Summary of Last Week’s Lectures

- Memory Latency Tolerance
- Runahead Execution
- Wrong Path Effects
- Prefetching
Today

- Multiprocessors
- Memory Consistency
- Cache Coherence
Multiprocessors and Issues in Multiprocessing
Readings: Multiprocessing

- **Required**

- **Recommended**
Memory Consistency

- **Required**
Readings: Cache Coherence

- **Required**

- **Recommended:**
  - Culler and Singh, *Parallel Computer Architecture*
    - Chapter 5.1 (pp 269 – 283), Chapter 5.3 (pp 291 – 305)
  - P&H, *Computer Organization and Design*
    - Chapter 5.8 (pp 534 – 538 in 4th and 4th revised eds.)
ABSTRACT: Several forthcoming successors to DRAM have the intriguing property that they retain their content when power is lost. Wide availability of such memory raises the possibility that long-lived, pointer-rich data might be maintained directly in main memory, across program runs and even system crashes. Special care must be taken, however, to assure that the values in memory will be mutually consistent in the wake of a crash, given that caches write values back in arbitrary order. This talk will survey research currently under way at the University of Rochester that aims to - formally specify what it means for a persistent data structure to be implemented correctly, - implement failure atomicity at reasonable cost on current and future architectures, - protect memory-mapped persistent structures from buggy applications.
System crash can result in permanent data corruption in NVM
CRASH CONSISTENCY PROBLEM

Example: Add a node to a linked list

1. Link to next
2. Link to prev

System crash can result in inconsistent memory state
One Key Challenge in Persistent Memory

- How to ensure consistency of system/data if all memory is persistent?

- Two extremes
  - Programmer transparent: Let the system handle it
  - Programmer only: Let the programmer handle it

- Many alternatives in-between...
CURRENT SOLUTIONS

Explicit interfaces to manage consistency

– NV-Heaps [ASPLOS’11], BPFS [SOSP’09], Mnemosyne [ASPLOS’11]

```
AtomicBegin {
  Insert a new node;
} AtomicEnd;
```

Limits adoption of NVM

Have to rewrite code with clear partition between volatile and non-volatile data

Burden on the programmers

How do we make legacy code work?
A NEW APPROACH: ThyNVM

Goal:
Software transparent consistency in persistent memory systems
ThyNVM: Summary

A new hardware-based checkpointing mechanism

- **Checkpoints** at *multiple granularities* to reduce both checkpointing latency and metadata overhead
- **Overlaps** checkpointing and *execution* to reduce checkpointing latency
- **Adapts** to *DRAM and NVM* characteristics

Performs within *4.9%* of an *idealized DRAM* with zero cost consistency
More About ThyNVM

- Jinglei Ren, Jishen Zhao, Samira Khan, Jongmoo Choi, Yongwei Wu, and Onur Mutlu,

"ThyNVM: Enabling Software-Transparent Crash Consistency in Persistent Memory Systems"

Proceedings of the 48th International Symposium on Microarchitecture (MICRO), Waikiki, Hawaii, USA, December 2015.

[Slides (pptx) (pdf)] [Lightning Session Slides (pptx) (pdf)] [Poster (pptx) (pdf)]
[Source Code]

ThyNVM: Enabling Software-Transparent Crash Consistency in Persistent Memory Systems

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One Key Challenge in Persistent Memory

Programming Ease to Exploit Persistence
Tools/Libraries to Help Programmers

- Himanshu Chauhan, Irina Calciu, Vijay Chidambaram, Eric Schkufza, Onur Mutlu, and Pratap Subrahmanyanam, "NVMove: Helping Programmers Move to Byte-Based Persistence"

Proceedings of the 4th Workshop on Interactions of NVM/Flash with Operating Systems and Workloads (INFLOW), Savannah, GA, USA, November 2016.

[Slides (pptx) (pdf)]

NVMOVE: Helping Programmers Move to Byte-Based Persistence

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Multiprocessors and Issues in Multiprocessing
Remember: Flynn’s Taxonomy of Computers


- **SISD**: Single instruction operates on single data element
- **SIMD**: Single instruction operates on multiple data elements
  - Array processor
  - Vector processor
- **MISD**: Multiple instructions operate on single data element
  - Closest form: systolic array processor, streaming processor
- **MIMD**: Multiple instructions operate on multiple data elements (multiple instruction streams)
  - Multiprocessor
  - Multithreaded processor
Why Parallel Computers?

