very RISC-like
RISC Test-And-Set

- **swap**: a load and store in one insn is not very “RISC”
  - Broken up into micro-ops, but then how is it made atomic?
- “Load-link” / “store-conditional” pairs
  - Atomic load/store pair
    ```
    label:
    load-link r1,0(&lock)
    // potentially other insns
    store-conditional r2,0(&lock)
    branch-not-zero label   // check for failure
    ```
  - On **load-link**, processor remembers address...
    - ...And looks for writes by other processors
    - If write is detected, next **store-conditional** will fail
      - Sets failure condition
  - Used by ARM, PowerPC, MIPS, Itanium
Lock Correctness

<table>
<thead>
<tr>
<th>Thread 0</th>
<th>Thread 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0: swap r1,0(&amp;lock)</td>
<td>A0: swap r1,0(&amp;lock)</td>
</tr>
<tr>
<td>A1: bnez r1,#A0</td>
<td>A1: bnez r1,#A0</td>
</tr>
<tr>
<td>CRITICAL_SECTION</td>
<td>A0: swap r1,0(&amp;lock)</td>
</tr>
<tr>
<td></td>
<td>A1: bnez r1,#A0</td>
</tr>
</tbody>
</table>

+ Lock actually works...
  • Thread 1 keeps spinning

• Sometimes called a “test-and-set lock”
  • Named after the common “test-and-set” atomic instruction
“Test-and-Set” Lock Performance

Thread 0
A0: swap r1,0(&lock)
A1: bnez r1,#A0
A0: swap r1,0(&lock)
A1: bnez r1,#A0

Thread 1
A0: swap r1,0(&lock)
A1: bnez r1,#A0
A0: swap r1,0(&lock)
A1: bnez r1,#A0

...but performs poorly
- Consider 3 processors rather than 2
- Processor 2 (not shown) has the lock and is in the critical section
- But what are processors 0 and 1 doing in the meantime?
  - Loops of swap, each of which includes a st
  - Repeated stores by multiple processors costly (more in a bit)
  - Generating a ton of useless interconnect traffic
Test-and-Test-and-Set Locks

• Solution: **test-and-test-and-set locks**
  
  • New acquire sequence
    
    A0: `ld r1,0(&lock)`
    A1: `bnez r1,A0`
    A2: `addi r1,1,r1`
    A3: `swap r1,0(&lock)`
    A4: `bnez r1,A0`
  
  • Within each loop iteration, before doing a **swap**
    
    • Spin doing a simple test (`ld`) to see if lock value has changed
    • Only do a **swap** (`st`) if lock is actually free
  
  • Processors can spin on a busy lock locally (in their own cache)
    
    + Less unnecessary interconnect traffic
  
  • Note: test-and-test-and-set is not a new instruction!
    
    • Just different software
Queue Locks

- Test-and-test-and-set locks can still perform poorly
  - If lock is contended for by many processors
  - Lock release by one processor, creates “free-for-all” by others
    - Interconnect gets swamped with swap requests

- **Software queue lock**
  - Each waiting processor spins on a different location (a queue)
  - When lock is released by one processor...
    - Only the next processors sees its location go “unlocked”
    - Others continue spinning locally, unaware lock was released
  - Effectively, passes lock from one processor to the next, in order
    + Greatly reduced network traffic (no mad rush for the lock)
    + Fairness (lock acquired in FIFO order)
  - Higher overhead in case of no contention (more instructions)
  - Poor performance if one thread is descheduled by O.S.
Programming With Locks Is Tricky

- Multicore processors are the way of the foreseeable future
  - thread-level parallelism anointed as parallelism model of choice
  - Just one problem...

- Writing lock-based multi-threaded programs is tricky!

- More precisely:
  - Writing programs that are correct is “easy” (not really)
  - Writing programs that are highly parallel is “easy” (not really)
  - **Writing programs that are both correct and parallel is difficult**
    - And that’s the whole point, unfortunately
  - Selecting the “right” kind of lock for performance
    - Spin lock, queue lock, ticket lock, read/writer lock, etc.
  - **Locking granularity issues**
Coarse-Grain Locks: Correct but Slow

- **Coarse-grain locks**: e.g., one lock for entire database
  - Easy to make correct: no chance for unintended interference
  - Limits parallelism: no two critical sections can proceed in parallel

```c
struct acct_t { int bal; … };  
shared struct acct_t  accts[MAX_ACCT];
shared Lock_t lock;
void debit(int id, int amt) {
  acquire(lock);
  if (accts[id].bal >= amt) {
    accts[id].bal -= amt;
  }
  release(lock);
}
```
Fine-Grain Locks: Parallel But Difficult

- **Fine-grain locks**: e.g., multiple locks, one per record
  - Fast: critical sections (to different records) can proceed in parallel
  - Difficult to make correct: easy to make mistakes
- This particular example is easy
  - Requires only one lock per critical section

```c
struct acct_t { int bal, Lock_t lock; … };
shared struct acct_t accts[MAX_ACCT];

void debit(int id, int amt) {
    acquire(accts[id].lock);
    if (accts[id].bal >= amt) {
        accts[id].bal -= amt;
    }
    release(accts[id].lock);
}
```

- What about critical sections that require two locks?
Multiple Locks

- **Multiple locks**: e.g., acct-to-acct transfer
  - Must acquire both `id_from`, `id_to` locks
  - Running example with accts 241 and 37
  - Simultaneous transfers 241 $\rightarrow$ 37 and 37 $\rightarrow$ 241
  - Contrived... but even contrived examples must work correctly too

```c
struct acct_t { int bal, Lock_t lock; ...};
shared struct acct_t accts[MAX_ACCT];
void transfer(int id_from, int id_to, int amt) {
    acquire(accts[id_from].lock);
    acquire(accts[id_to].lock);
    if (accts[id_from].bal >= amt) {
        accts[id_from].bal -= amt;
        accts[id_to].bal += amt;
    }
    release(accts[id_to].lock);
    release(accts[id_from].lock);
}
```
Multiple Locks And Deadlock

Thread 0

id_from = 241;
id_to = 37;
acquire(accts[241].lock);
// wait to acquire lock 37
// waiting...
// still waiting...

Thread 1

id_from = 37;
id_to = 241;
acquire(accts[37].lock);
// wait to acquire lock 241
// waiting...
// ...

• **Deadlock**: circular wait for shared resources
  • Thread 0 has lock 241 waits for lock 37
  • Thread 1 has lock 37 waits for lock 241
  • Obviously this is a problem
  • The solution is ...
Correct Multiple Lock Program

- **Always acquire multiple locks in same order**
  - Just another thing to keep in mind when programming

```c
struct acct_t { int bal, Lock_t lock; ... };
shared struct acct_t accts[MAX_ACCT];
void transfer(int id_from, int id_to, int amt) {
    int id_first = min(id_from, id_to);
    int id_second = max(id_from, id_to);

    acquire(accts[id_first].lock);
    acquire(accts[id_second].lock);
    if (accts[id_first].bal >= amt) {
        accts[id_from].bal -= amt;
        accts[id_to].bal += amt;
    }
    release(accts[id_second].lock);
    release(accts[id_first].lock);
}
```
Correct Multiple Lock Execution

Thread 0

id_from = 241;
id_to = 37;
id_first = min(241,37)=37;
id_second = max(37,241)=241;
acquire(accts[37].lock);
acquire(accts[241].lock);
// do stuff
release(accts[241].lock);
release(accts[37].lock);

Thread 1

id_from = 37;
id_to = 241;
id_first = min(37,241)=37;
id_second = max(37,241)=241;
// wait to acquire lock 37
acquire(accts[37].lock);
// waiting...
// ...
// ...
release(accts[241].lock);
release(accts[37].lock);

• Great, are we done? No
More Lock Madness

- What if...
  - Some actions (e.g., deposits, transfers) require 1 or 2 locks...
  - ...and others (e.g., prepare statements) require all of them?
  - Can these proceed in parallel?

- What if...
  - There are locks for global variables (e.g., operation id counter)?
  - When should operations grab this lock?

- What if... what if... what if...

- **So lock-based programming is difficult...**
- **...wait, it gets worse**
And To Make It Worse...

- **Acquiring locks is expensive…**
  - By definition requires a slow atomic instructions
    - Specifically, acquiring write permissions to the lock
    - Ordering constraints (see soon) make it even slower

- **…and 99% of the time un-necessary**
  - Most concurrent actions don’t actually share data
    - You paying to acquire the lock(s) for no reason

- **Fixing these problem is an area of active research**
  - One proposed solution “Transactional Memory”
  - Programmer uses construct: “atomic { ... code ... }”
    - Hardware, compiler & runtime executes the code “atomically”
    - Uses speculation, rolls back on conflicting accesses
Research: Transactional Memory (TM)

- **Transactional Memory (TM) goals:**
  + Programming simplicity of coarse-grain locks
  + Higher concurrency (parallelism) of fine-grain locks
    - Critical sections only serialized if data is actually shared
  + Lower overhead than lock acquisition
  + Hot academic & industrial research topic (or was a few years ago)
  + No fewer than nine research projects:
    - Brown, Stanford, MIT, Wisconsin, Texas, Rochester, Sun/Oracle, Intel
    - Penn, too

- **Update:**
  - Intel announced TM support in “Haswell” core (shipping in 2013)
Transactional Memory: The Big Idea

- Big idea I: **no locks, just shared data**

- Big idea II: **optimistic (speculative) concurrency**
  - Execute critical section speculatively, abort on conflicts
  - “Better to beg for forgiveness than to ask for permission”

```c
struct acct_t { int bal; ... };  
shared struct acct_t accts[MAX_ACCT];
void transfer(int id_from, int id_to, int amt) {
  begin_transaction();
  if (accts[id_from].bal >= amt) {
    accts[id_from].bal -= amt;
    accts[id_to].bal += amt;
  }
  end_transaction();
}
```
Transactional Memory: Read/Write Sets

- **Read set**: set of shared addresses critical section reads
  - Example: `accts[37].bal, accts[241].bal`
- **Write set**: set of shared addresses critical section writes
  - Example: `accts[37].bal, accts[241].bal`

```c
struct acct_t { int bal; ... };  
shared struct acct_t  accts[MAX_ACCT];
void transfer(int id_from, int id_to, int amt) {
    begin_transaction();
    if (accts[id_from].bal >= amt) {
        accts[id_from].bal -= amt;
        accts[id_to].bal += amt;
    }
    end_transaction();
}
```
Transactional Memory: Begin

- `begin_transaction`
  - Take a local register checkpoint
  - Begin locally tracking read set (remember addresses you read)
    - See if anyone else is trying to write it
  - Locally buffer all of your writes (invisible to other processors)
    + **Local actions only: no lock acquire**

```c
struct acct_t { int bal; ... };
shared struct acct_t accts[MAX_ACCT];
void transfer(int id_from, int id_to, int amt) {
    begin_transaction();
    if (accts[id_from].bal >= amt) {
        accts[id_from].bal -= amt;
        accts[id_to].bal += amt;
    }
    end_transaction();
}
```
Transactional Memory: End

- **end_transaction**
  - Check read set: is all data you read still valid (i.e., no writes to any)
  - Yes? Commit transactions: commit writes
  - No? Abort transaction: restore checkpoint

```c
struct acct_t { int bal; ... };  
shared struct acct_t accts[MAX_ACCT];  
void transfer(int id_from, int id_to, int amt) {
    begin_transaction();
    if (accts[id_from].bal >= amt) {
        accts[id_from].bal -= amt;
        accts[id_to].bal += amt;
    }
    end_transaction();
}
```
Transactional Memory Implementation

- How are read-set/write-set implemented?
  - Track locations accessed using bits in the cache

- Read-set: additional “transactional read” bit per block
  - Set on reads between begin_transaction and end_transaction
  - Any other write to block with set bit $\Rightarrow$ triggers abort
  - Flash cleared on transaction abort or commit

- Write-set: additional “transactional write” bit per block
  - Set on writes between begin_transaction and end_transaction
  - Before first write, if dirty, initiate writeback (“clean” the block)
  - Flash cleared on transaction commit
  - On transaction abort: blocks with set bit are invalidated
Transactional Execution

Thread 0

id_from = 241;
id_to = 37;

begin_transaction();
if(accts[241].bal > 100) {
    ...
    // write accts[241].bal
    // abort
}

Thread 1

id_from = 37;
id_to = 241;

begin_transaction();
if(accts[37].bal > 100) {
    accts[37].bal -= amt;
    acts[241].bal += amt;
}
end_transaction();
// no writes to accts[241].bal
// no writes to accts[37].bal
// commit
Transactional Execution II (More Likely)

• Critical sections execute in parallel
So, Let’s Just Do Transactions?