- **Parallelism:** Doing multiple things at a time
- **Things:** instructions, operations, tasks

**Main (or Original) Goal**

- Improve performance (Execution time or task throughput)
  - Execution time of a program governed by Amdahl’s Law

**Other Goals**

- Reduce power consumption
  - (4N units at freq F/4) consume less power than (N units at freq F)
  - Why?
- Improve cost efficiency and scalability, reduce complexity
  - Harder to design a single unit that performs as well as N simpler units
- **Improve dependability:** Redundant execution in space
Types of Parallelism and How to Exploit Them

- Instruction Level Parallelism
  - Different instructions within a stream can be executed in parallel
  - Pipelining, out-of-order execution, speculative execution, VLIW
  - Dataflow

- Data Parallelism
  - Different pieces of data can be operated on in parallel
  - SIMD: Vector processing, array processing
  - Systolic arrays, streaming processors

- Task Level Parallelism
  - Different “tasks/threads” can be executed in parallel
  - Multithreading
  - Multiprocessing (multi-core)
Task-Level Parallelism: Creating Tasks

- Partition a single problem into multiple related tasks (threads)
  - Explicitly: Parallel programming
    - Easy when tasks are natural in the problem
      - Web/database queries
    - Difficult when natural task boundaries are unclear
  - Transparently/implicitly: Thread level speculation
    - Partition a single thread speculatively

- Run many independent tasks (processes) together
  - Easy when there are many processes
    - Batch simulations, different users, cloud computing workloads
  - Does not improve the performance of a single task
Multiprocessing Fundamentals
Multiprocessor Types

- Loosely coupled multiprocessors
  - No shared global memory address space
  - Multicomputer network
    - Network-based multiprocessors
  - Usually programmed via message passing
    - Explicit calls (send, receive) for communication

- Tightly coupled multiprocessors
  - Shared global memory address space
  - Traditional multiprocessing: symmetric multiprocessing (SMP)
    - Existing multi-core processors, multithreaded processors
  - Programming model similar to uniprocessors (i.e., multitasking uniprocessor) except
    - Operations on shared data require synchronization
Main Design Issues in Tightly-Coupled MP

- **Shared memory synchronization**
  - How to handle locks, atomic operations

- **Cache coherence**
  - How to ensure correct operation in the presence of private caches

- **Memory consistency: Ordering of memory operations**
  - What should the programmer expect the hardware to provide?

- **Shared resource management**

- **Communication: Interconnects**
Main Programming Issues in Tightly-Coupled MP

- **Load imbalance**
  - How to partition a single task into multiple tasks

- **Synchronization**
  - How to synchronize (efficiently) between tasks
  - How to communicate between tasks
  - Locks, barriers, pipeline stages, condition variables, semaphores, atomic operations, ...

- **Ensuring correct operation while optimizing for performance**
Aside: Hardware-based Multithreading

- **Coarse grained**
  - Quantum based
  - Event based (switch-on-event multithreading), e.g., switch on L3 miss

- **Fine grained**
  - Cycle by cycle

- **Simultaneous**
  - Can dispatch instructions from multiple threads at the same time
  - Good for improving execution unit utilization
Limits of Parallel Speedup
Parallel Speedup Example

- \(a_4x^4 + a_3x^3 + a_2x^2 + a_1x + a_0\)

- Assume given inputs: \(x\) and each \(a_i\)

- Assume each operation 1 cycle, no communication cost, each op can be executed in a different processor

- How fast is this with a single processor?
  - Assume no pipelining or concurrent execution of instructions

- How fast is this with 3 processors?
\[ R = a_4 x^4 + a_3 x^3 + a_2 x^2 + a_1 x + a_0 \]

Single processor: 11 operations (data flow graph)

\[ T_1 = 11 \text{ cycles} \]
\[ R = a_4 x^4 + a_3 x^3 + a_2 x^2 + a_1 x + a_0 \]

Three processors: \( T_3 \) (execution with 3 proc.)

\[ T_3 = 5 \text{ cycles} \]
Speedup with 3 Processors

\[ T_3 = 5 \text{ cycles} \]

\[ \text{Speedup with 3 processors} = \frac{11}{5} = 2.2 \]

\[ \left( \frac{T_1}{T_3} \right) \]

Is this a fair comparison?
Revisiting the Single-Processor Algorithm

$T_1 = 8$ cycles

Speedup with 3 proc. = \( \frac{T_1^{\text{best}}}{T_3} = \frac{8}{5} = 1.6 \)
Superlinear Speedup

- Can speedup be greater than \( P \) with \( P \) processing elements?

- **Unfair comparisons**
  Compare best parallel algorithm to wimpy serial algorithm \( \rightarrow \) unfair

- **Cache/memory effects**
  More processors \( \rightarrow \) more cache or memory \( \rightarrow \) fewer misses in cache/mem
Utilization, Redundancy, Efficiency

- Traditional metrics
  - Assume all P processors are tied up for parallel computation

- Utilization: How much processing capability is used
  - $U = \frac{\text{(# Operations in parallel version)}}{\text{(processors x Time)}}$

- Redundancy: how much extra work is done with parallel processing
  - $R = \frac{\text{(# of operations in parallel version)}}{\text{(# operations in best single processor algorithm version)}}$

- Efficiency
  - $E = \frac{\text{(Time with 1 processor)}}{\text{(processors x Time with P processors)}}$
  - $E = \frac{U}{R}$
Utilization of a Multiprocessor