- What if...
  - Read-set or write-set bigger than cache?
  - Transaction gets swapped out in the middle?
  - Transaction wants to do I/O or SYSCALL (not-abortable)?

- How do we transactify existing lock based programs?
  - Replace acquire with begin_trans does not always work

- Several different kinds of transaction semantics
  - Are transactions atomic relative to code outside of transactions?

- Do we want transactions in hardware or in software?
  - What we just saw is hardware transactional memory (HTM)

- That’s what these research groups are looking at
  - Best-effort hardware TM: Azul systems, Sun’s Rock processor
Speculative Lock Elision

Processor 0

```c
acquire(accts[37].lock); // don't actually set lock to 1
// begin tracking read/write sets
// CRITICAL_SECTION
// check read set
// no conflicts? Commit, don't actually set lock to 0
// conflicts? Abort, retry by acquiring lock
release(accts[37].lock);
```

• Alternately, keep the locks, but...
• ... speculatively transactify lock-based programs in hardware
  • **Speculative Lock Elision (SLE)** [Rajwar+, MICRO’01]
    • Captures most of the advantages of transactional memory...
      + No need to rewrite programs
      + Can always fall back on lock-based execution (overflow, I/O, etc.)
Roadmap Checkpoint

- Thread-level parallelism (TLP)
- Shared memory model
  - Multiplexed uniprocessor
  - Hardware multithreading
  - Multiprocessing
- Synchronization
  - Lock implementation
  - Locking gotchas
- Cache coherence
  - Bus-based protocols
  - Directory protocols
- Memory consistency models
Recall: Simplest Multiprocessor

- What if we don’t want to share the L1 caches?
  - Bandwidth and latency issue

- Solution: use per-processor ("private") caches
  - Coordinate them with a Cache Coherence Protocol
Shared-Memory Multiprocessors

- **Conceptual model**
  - The shared-memory abstraction
  - Familiar and feels natural to programmers
  - Life would be easy if systems actually looked like this...
Shared-Memory Multiprocessors

- ...but systems actually look more like this
  - Processors have caches
  - Memory may be physically distributed
  - Arbitrary interconnect
Revisiting Our Motivating Example

- Two $100 withdrawals from account #241 at two ATMs
  - Each transaction maps to thread on different processor
  - Track `accts[241].bal` (address is in $r3)
No-Cache, No-Problem

- Scenario I: processors have no caches
  - No problem

<table>
<thead>
<tr>
<th>Processor 0</th>
<th>Processor 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0: addi $r3,$r1,&amp;accts</td>
<td>CPU0</td>
</tr>
<tr>
<td>1: lw $r4,0($r3)</td>
<td></td>
</tr>
<tr>
<td>2: blt $r4,$r2,6</td>
<td></td>
</tr>
<tr>
<td>3: sub $r4,$r4,$r2</td>
<td></td>
</tr>
<tr>
<td>4: sw $r4,0($r3)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CPU0</th>
<th>CPU1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$500</td>
<td>$500</td>
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<tr>
<td>$500</td>
<td>$500</td>
</tr>
<tr>
<td>$400</td>
<td>$400</td>
</tr>
<tr>
<td>$300</td>
<td>$300</td>
</tr>
</tbody>
</table>
### Cache Incoherence

- **Scenario II(a):** processors have write-back caches
  - Potentially 3 copies of `accts[241].bal`: memory, two caches
  - Can get incoherent (inconsistent)

<table>
<thead>
<tr>
<th>Processor 0</th>
<th>Processor 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0: addi $r3,$r1,&amp;accts</td>
<td></td>
</tr>
<tr>
<td>1: lw $r4,0($r3)</td>
<td></td>
</tr>
<tr>
<td>2: blt $r4,$r2,6</td>
<td></td>
</tr>
<tr>
<td>3: sub $r4,$r4,$r2</td>
<td></td>
</tr>
<tr>
<td>4: sw $r4,0($r3)</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>CPU0</th>
<th>CPU1</th>
<th>Mem</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$500</td>
</tr>
<tr>
<td>$500</td>
<td>$500</td>
<td></td>
</tr>
<tr>
<td>$400</td>
<td>$500</td>
<td>$500</td>
</tr>
<tr>
<td>$400</td>
<td>$400</td>
<td>$500</td>
</tr>
</tbody>
</table>
Write-Through Doesn’t Fix It

- **Scenario II(b):** processors have write-through caches
  - This time only two (different) copies of `accts[241].bal`
  - No problem? What if another withdrawal happens on processor 0?
What To Do?

- No caches?
  - Too slow

- Make shared data uncachable?
  - Faster, but still too slow
    - Entire `accts` database is technically “shared”

- Flush all other caches on writes to shared data?
  - Can work well in some cases, but can make caches ineffective

- **Hardware cache coherence**
  - Rough goal: all caches have same data at all times
    + Minimal flushing, maximum caching → best performance
Bus-based Multiprocessor

- Simple multiprocessors use a bus
  - All processors see all requests at the same time, same order
- Memory
  - Single memory module, -or-
  - Banked memory module
Hardware Cache Coherence

- **Coherence**: all copies have same data at all times
- **Coherence controller**: Examines bus traffic (addresses and data), executes coherence protocol, what to do with local copy when you see different things happening on bus
- **Each processors runs a state machine**
- Three processor-initiated events
  - **Ld**: load  **St**: store  **WB**: write-back
- Two remote-initiated events
  - **LdMiss**: read miss from another processor
  - **StMiss**: write miss from another processor
VI (MI) Coherence Protocol

- **VI (valid-invalid) protocol**: aka “MI”
  - Two states (per block in cache)
    - **V (valid)**: have block
    - **I (invalid)**: don’t have block
      + Can implement with valid bit

- Protocol diagram (left & next slide)
  - Summary
    - If anyone wants to read/write block
    - Give it up: transition to I state
    - Write-back if your own copy is dirty

- This is an **invalidate protocol**

- **Update protocol**: copy data, don’t invalidate
  - Sounds good, but uses too much bandwidth
### VI Protocol State Transition Table

<table>
<thead>
<tr>
<th>State</th>
<th>This Processor</th>
<th>Other Processor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load</td>
<td>Store</td>
</tr>
<tr>
<td>Invalid (I)</td>
<td>Load Miss → V</td>
<td>Store Miss → V</td>
</tr>
<tr>
<td>Valid (V)</td>
<td>Hit</td>
<td>Hit</td>
</tr>
</tbody>
</table>

- Rows are “states”
  - I vs V
- Columns are “events”
  - Writeback events not shown
- Memory controller not shown
  - **Memory sends data when no processor responds**
**VI Protocol (Write-Back Cache)**

- **lw** by processor 1 generates an “other load miss” event (LdMiss)
- Processor 0 responds by sending its dirty copy, transitioning to **I**

### Instructions

#### Processor 0
1. addi $r3,$r1,&accts
2. lw $r4,0($r3)
3. blt $r4,$r2,6
4. sub $r4,$r4,$r2
5. sw $r4,0($r3)

#### Processor 1
0: addi $r3,$r1,&accts
1: lw $r4,0($r3)
2: blt $r4,$r2,6
3: sub $r4,$r4,$r2
4: sw $r4,0($r3)

<table>
<thead>
<tr>
<th>CPU0</th>
<th>CPU1</th>
<th>Mem</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>500</td>
</tr>
<tr>
<td>V:500</td>
<td></td>
<td>500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V:400</td>
<td></td>
<td>500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V:300</td>
<td></td>
<td>400</td>
</tr>
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<td></td>
<td></td>
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</tr>
</tbody>
</table>
VI → MSI

- **VI protocol is inefficient**
  - Only one cached copy allowed in entire system
  - Multiple copies can’t exist even if read-only
    - Not a problem in example
    - Big problem in reality
- **MSI (modified-shared-invalid)**
  - Fixes problem: splits “V” state into two states
    - **M (modified)**: local dirty copy
    - **S (shared)**: local clean copy
  - Allows **either**
    - Multiple read-only copies (S-state) --OR--
    - Single read/write copy (M-state)
## MSI Protocol State Transition Table

<table>
<thead>
<tr>
<th>State</th>
<th>This Processor</th>
<th>Other Processor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load</td>
<td>Store</td>
</tr>
<tr>
<td>Invalid (I)</td>
<td>Load Miss $\rightarrow$ S</td>
<td>Store Miss $\rightarrow$ M</td>
</tr>
<tr>
<td>Shared (S)</td>
<td>Hit</td>
<td>Upgrade Miss $\rightarrow$ M</td>
</tr>
<tr>
<td>Modified (M)</td>
<td>Hit</td>
<td>Hit</td>
</tr>
</tbody>
</table>

- $M \rightarrow S$ transition also updates memory
  - After which memory will respond (as all processors will be in S)
MSI Protocol (Write-Back Cache)

Processor 0
0: addi $r3,$r1,&accts
1: lw $r4,0($r3)
2: blt $r4,$r2,6
3: sub $r4,$r4,$r2
4: sw $r4,0($r3)

Processor 1
0: addi $r3,$r1,&accts
1: lw $r4,0($r3)
2: blt $r4,$r2,6
3: sub $r4,$r4,$r2
4: sw $r4,0($r3)

- **lw** by processor 1 generates a “other load miss” event (LdMiss)
  - Processor 0 responds by sending its dirty copy, transitioning to S
- **sw** by processor 1 generates a “other store miss” event (StMiss)
  - Processor 0 responds by transitioning to I
Cache Coherence and Cache Misses

- Coherence introduces two new kinds of cache misses
  - **Upgrade miss**
    - On stores to read-only blocks
    - Delay to acquire write permission to read-only block
  - **Coherence miss**
    - Miss to a block evicted by another processor’s requests
- Making the cache larger…
  - Doesn’t reduce these type of misses
  - So, as cache grows large, these sorts of misses dominate
- **False sharing**
  - Two or more processors sharing parts of the same block
  - But *not* the same bytes within that block (no actual sharing)
  - Creates pathological “ping-pong” behavior
  - Careful data placement may help, but is difficult
Snooping Example: Step #1

**Cache**

<table>
<thead>
<tr>
<th>P0</th>
<th>P1</th>
<th>P2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Addr</strong></td>
<td><strong>Data</strong></td>
<td><strong>State</strong></td>
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</tr>
</tbody>
</table>

**Load A**

**Miss!**

**Bus**

**Shared Cache**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000</td>
<td>Modified</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>Idle</td>
</tr>
</tbody>
</table>

**Memory**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
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</tbody>
</table>
Snooping Example: Step #2

<table>
<thead>
<tr>
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<th>State</th>
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<tr>
<th>P₀</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Load A</td>
<td></td>
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</table>

<table>
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<th>Cache</th>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>500</td>
<td>M</td>
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</table>

<table>
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<table>
<thead>
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<th>Cache</th>
<th>Addr</th>
<th>Data</th>
<th>State</th>
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<table>
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<table>
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<th>Cache</th>
<th>Addr</th>
<th>Data</th>
<th>State</th>
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<table>
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</table>

<table>
<thead>
<tr>
<th>Shared Cache</th>
<th>Addr</th>
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<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>1000</td>
<td>Modified</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0</td>
<td>Idle</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Memory</th>
<th>Addr</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0</td>
</tr>
</tbody>
</table>
Snooping Example: Step #3

- **P₀**
  - Cache:
    - Addr | Data | State
    - --   | --   | --
    - --   | --   | --

- **P₁**
  - Cache:
    - Addr | Data | State
    - A    | 500  | S
    - --   | --   | --

- **P₂**
  - Cache:
    - Addr | Data | State
    - --   | --   | --
    - --   | --   | --

**Load A**

**Response:** Addr=A, Data=500

- **Bus**

- **Shared Cache**
  - Addr | Data | State
  - A    | 1000 | Modified
  - B    | 0    | Idle

- **Memory**
  - A    | 1000
  - B    | 0
Snooping Example: Step #4

**Cache**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<td>S</td>
</tr>
<tr>
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</table>

Load A

**Cache**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
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<td>500</td>
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<td>--</td>
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**Cache**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>--</td>
<td>--</td>
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<tr>
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<td>--</td>
</tr>
</tbody>
</table>