**Utility metrics.**

**Utilization:** How much processing capability we use

\[
U = \frac{\text{10 operations (in parallel version)}}{3 \text{ processors} \times 5 \text{ time units}} = \frac{10}{15}
\]

\[
U = \frac{\text{Ops with } p \text{ proc.}}{p \times T_p}
\]
Redundancy: How much extra work due to multiprocessing

\[
R = \frac{\text{Ops with } p \text{ proc. best}}{\text{Ops with 1 proc. best}} = \frac{10}{8}
\]

\[R \text{ is always } \geq 1\]

Efficiency: How much resource we use compared to how much resource we can get away with

\[
E = \frac{1. T_1^{\text{best}}}{p. T_p^{\text{best}}} \quad (\text{tying up 1 proc for } T_p \text{ time units})
\]

\[= \frac{8}{15} \quad (E = \frac{U}{R})\]
Amdahl’s Law and Caveats of Parallelism
Caveats of Parallelism (I)

Why the reality? (diminishing returns)

\[ T_P = \alpha \cdot \frac{T_1}{p} + (1-\alpha) \cdot T_1 \]

parallelizable part/fraction of the single-processor program

non-parallelizable part
Amdahl’s Law

\[
\text{Speedup with } p \text{ proc.} = \frac{T_1}{T_p} = \frac{1}{\frac{\alpha}{p} + (1-\alpha)}
\]

\[
\text{Speedup as } p \to \infty = \frac{1}{1 - \alpha} \rightarrow \text{bottleneck for parallel Speedup}
\]
Amdahl’s Law Implication 1

Adding more and more processors gives less and less benefit if $\alpha < 1$
Amdahl’s Law Implication 2

The benefit (speedup) is small until $\alpha \approx 1$.
Caveats of Parallelism (II)

- Amdahl’s Law
  - \( f \): Parallelizable fraction of a program
  - \( N \): Number of processors

\[
\text{Speedup} = \frac{1}{1 - f} + \frac{f}{N}
\]


- Maximum speedup limited by serial portion: Serial bottleneck

- Parallel portion is usually not perfectly parallel
  - **Synchronization** overhead (e.g., updates to shared data)
  - **Load imbalance** overhead (imperfect parallelization)
  - **Resource sharing** overhead (contention among \( N \) processors)
Sequential Bottleneck

![Graph showing speedup versus parallel fraction for different values of N (10, 100, 1000).](image)

- **N=10**
- **N=100**
- **N=1000**
Why the Sequential Bottleneck?

- Parallel machines have the sequential bottleneck

- Main cause: Non-parallelizable operations on data (e.g. non-parallelizable loops)
  
  $$\text{for } (i = 0 ; i < N; i++)$$
  

- There are other causes as well:
  - Single thread prepares data and spawns parallel tasks (usually sequential)
Another Example of Sequential Bottleneck (I)

Another Example of Sequential Bottleneck (II)

Bottlenecks in Parallel Portion

- **Synchronization**: Operations manipulating shared data cannot be parallelized
  - Locks, mutual exclusion, barrier synchronization
  - **Communication**: Tasks may need values from each other
    - Causes thread serialization when shared data is contended

- **Load Imbalance**: Parallel tasks may have different lengths
  - Due to imperfect parallelization or microarchitectural effects
  - Reduces speedup in parallel portion

- **Resource Contention**: Parallel tasks can share hardware resources, delaying each other
  - Replicating all resources (e.g., memory) expensive
  - Additional latency not present when each task runs alone
Bottlenecks in Parallel Portion: Another View

- Threads in a multi-threaded application can be inter-dependent
  - As opposed to threads from different applications

- Such threads can synchronize with each other
  - Locks, barriers, pipeline stages, condition variables, semaphores, ...

- Some threads can be on the critical path of execution due to synchronization; some threads are not

- Even within a thread, some “code segments” may be on the critical path of execution; some are not
Remember: Critical Sections

- Enforce mutually exclusive access to shared data
- Only one thread can be executing it at a time
- Contended critical sections make threads wait → threads causing serialization can be on the critical path

Each thread:
loop {
  Compute
  lock(A)
  Update shared data
  unlock(A)
}
Remember: Barriers

- Synchronization point
- Threads have to wait until all threads reach the barrier
- Last thread arriving to the barrier is on the critical path

Each thread:

```java
loop1 {
    Compute
}

barrier

loop2 {
    Compute
}
```
Remember: Stages of Pipelined Programs

- Loop iterations are statically divided into code segments called *stages*
- Threads execute stages on different cores
- Thread executing the slowest stage is on the critical path

```
loop {
    Compute1
    Compute2
    Compute3
}
```
Difficulty in Parallel Programming

- Little difficulty if parallelism is natural
  - “Embarrassingly parallel” applications
  - Multimedia, physical simulation, graphics
  - Large web servers, databases?