Response: Addr=A, Data=500

**Shared Cache**

<table>
<thead>
<tr>
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<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500</td>
<td>Shared, Dirty</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>Idle</td>
</tr>
</tbody>
</table>

**Memory**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
</tr>
</tbody>
</table>
Snooping Example: Step #5

Load A ← 500

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<th>Addr</th>
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<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₀</td>
<td>A</td>
<td>500</td>
<td>S</td>
</tr>
<tr>
<td></td>
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</table>

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<tbody>
<tr>
<td>P₁</td>
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<td>S</td>
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<table>
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<tbody>
<tr>
<td>P₂</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shared Cache</th>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500</td>
<td></td>
<td>Shared, Dirty</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td></td>
<td>Idle</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Memory</th>
<th>Addr</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Snooping Example: Step #6

<table>
<thead>
<tr>
<th>Cache</th>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500</td>
<td>S</td>
<td>Miss!</td>
</tr>
<tr>
<td>P_0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Store 400 -> A

<table>
<thead>
<tr>
<th>Cache</th>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>P_1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cache</th>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>P_2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bus</th>
<th></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Shared Cache</th>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500</td>
<td>S</td>
<td>Shared, Dirty</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>Idle</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Memory</th>
<th>Addr</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

CIS 371 (Martin): Multicore
Snooping Example: Step #7

P_0

Miss!

UpgradeMiss: Addr=A

P_1

P_2

Cache

Addr | Data | State
---|---|---
A | 500 | S
-- | -- | --

Cache

Addr | Data | State
---|---|---
A | 500 | S
-- | -- | --

Cache

Addr | Data | State
---|---|---
-- | -- | --
-- | -- | --

Cache

Addr | Data | State
---|---|---
A | 500 | Shared, Dirty
B | 0 | Idle

Memory

Addr | Data
---|---
A | 1000
B | 0
Snooping Example: Step #8

- **P₀**
  - Store 400 -> A
  - Cache:
    - Addr: A
      - Data: 500
      - State: S
    - Addr: 
      - Data: 
      - State: 
- **P₁**
  - Cache:
    - Addr: A
      - Data: --
      - State: I
    - Addr: 
      - Data: 
      - State: 
- **P₂**
  - Cache:
    - Addr: 
      - Data: 
      - State: 
    - Addr: 
      - Data: 
      - State: 

UpgradeMiss: Addr=A

**Bus**

**Shared Cache**

- Addr: A
  - Data: 500
  - State: Modified
- Addr: B
  - Data: 0
  - State: Idle

**Memory**

- A: 1000
- B: 0
Snooping Example: Step #9

<table>
<thead>
<tr>
<th>Cache</th>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₀</td>
<td>A</td>
<td>500</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Miss!

<table>
<thead>
<tr>
<th>Cache</th>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁</td>
<td>A</td>
<td>--</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cache</th>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₂</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Store 400 -> A

<table>
<thead>
<tr>
<th>Shared Cache</th>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>500</td>
<td>Modified</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0</td>
<td>Idle</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Memory</th>
<th>Addr</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0</td>
</tr>
</tbody>
</table>

CIS 371 (Martin): Multicore
Snooping Example: Step #10

P0

Cache

Addr | Data | State
--- | --- | ---
A | 400 | M
-- | -- | --

Store 400 -> A

Miss!

P1

Cache

Addr | Data | State
--- | --- | ---
A | -- | I
-- | -- | --

P2

Cache

Addr | Data | State
--- | --- | ---
-- | -- | --
-- | -- | --

Bus

Shared Cache

Addr | Data | State
--- | --- | ---
A | 500 | Modified
B | 0 | Idle

Memory

Addr | Data
--- | ---
A | 1000
B | 0

CIS 371 (Martin): Multicore
Exclusive Clean Protocol Optimization

- Most modern protocols also include **E (exclusive)** state
  - Interpretation: “I have the only cached copy, and it’s a **clean** copy”
  - Why would this state be useful?

```
Processor 0                      Processor 1
0:  addi $r3,$r1,&accts          CPU0  CPU1  Mem
1:  lw  $r4,0($r3)                CPU0  CPU1  Mem
2:  blt  $r4,$r2,6
3:  sub  $r4,$r4,$r2
4:  sw  $r4,0($r3)  (No miss!)  M:400  500
```
# Mesi Protocol State Transition Table

<table>
<thead>
<tr>
<th>State</th>
<th>This Processor</th>
<th>Other Processor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load</td>
<td>Store</td>
<td>Load Miss</td>
</tr>
<tr>
<td>Invalid (I)</td>
<td>Miss ➔ S or E</td>
<td>Miss ➔ M</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Store Miss</td>
</tr>
<tr>
<td>Shared (S)</td>
<td>Hit</td>
<td>Upg Miss ➔ M</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exclusive (E)</td>
<td>Hit</td>
<td>Hit ➔ M</td>
<td>Send Data ➔ S</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Send Data ➔ I</td>
</tr>
<tr>
<td>Modified (M)</td>
<td>Hit</td>
<td>Hit</td>
<td>Send Data ➔ S</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Send Data ➔ I</td>
</tr>
</tbody>
</table>

- Load misses lead to “E” if no other processors is caching the block
Snooping Bandwidth Scaling Problems

- Coherence events generated on...
  - L2 misses (and writebacks)
- Problem#1: \( N^2 \) bus traffic
  - All N processors send their misses to all N-1 other processors
  - Assume: 2 IPC, 2 Ghz clock, 0.01 misses/insn per processor
  - 0.01 misses/insn * 2 insn/cycle * 2 cycle/ns * 64 B blocks
    \[= 2.56 \text{ GB/s... per processor} \]
  - With 16 processors, that’s 40 GB/s! With 128 that’s 320 GB/s!!
  - You can use multiple buses... but that complicates the protocol
- Problem#2: \( N^2 \) processor snooping bandwidth
  - 0.01 events/insn * 2 insn/cycle = 0.02 events/cycle per processor
  - 16 processors: 0.32 bus-side tag lookups per cycle
    - Add 1 extra port to cache tags? Okay
  - 128 processors: 2.56 tag lookups per cycle! 3 extra tag ports?
“Scalable” Cache Coherence