- Difficulty is in
  - Getting parallel programs to work correctly
  - Optimizing performance in the presence of bottlenecks

- Much of parallel computer architecture is about
  - Designing machines that overcome the sequential and parallel bottlenecks to achieve higher performance and efficiency
  - Making programmer’s job easier in writing correct and high-performance parallel programs
Memory Ordering in Multiprocessors
Readings: Memory Consistency

- **Required**

- **Recommended**
Memory Consistency vs. Cache Coherence

- **Consistency** is about ordering of all memory operations from different processors (i.e., to different memory locations)
  - Global ordering of accesses to all memory locations

- **Coherence** is about ordering of operations from different processors to the same memory location
  - Local ordering of accesses to each cache block
Difficulties of Multiprocessing

- Much of **parallel computer architecture** is about
  
  - Designing machines that overcome the sequential and parallel bottlenecks to achieve higher performance and efficiency
  
  - Making programmer’s job easier in writing correct and high-performance parallel programs
Ordering of Operations

- Operations: A, B, C, D
  - In what order should the hardware execute (and report the results of) these operations?

- A contract between programmer and microarchitect
  - Specified by the ISA

- Preserving an “expected” (more accurately, “agreed upon”) order simplifies programmer’s life
  - Ease of debugging; ease of state recovery, exception handling

- Preserving an “expected” order usually makes the hardware designer’s life difficult
  - Especially if the goal is to design a high performance processor: Recall load-store queues in out of order execution and their complexity
Memory Ordering in a Single Processor

- Specified by the von Neumann model
- Sequential order
  - Hardware *executes* the load and store operations in the order specified by the sequential program

- Out-of-order execution does not change the semantics
  - Hardware *retires* (reports to software the results of) the load and store operations in the order specified by the sequential program

- Advantages: 1) Architectural state is precise within an execution.
  2) Architectural state is consistent across different runs of the program
     → Easier to debug programs

- Disadvantage: Preserving order adds overhead, reduces performance, increases complexity, reduces scalability
Memory Ordering in a Dataflow Processor

- A memory operation executes when its operands are ready.

- Ordering specified only by data dependencies.

- Two operations can be executed and retired in any order if they have no dependency.

- Advantage: Lots of parallelism $\rightarrow$ high performance.

- Disadvantages:
  - Precise state is very hard to maintain (No specified order) $\rightarrow$ Very hard to debug.
  - Order can change across runs of the same program $\rightarrow$ Very hard to debug.
Memory Ordering in a MIMD Processor

- Each processor’s memory operations are in sequential order with respect to the “thread” running on that processor (assume each processor obeys the von Neumann model).

- Multiple processors execute memory operations concurrently.

- How does the memory see the order of operations from all processors?
  - In other words, what is the ordering of operations across different processors?
Why Does This Even Matter?

- Ease of debugging
  - It is nice to have the same execution done at different times to have the same order of execution → Repeatability

- Correctness
  - Can we have incorrect execution if the order of memory operations is different from the point of view of different processors?

- Performance and overhead
  - Enforcing a strict “sequential ordering” can make life harder for the hardware designer in implementing performance enhancement techniques (e.g., OoO execution, caches)
When Could Order Affect Correctness?

- When protecting shared data
Protecting Shared Data

- Threads are not allowed to update shared data concurrently
  - For correctness purposes

- Accesses to shared data are encapsulated inside critical sections or protected via synchronization constructs (locks, semaphores, condition variables)

- Only one thread can execute a critical section at a given time
  - Mutual exclusion principle

- A multiprocessor should provide the correct execution of synchronization primitives to enable the programmer to protect shared data
Supporting Mutual Exclusion

- Programmer needs to make sure mutual exclusion (synchronization) is correctly implemented
  - We will assume this
  - But, correct parallel programming is an important topic
    - http://www.cs.utexas.edu/users/EWD/transcriptions/EWD01xx/EWD123.html
    - See Dekker’s algorithm for mutual exclusion

- Programmer relies on hardware primitives to support correct synchronization
- If hardware primitives are not correct (or unpredictable), programmer’s life is tough
- If hardware primitives are correct but not easy to reason about or use, programmer’s life is still tough
Assume $P_1$ is in critical section.
Intuitively, it must have executed A,
which means $F_1$ must be 1 (as A happens before B),
which means $P_2$ should not enter the critical section.
A Question

- Can the two processors be in the critical section at the same time given that they both obey the von Neumann model?
- Answer: yes
An Incorrect Result (due to an implementation that does not provide sequential consistency)

Time 0:
- $P_1$ executes $A$ (set $F_1 = 1$)
- $A$ is sent to memory
- $P_2$ executes $X$ (set $F_2 = 1$)
- $X$ is sent to memory

$S + F_1$ complete (from $P_1$'s view)

$S + F_2$ complete (from $P_2$'s view)
Both Processors in Critical Section

\[ \text{time 0:} \quad P_1 \text{ executes } A \quad \text{ (set } F_1 = 1) \quad D + F_1 \text{ complete (from } P_1 \text{'s view)} \]
\[ \text{A is sent to memory} \]

\[ \text{time 1:} \quad P_2 \text{ executes } X \quad \text{ (set } F_2 = 1) \quad D + F_2 \text{ complete (from } P_2 \text{'s view)} \]
\[ \text{X is sent to memory} \]

\[ \text{time 1:} \quad P_1 \text{ executes } B \quad \text{ (test } F_2 == 0) \quad \text{ld } F_2 \text{ started} \]
\[ \text{B is sent to memory} \]

\[ \text{time 50:} \quad \text{Memory sends back to } P_1 \quad \text{F}_2 \text{ (0) ld } F_2 \text{ complete} \]

\[ \text{time 51:} \quad \underline{P_1 \text{ is in critical section}} \]

\[ \text{time 100:} \quad \text{Memory completes } A \quad F_1 = 1 \text{ in memory (too late!)} \]

\[ \text{time 100:} \quad \text{Memory completes } X \quad F_2 = 1 \text{ in memory (too late!)} \]
A appeared to happen before X

X appeared to happen before A

These two processors did not see the same order of operations in memory
The Problem

- The two processors did **NOT** see the same order of operations to memory
- The “happened before” relationship between multiple updates to memory was inconsistent between the two processors’ points of view
- As a result, each processor thought the other was **not** in the critical section
How Can We Solve The Problem?

- **Idea:** Sequential consistency

- All processors see the same order of operations to memory
- i.e., all memory operations happen in an order (called the global total order) that is consistent across all processors

- Assumption: within this global order, each processor’s operations appear in sequential order with respect to its own operations.
Sequential Consistency


A multiprocessor system is sequentially consistent if:

- the result of any execution is the same as if the operations of all the processors were executed in some sequential order

AND

- the operations of each individual processor appear in this sequence in the order specified by its program

This is a memory ordering model, or memory model

- Specified by the ISA
Programmer’s Abstraction

- Memory is a switch that services one load or store at a time from any processor
- All processors see the currently serviced load or store at the same time
- Each processor’s operations are serviced in program order
Sequentially Consistent Operation Orders

- Potential correct global orders (all are correct):
  - A B X Y
  - A X B Y
  - A X Y B
  - X A B Y
  - X A Y B
  - X Y A B

- Which order (interleaving) is observed depends on implementation and dynamic latencies
Consequences of Sequential Consistency

- Corollaries

1. Within the same execution, all processors see the same global order of operations to memory
   - No correctness issue
   - Satisfies the “happened before” intuition

2. Across different executions, different global orders can be observed (each of which is sequentially consistent)
   - Debugging is still difficult (as order changes across runs)
Issues with Sequential Consistency?

- Nice abstraction for programming, but two issues:
  - Too conservative ordering requirements
  - Limits the aggressiveness of performance enhancement techniques

- Is the total global order requirement too strong?
  - Do we need a global order across all operations and all processors?
  - How about a global order only across all stores?
    - Total store order memory model; unique store order model
  - How about enforcing a global order only at the boundaries of synchronization?
    - Relaxed memory models
    - Acquire-release consistency model
Issues with Sequential Consistency?

- Performance enhancement techniques that could make SC implementation difficult

- Out-of-order execution
  - Loads happen out-of-order with respect to each other and with respect to independent stores → makes it difficult for all processors to see the same global order of all memory operations

- Caching
  - A memory location is now present in multiple places
  - Prevents the effect of a store to be seen by other processors → makes it difficult for all processors to see the same global order of all memory operations
Weaker Memory Consistency

- The ordering of operations is important when the order affects operations on shared data \(\Rightarrow\) i.e., when processors need to synchronize to execute a “program region”

- Weak consistency
  - Idea: Programmer specifies regions in which memory operations do not need to be ordered
  - “Memory fence” instructions delineate those regions
    - All memory operations before a fence must complete before fence is executed
    - All memory operations after the fence must wait for the fence to complete
    - Fences complete in program order
  - All synchronization operations act like a fence
Tradeoffs: Weaker Consistency

- **Advantage**
  - No need to guarantee a very strict order of memory operations
    - Enables the hardware implementation of performance enhancement techniques to be *simpler*
    - Can be *higher performance* than stricter ordering

- **Disadvantage**
  - More *burden on the programmer* or software (need to get the “fences” correct)

- Another example of the programmer-microarchitect tradeoff
4. Sequential Consistency [30 points]

Two threads (A and B) are concurrently running on a dual-core processor that implements a sequentially consistent memory model. Assume that the value at address 0x1000 is initialized to 0.

Thread A  Thread B
X1: st 0x1, (0x1000)  Y1: st 0x3, (0x1000)
X2: ld $r1, (0x1000)  Y2: ld $r3, (0x1000)
X3: st 0x2, (0x1000)  Y3: st 0x4, (0x1000)
X4: ld $r2, (0x1000)  Y4: ld $r4, (0x1000)

(a) List all possible values that can be stored in $r3 after both threads have finished executing.
Example Question (II)

(b) After both threads have finished executing, you find that \((r_1, r_2, r_3, r_4) = (1, 2, 3, 4)\). How many different instruction interleavings of the two threads produce this result?