- Part I: **bus bandwidth**
  - Replace non-scalable bandwidth substrate (bus)...
  - ...with scalable one (point-to-point network, e.g., mesh)

- Part II: **processor snooping bandwidth**
  - Most snoops result in no action
  - Replace non-scalable broadcast protocol...
  - ...with scalable **directory protocol** (only notify processors that care)
Point-to-Point Interconnects

- Single “bus” does not scale to larger core counts
  - Also poor electrical properties (long wires, high capacitance, etc.)
- Alternative: on-chip interconnection network
  - Routers move packets over short point-to-point links
  - Examples: on-chip mesh or ring interconnection networks
- Used within a multicore chip
  - Each “node”: a core, L1/L2 caches, and a “bank” (1/nth) of the L3 cache
  - Multiple memory controllers (which talk to off-chip DRAM)
- Can also connect arbitrarily large number of chips
  - Massively parallel processors (MPPs)
  - Distributed memory: non-uniform memory architecture (NUMA)
Directory Coherence Protocols

- **Directories**: non-broadcast coherence protocol
  - Extend memory (or shared cache) to track caching information
  - For each physical cache block, track:
    - **Owner**: which processor has a dirty copy (I.e., M state)
    - **Sharers**: which processors have clean copies (I.e., S state)
  - Processor sends coherence event to directory
    - Directory sends events only to processors *as needed*
  - Avoids non-scalable broadcast used by snooping protocols
  - For multicore with shared L3 cache, put directory info in cache tags

- For high-throughput, directory can be banked/partitioned
  - Use address to determine which bank/module holds a given block
    - That bank/module is called the “home” for the block
MSI Directory Protocol

- Processor side
  - Directory follows its own protocol
- Similar to bus-based MSI
  - Same three states
  - Same five actions (keep BR/BW names)
  - Minus red arcs/actions
    - Events that would not trigger action anyway
      + Directory won’t bother you unless you need to act
MSI Directory Protocol

- **ld** by P1 sends BR to directory
  - Directory sends BR to P0, P0 sends P1 data, does WB, goes to **S**
- **st** by P1 sends BW to directory
  - Directory sends BW to P0, P0 goes to **I**
Directory Example: Step #1

P₀

Cache

Addr | Data | State
--- | --- | ---
-- | -- | --
-- | -- | --

Load A

Miss!

P₁

Cache

Addr | Data | State
--- | --- | ---
A | 500 | Modified
-- | -- | --

P₂

Cache

Addr | Data | State
--- | --- | ---
-- | -- | --
-- | -- | --

Point-to-Point Interconnect

Shared Cache

Addr | Data | State | Sharers
--- | --- | --- | ---
A | 1000 | Modified | P₁
B | 0 | Idle | --

Memory

Addr | Data
--- | ---
A | 1000
B | 0
Directory Example: Step #2

**P₀**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

**Load A**

**P₁**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500</td>
<td>M</td>
</tr>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

**LdMiss: Addr=A**

**P₂**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

**Point-to-Point Interconnect**

**Shared Cache**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
<th>Sharers</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000</td>
<td>Blocked</td>
<td>P₁</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>Idle</td>
<td>--</td>
</tr>
</tbody>
</table>

**LdMissForward: Addr=A, Req=P₀**

**Memory**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
</tr>
</tbody>
</table>
Directory Example: Step #3

**Cache**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

**Cache**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500</td>
<td>S</td>
</tr>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

**Cache**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

**Load A**

**Response:** Addr=A, Data=500

**Point-to-Point Interconnect**

**Shared Cache**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
<th>Sharers</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000</td>
<td>Blocked</td>
<td>P1</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>Idle</td>
<td>--</td>
</tr>
</tbody>
</table>

**Memory**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
</tr>
</tbody>
</table>
Directory Example: Step #4

Load A

Response: Addr=A, Data=500

Point-to-Point Interconnect

CIS 371 (Martin): Multicore
Directory Example: Step #5

Load A ← 500

Unblock: Addr=A, Data=500

Point-to-Point Interconnect

Shared Cache

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
<th>Sharers</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500</td>
<td>Shared, Dirty</td>
<td>P0, P1</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>Idle</td>
<td></td>
</tr>
</tbody>
</table>

Memory

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
</tr>
</tbody>
</table>
Directory Example: Step #6

Point-to-Point Interconnect

Cache

P₀

Addr  Data  State
A  500  S
--  --  --

Miss!

P₁

Addr  Data  State
A  500  S
--  --  --

P₂

Addr  Data  State
--  --  --
--  --  --

Store 400 -> A

Miss!

Point-to-Point Interconnect

Shared Cache

Addr  Data  State  Sharers
A  500  Shared, Dirty  P₀, P₁
B  0  Idle  --

Memory

Addr  Data
A  1000
B  0

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Directory Example: Step #7

**Point-to-Point Interconnect**

**Cache**

- **P0**
  - Store 400 -> A
  - UpgradeMiss: Addr=A
  - Cache:
    | Addr | Data | State |
    |------|------|-------|
    | A    | 500  | S     |
    | --   | --   | --    |

- **P1**
  - Cache:
    | Addr | Data | State |
    |------|------|-------|
    | A    | 500  | S     |
    | --   | --   | --    |

- **P2**
  - Cache:
    | Addr | Data | State |
    |------|------|-------|
    | --   | --   | --    |
    | --   | --   | --    |

**Shared Cache**

- **Addr** | **Data** | **State** | **Sharers**
- A         | 500     | Blocked   | P0, P1
- B         | 0       | Idle      | --

**Memory**

- **Addr** | **Data**
- A         | 1000
- B         | 0

**Invalidate**: Addr=A, Req=P0, Acks=1
Directory Example: Step #8

###!(:P0)

**Cache**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500</td>
<td>S</td>
</tr>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Store 400 -> A

---

###!(:P1)

**Cache**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>--</td>
<td>I</td>
</tr>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

---

###!(:P2)

**Cache**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

---

**Shared Cache**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
<th>Sharers</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500</td>
<td>Blocked</td>
<td>P0, P1</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>Idle</td>
<td>--</td>
</tr>
</tbody>
</table>