(c) What is the total number of all possible instruction interleavings? You need not expand factorials.

(d) On a non-sequentially consistent processor, is the total number of all possible instruction interleavings less than, equal to, or greater than your answer to question (c)?
Caching in Multiprocessors

- Caching not only complicates ordering of all operations...
  - A memory location can be present in multiple caches
  - Prevents the effect of a store or load to be seen by other processors → makes it difficult for all processors to see the same global order of (all) memory operations

- ... but it also complicates ordering of operations on a single memory location
  - A single memory location can be present in multiple caches
  - Makes it difficult for processors that have cached the same location to have the correct value of that location (in the presence of updates to that location)
Cache Coherence
Readings: Cache Coherence

Required

- Culler and Singh, *Parallel Computer Architecture*
  - Chapter 5.1 (pp 269 – 283), Chapter 5.3 (pp 291 – 305)
- P&H, *Computer Organization and Design*
  - Chapter 5.8 (pp 534 – 538 in 4th and 4th revised eds.)

Recommended

Shared Memory Model

- Many parallel programs communicate through *shared memory*
- Proc 0 writes to an address, followed by Proc 1 reading
  - This implies communication between the two

```
Proc 0
Mem[A] = 1

Proc 1
...
```

- Each read should receive the value last written by anyone
  - This requires synchronization (what does last written mean?)
- What if Mem[A] is cached (at either end)?
Cache Coherence

- Basic question: If multiple processors cache the same block, how do they ensure they all see a consistent state?

Diagram:
- Two processors (P1, P2)
- Interconnection Network
- Main Memory
- Connection between processors and main memory with a 1000 symbol
The Cache Coherence Problem

P1

Interconnection Network

P2

Main Memory

ld r2, x

1000
The Cache Coherence Problem

Interconnection Network

Main Memory

P1

1000

P2

1000

ld r2, x

ld r2, x
The Cache Coherence Problem

ld r2, x
add r1, r2, r4
st x, r1

ld r2, x

Interconnection Network

P1

P2

Main Memory

x 1000

2000

1000
The Cache Coherence Problem

ld r2, x
add r1, r2, r4
st x, r1

ld r2, x

Should NOT load 1000

ld r5, x

Interconnection Network

Main Memory

P1

P2

2000

1000

1000

x
Cache Coherence: Whose Responsibility?

- **Software**
  - Can the programmer ensure coherence if caches are invisible to software?
  - What if the ISA provided a cache flush instruction?
    - FLUSH-LOCAL A: Flushes/invalidates the cache block containing address A from a processor’s local cache.
    - FLUSH-GLOBAL A: Flushes/invalidates the cache block containing address A from all other processors’ caches.
    - FLUSH-CACHE X: Flushes/invalidates all blocks in cache X.

- **Hardware**
  - Simplifies software’s job
  - One idea: Invalidate all other copies of block A when a processor writes to it
A Very Simple Coherence Scheme (VI)

- Caches “snoop” (observe) each other’s write/read operations. If a processor writes to a block, all others invalidate the block.

- A simple protocol:
  - Write-through, no-write-allocate cache
  - Actions of the local processor on the cache block: PrRd, PrWr,
  - Actions that are broadcast on the bus for the block: BusRd, BusWr
(Non-)Solutions to Cache Coherence

- No hardware based coherence
  - Keeping caches coherent is software’s responsibility
    + Makes microarchitect’s life easier
  - Makes average programmer’s life much harder
    - need to worry about hardware caches to maintain program correctness?
  - Overhead in ensuring coherence in software (e.g., page protection and page-based software coherence)

- All caches are shared between all processors
  + No need for coherence
  - Shared cache becomes the bandwidth bottleneck
  - Very hard to design a scalable system with low-latency cache access this way
Maintaining Coherence

- Need to guarantee that all processors see a consistent value (i.e., consistent updates) for the same memory location.

- Writes to location A by P0 should be seen by P1 (eventually), and all writes to A should appear in some order.

- Coherence needs to provide:
  - Write propagation: guarantee that updates will propagate
  - Write serialization: provide a consistent order seen by all processors for the same memory location

- Need a global point of serialization for this store ordering
Hardware Cache Coherence

- Basic idea:
  - A processor/cache broadcasts its write/update to a memory location to all other processors
  - Another cache that has the location either updates or invalidates its local copy
Coherence: Update vs. Invalidate

- How can we *safely update replicated data*?
  - Option 1 (Update protocol): push an update to all copies
  - Option 2 (Invalidate protocol): ensure there is only one copy (local), update it

- **On a Read:**
  - If local copy is Invalid, put out request
  - (If another node has a copy, it returns it, otherwise memory does)
Coherence: Update vs. Invalidate (II)

- **On a Write:**
  - Read block into cache as before

**Update Protocol:**
- Write to block, and simultaneously broadcast written data and address to sharers
- (Other nodes update the data in their caches if block is present)

**Invalidate Protocol:**
- Write to block, and simultaneously broadcast invalidation of address to sharers
- (Other nodes invalidate block in their caches if block is present)
Update vs. Invalidate Tradeoffs

- Which do we want?
  - Write frequency and sharing behavior are critical

- **Update**
  - If sharer set is constant and updates are infrequent, avoids the cost of invalidate-reaquire (broadcast update pattern)
  - If data is rewritten without intervening reads by other cores, updates were useless
  - Write-through cache policy ➔ bus becomes bottleneck

- **Invalidate**
  - After invalidation broadcast, core has exclusive access rights
  - Only cores that keep reading after each write retain a copy
  - If write contention is high, leads to ping-pong (rapid invalidation-reaquire traffic from different processors)
Two Cache Coherence Methods

- How do we ensure that the proper caches are updated?

- **Snoopy Bus** [Goodman ISCA 1983, Papamarcos+ ISCA 1984]
  - Bus-based, single point of serialization for all memory requests
  - Processors observe other processors’ actions
    - E.g.: P1 makes “read-exclusive” request for A on bus, P0 sees this and invalidates its own copy of A

- **Directory** [Censier and Feautrier, IEEE ToC 1978]
  - Single point of serialization per block, distributed among nodes
  - Processors make explicit requests for blocks
  - Directory tracks which caches have each block
  - Directory coordinates invalidation and updates
    - E.g.: P1 asks directory for exclusive copy, directory asks P0 to invalidate, waits for ACK, then responds to P1
Directory Based Cache Coherence
Directory Based Coherence

- **Idea:** A logically-central directory keeps track of where the copies of each cache block reside. Caches consult this directory to ensure coherence.

- **An example mechanism:**
  - For each cache block in memory, store $P+1$ bits in directory
    - One bit for each cache, indicating whether the block is in cache
    - Exclusive bit: indicates that a cache has the only copy of the block and can update it without notifying others
  - On a read: set the cache’s bit and arrange the supply of data
  - On a write: invalidate all caches that have the block and reset their bits
  - Have an “exclusive bit” associated with each block in each cache (so that the cache can update the exclusive block silently)
Directory Based Coherence Example (I)

Example directory based scheme

\( P=4 \)

\[ \begin{array}{cccccc}
0 & 0 & 0 & 0 & 0 & 0 \\
\end{array} \]

Exclusive bit

No cache has the block

\( P \) takes a read miss to block A

\[ \begin{array}{cccccc}
0 & 0 & 0 & 0 & 0 & 0 \\
\end{array} \rightarrow \begin{array}{cccccc}
0 & 1 & 0 & 0 & 0 & 0 \\
\end{array} \]

\( P_3 \) takes a read miss

\[ \begin{array}{cccccc}
0 & 1 & 0 & 1 & 0 & 0 \\
\end{array} \]
(3) P₂ takes a write miss
→invalidate P₁ & P₃'s cache
→write request → P₂ has the 
exclusive copy of the block
now. Set the Exclusive bit
→ P₂ can now update the block without notifying
any other processor or the directory
→ P₂ needs to have a bit in its cache indicating
it can perform exclusive updates to that block
→private/exclusive bit per cache block

(4) P₃ takes a write miss
→Mem Controller requests block from P₂
→Mem Controller gives block to P₃
→P₂ invalidates its copy

(5) P₂ takes a read miss
→P₃ supplies it
Directory Optimizations

- Directory is the coordinator for all actions to be performed on the block by any processor
  - Guarantees correctness, ordering

- Yet, there are many opportunities for optimization
  - Enabled by bypassing the directory and directly communicating between caches
  - We will see this later
We did not cover the following slides in lecture. They are for your benefit.
Snoopy Cache Coherence
Snoopy Cache Coherence

- **Idea:**
  - All caches “snoop” all other caches’ read/write requests and keep the cache block coherent
  - Each cache block has “coherence metadata” associated with it in the tag store of each cache

- **Easy to implement if all caches share a common bus**
  - Each cache broadcasts its read/write operations on the bus
  - Good for small-scale multiprocessors
  - What if you would like to have a 1000-node multiprocessor?
**SNOOPY CACHE**

Each Cache observes its own processor & the bus
- Changes the state of the cached block based on observed actions by processor & the bus

Processor actions to a block:
- PR (Proc. Read)
- RW (Proc. Write)

Bus actions to a block:
- BR (Bus Read)
- BW (Bus Write)

or BRx (Bus Read Exclusive)
A Simple Snoopy Cache Coherence Protocol

- Caches “snoop” (observe) each others’ write/read operations
- A simple protocol (VI protocol):