---

**Memory**

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
</tr>
</tbody>
</table>

---

Ack: Addr=A, Acks=1

Invalidate: Addr=A, Req=P0, Acks=1
Directory Example: Step #9

Point-to-Point Interconnect

Cache

Store 400 -> A

P0

Addr | Data | State
---|---|---
A | 500 | M
-- | -- | --

P1

Addr | Data | State
---|---|---
A | -- | I
-- | -- | --

P2

Addr | Data | State
---|---|---
-- | -- | --
-- | -- | --

Point-to-Point Interconnect

Shared Cache

Addr | Data | State | Sharers
---|---|---|---
A | 500 | Blocked | P0, P1
B | 0 | Idle | --

Memory

Addr | Data
---|---
A | 1000
B | 0
Directory Example: Step #10

Cache

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>400</td>
<td>M</td>
</tr>
<tr>
<td>--</td>
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</tr>
</tbody>
</table>

Store 400 -> A

Point-to-Point Interconnect

Unblock: Addr=A

Cache

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>--</td>
<td>I</td>
</tr>
<tr>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Cache

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Shared Cache

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
<th>State</th>
<th>Sharers</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>500</td>
<td>Modified</td>
<td>P0</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>Idle</td>
<td>--</td>
</tr>
</tbody>
</table>

Memory

<table>
<thead>
<tr>
<th>Addr</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
</tr>
</tbody>
</table>
Directory Flip Side: Latency

- Directory protocols
  - Lower bandwidth consumption → more scalable
    - Longer latencies

- Two read miss situations

- Unshared: get data from memory
  - Snooping: 2 hops (P0→memory→P0)
  - Directory: 2 hops (P0→memory→P0)

- Shared or exclusive: get data from other processor (P1)
  - Assume cache-to-cache transfer optimization
  - Snooping: 2 hops (P0→P1→P0)
    - Directory: 3 hops (P0→memory→P1→P0)
  - Common, with many processors high probability someone has it
Coherence Recap & Alternatives

- Keeps caches “coherent”
  - Load returns the most recent stored value by any processor
  - And thus keeps caches transparent to software

- Directory-based protocol scale coherence
  - Perhaps to 1000s of cores
  - See “Why On-Chip Cache Coherence is Here to Stay”

- Alternatives to cache coherence
  - #1: no caching of shared data (slow)
  - #2: requiring software to explicitly “flush” data (hard to use)
    - Using some new instructions
  - #3: message passing (programming without shared memory)
    - Used in clusters of machines for high-performance computing
Roadmap Checkpoint

- Thread-level parallelism (TLP)
- Shared memory model
  - Multiplexed uniprocessor
  - Hardware multithreading
  - Multiprocessing
- Synchronization
  - Lock implementation
  - Locking gotchas
- Cache coherence
  - Bus-based protocols
  - Directory protocols
- **Memory consistency models**
Shared Memory Example #1

• **Initially: all variables zero** (that is, $x$ is 0, $y$ is 0)

<table>
<thead>
<tr>
<th>thread 1</th>
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<tbody>
<tr>
<td>store 1 → $y$</td>
<td>store 1 → $x$</td>
</tr>
<tr>
<td>load $x$</td>
<td>load $y$</td>
</tr>
</tbody>
</table>

• What value pairs can be read by the two loads? ($x$, $y$)
Shared Memory Example #2

- **Initially: all variables zero** (that is, $x$ is 0, $y$ is 0)

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<thead>
<tr>
<th>thread 1</th>
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<tbody>
<tr>
<td>store 1 $\rightarrow$ y</td>
<td>load $x$</td>
</tr>
<tr>
<td>store 1 $\rightarrow$ x</td>
<td>load $y$</td>
</tr>
</tbody>
</table>

- What value pairs can be read by the two loads? $(x, y)$
Shared Memory Example #3

- Initially: all variables zero (flag is 0, a is 0)

<table>
<thead>
<tr>
<th>thread 1</th>
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<tbody>
<tr>
<td>store 1 → a</td>
<td>while (flag == 0) { }</td>
</tr>
<tr>
<td>store 1 → flag</td>
<td>load a</td>
</tr>
</tbody>
</table>

- What value can be read by “load a”?
“Answer” to Example #1

- Initially: all variables zero (that is, x is 0, y is 0)

<table>
<thead>
<tr>
<th>thread 1</th>
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</tr>
<tr>
<td>load \text{x}</td>
<td>load \text{y}</td>
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</tbody>
</table>

- What value pairs can be read by the two loads?

<p>| | | |</p>
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- What about (x=0, y=0)?
“Answer” to Example #2

- Initially: all variables zero (that is, \( x = 0 \), \( y = 0 \))

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- What value pairs can be read by the two loads?
  - \((x=1, y=1)\)
  - \((x=0, y=0)\)
  - \((x=0, y=1)\)

- Is \((x=1, y=0)\) allowed?
“Answer” to Example #3

• **Initially: all variables zero** (flag is 0, a is 0)

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• What value can be read by “load a”?  
  • “load a” can see the value “1”

• Can “load a” read the value zero?
What is Going On?

• Reordering of memory operations to different addresses!

• **In the compiler**
  • Compiler is generally allowed to re-order memory operations to different addresses
  • Many other compiler optimizations also cause problems

• **In the hardware**
  • To tolerate write latency
    • Processes don’t wait for writes to complete
    • And why should they? No reason on a uniprocessors
  • To simplify out-of-order execution
Memory Consistency

- **Memory coherence**
  - Creates globally uniform (consistent) view...
  - Of a single memory location (in other words: cache blocks)
    - Not enough
      - Cache blocks A and B can be individually consistent...
      - But inconsistent with respect to each other

- **Memory consistency**
  - Creates globally uniform (consistent) view...
  - Of all memory locations relative to each other

- Who cares? Programmers
  - Globally inconsistent memory creates mystifying behavior
Coherence vs. Consistency

A=0  flag=0
Processor 0
A=1;
flag=1;
Processor 1
while (!flag); // spin
print A;

- **Intuition says**: P1 prints A=1
- **Coherence says**: absolutely nothing
  - P1 can see P0’s write of flag before write of A!!! How?
    - P0 has a coalescing store buffer that reorders writes
    - Or out-of-order load execution
    - Or compiler reorders instructions
- Imagine trying to figure out why this code sometimes “works” and sometimes doesn’t
- **Real systems** are allowed to act in this strange manner
  - What is allowed? defined as part of the ISA and/or language
Why? To Hide Store Miss Latency

• Why? Why Allow Such Odd Behavior?
  • Reason #1: hiding store miss latency

• Recall (back from caching unit)
  • Hiding store miss latency
  • How? Store buffer

• Said it would complicate multiprocessors
  • Yes. It does.
Recall: Write Misses and Store Buffers

- Read miss?
  - Load can’t go on without the data, it must stall
- Write miss?
  - Technically, no instruction is waiting for data, why stall?

- **Store buffer**: a small buffer
  - Stores put address/value to store buffer, *keep going*
  - Store buffer writes stores to D$ in the background
  - Loads must search store buffer (in addition to D$)
  - Eliminates stalls on write misses (mostly)
  - Creates some problems (later)

- Store buffer vs. writeback-buffer
  - Store buffer: “in front” of D$, for hiding store misses
  - Writeback buffer: “behind” D$, for hiding writebacks
Two Kinds of Store Buffers

- FIFO (First-in, First-out) store buffers
  - All stores enter the store buffer, drain into the cache in-order
  - In an in-order processor...
    - Allows later loads to execute under store miss
  - In an out-of-order processor...
    - Instructions “commit” with older stores still in the store queue

- “Coalescing” store buffers
  - Organized like a mini-cache (tags, blocks, etc.)
    - But with per-byte valid bits
  - At commit, stores that miss the cache placed in store buffer
    - Stores that hit in the cache, written into cache
  - When the store miss returns, all stores to that address drain into the cache
    - That is, not necessarily in FIFO (first-in, first-out) order
Store Buffers & Consistency

Consider the following execution:

- Processor 0’s write to A, misses the cache. Put in store buffer.
- Processor 0 keeps going
- Processor 0 write “1” to flag hits, writes to the cache
- Processor 1 reads flag, misses cache, gets the value “1” from P0
- Processor 1 exits loop
- Processor 1 prints “0” for A (sees “old” value)

Ramification: store buffers can cause “strange” behavior
- How strange depends on lots of things

Out-of-order execution also can cause problems...
Simplifying Out-of-Order Execution

- Why? Why Allow Such Odd Behavior?
  - Reason #2: simplifying out-of-order execution

- One key benefit of out-of-order execution:
  - Out-of-order execution of loads to (same or different) addresses

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- Uh, oh.
Simplifying Out-of-Order Execution

- Two options:
  - Option #1: **allow** this sort of “odd” reordering
  - Option #2: hardware **detects & prevents** such reorderings

- How to prevent?
  - Scan the Load Queue (LQ) on stores from **other** threads
  - Flush and rollback on conflict

- How to detect these stores from other threads?
  - Leverage cache coherence!
  - As long as a block remains in a private per-core cache...
    - Another core can’t write to it!
  - Thus, anytime a block leaves the cache (invalidation or eviction)...
    - Scan the load queue. If any loads to the address have executed but not committed, squash the pipeline and restart
3 Classes of Memory Consistency Models

- **Sequential consistency (SC)** (MIPS, PA-RISC)
  - Formal definition of memory view programmers expect
  - 1. Processors see their own loads and stores in program order
  - 2. Processors see others’ loads and stores in program order
  - 3. All processors see same global load/store ordering
  - Corresponds to some sequential interleaving of uniprocessor orders
  - **Indistinguishable from multi-programmed uni-processor**

- **Processor consistency (PC)** (x86, SPARC)
  - Allows a in-order (FIFO) store buffer
    - Stores can be deferred, but must be put into the cache in order

- **Release consistency (RC)** (ARM, Itanium, PowerPC)
  - Allows an un-ordered coalescing store buffer
    - Stores can be put into cache in any order
  - Loads re-ordered, too.
Answer to Example #1

- **Initially: all variables zero** (that is, x is 0, y is 0)

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- What about (x=0, y=0)? Yes! (for x86, SPARC, ARM, PowerPC)
Answer to Example #2

- Initially: all variables zero (that is, x is 0, y is 0)

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- What value pairs can be read by the two loads?
  - (x=1, y=1)
  - (x=0, y=0)
  - (x=0, y=1)

- Is (x=1, y=0) allowed?
  - Yes! (for ARM, PowerPC, Itanium, and Alpha)
  - No! (for Intel/AMD x86, Sun SPARC, IBM 370)
    - Assuming the compiler didn’t reorder anything...
Initial variables are zero (flag is 0, a is 0)

• What value can be read by “load a”?  
  • “load a” can see the value “1”  

• Can “load a” read the value zero? (same as last slide)
  • Yes! (for ARM, PowerPC, Itanium, and Alpha)
  • No! (for Intel/AMD x86, Sun SPARC, IBM 370)
    • Assuming the compiler didn’t reorder anything...
Restoring Order (Hardware)

- Sometimes we need ordering (mostly we don’t)
  - Prime example: ordering between “lock” and data
- How? insert **Fences (memory barriers)**
  - Special instructions, part of ISA
- Example
  - Ensure that loads/stores don’t cross lock acquire/release operation
    ```
    acquire
    fence
    critical section
    fence
    release
    ```
- How do fences work?
  - They stall execution until write buffers are empty
  - Makes lock acquisition and release slow(er)
- **Use synchronization library, don’t write your own**
Restoring Order (Software)

- These slides have focused mostly on hardware reordering
  - But the compiler also reorders instructions (reason #3)
- How do we tell the compiler to not reorder things?
  - Depends on the language...
- In Java:
  - The built-in “synchronized” constructs informs the compiler to limit its optimization scope (prevent reorderings across synchronization)
  - Or, programmer uses “volatile” keyword to explicitly mark variables
  - Java compiler also inserts the hardware-level ordering instructions
- In C/C++:
  - Much more murky, as language doesn’t define synchronization
  - Lots of hacks: “inline assembly”, volatile, atomic (newly proposed)
  - Programmer may need to explicitly insert hardware-level fences
- **Use synchronization library, don’t write your own**
Summary

- Explicit parallelism
- Shared memory model
  - Multiplexed uniprocessor
  - Hardware multithreading
  - Multiprocessing
- Synchronization
  - Lock implementation
  - Locking gotchas
- Cache coherence
  - VI, MSI, MESI
  - Bus-based protocols
  - Directory protocols
- Memory consistency