- **Write-through**, no-write-allocate cache
- Actions of the local processor on the cache block: PrRd, PrWr,
- Actions that are broadcast on the bus for the block: BusRd, BusWr
Extending the Protocol

- What if you want write-back caches?
  - We want a “modified” state
A More Sophisticated Protocol: MSI

- Extend metadata per block to encode three states:
  - **M**(odified): cache line is the only cached copy and is dirty
  - **S**(hared): cache line is potentially one of several cached copies
  - **I**(nvalid): cache line is not present in this cache

- Read miss makes a *Read* request on bus, transitions to **S**
- Write miss makes a *ReadEx* request, transitions to **M** state
- When a processor snoops *ReadEx* from another writer, it must invalidate its own copy (if any)
- **S→M** *upgrade* can be made without re-reading data from memory (via *Invalidations*)
MSI State Machine

[Culler/Singh96]
The Problem with MSI

- A block is in no cache to begin with
- Problem: On a read, the block immediately goes to “Shared” state although it may be the only copy to be cached (i.e., no other processor will cache it)

Why is this a problem?
- Suppose the cache that read the block wants to write to it at some point
- It needs to broadcast “invalidate” even though it has the only cached copy!
- *If the cache knew it had the only cached copy in the system, it could have written to the block without notifying any other cache → saves unnecessary broadcasts of invalidations*
The Solution: MESI

- **Idea:** Add another state indicating that this is the only cached copy and it is clean.
  - *Exclusive* state

- Block is placed into the *exclusive* state if, during *BusRd*, no other cache had it
  - Wired-OR “shared” signal on bus can determine this: snooping caches assert the signal if they also have a copy

- Silent transition *Exclusive* $\rightarrow$ *Modified* is possible on write!

- MESI is also called the *Illinois protocol*
Papamarcos & Patel, ISCA 1984

Illinois Protocol

4 States

M: Modified (Exclusive copy, modified)
E: Exclusive ("","", clean)
S: Shared (Shared copy, clean)
I: Invalid
MESI State Machine
MESI State Machine

[Culler/Singh96]
A transition from a single-owner state (Exclusive or Modified) to Shared is called a **downgrade**, because the transition takes away the owner's right to modify the data.

A transition from Shared to a single-owner state (Exclusive or Modified) is called an **upgrade**, because the transition grants the ability to the owner (the cache which contains the respective block) to write to the block.
MESI State Machine from Optional Lab 5
Intel Pentium Pro

slide credit: Yale Patt
Snoopy Invalidation Tradeoffs

- Should a downgrade from M go to S or I?
  - S: if data is likely to be reused (before it is written to by another processor)
  - I: if data is likely to be not reused (before it is written to by another)

- Cache-to-cache transfer
  - On a BusRd, should data come from another cache or memory?
    - Another cache
      - May be faster, if memory is slow or highly contended
    - Memory
      - Simpler: no need to wait to see if another cache has the data first
      - Less contention at the other caches
      - Requires writeback on M downgrade

- Writeback on Modified->Shared: necessary?
  - One possibility: **Owner** (O) state (MOESI protocol)
    - One cache owns the latest data (memory is not updated)
    - Memory writeback happens when all caches evict copies
The Problem with MESI

- Observation: Shared state requires the data to be clean
  - i.e., all caches that have the block have the up-to-date copy and so does the memory
- Problem: Need to write the block to memory when BusRd happens when the block is in Modified state

- Why is this a problem?
  - Memory can be updated unnecessarily → some other processor may want to write to the block again
Improving on Mesi

- Idea 1: Do not transition from M→S on a BusRd. Invalidate the copy and supply the modified block to the requesting processor directly without updating memory.

- Idea 2: Transition from M→S, but designate one cache as the owner (O), who will write the block back when it is evicted.
  - Now “Shared” means “Shared and potentially dirty”
  - This is a version of the MOESI protocol
Tradeoffs in Sophisticated Cache Coherence Protocols

- The protocol can be optimized with more states and prediction mechanisms to
  + Reduce unnecessary invalidates and transfers of blocks

- However, more states and optimizations
  -- Are more difficult to design and verify (lead to more cases to take care of, race conditions)
  -- Provide diminishing returns
Revisiting Two Cache Coherence Methods

- How do we ensure that the proper caches are updated?

- **Snoopy Bus** [Goodman ISCA 1983, Papamarcos+ ISCA 1984]
  - Bus-based, single point of serialization *for all memory requests*
  - Processors observe other processors’ actions
    - E.g.: P1 makes “read-exclusive” request for A on bus, P0 sees this and invalidates its own copy of A

- **Directory** [Censier and Feautrier, IEEE ToC 1978]
  - Single point of serialization *per block*, distributed among nodes
  - Processors make explicit requests for blocks
  - Directory tracks which caches have each block
  - Directory coordinates invalidation and updates
    - E.g.: P1 asks directory for exclusive copy, directory asks P0 to invalidate, waits for ACK, then responds to P1
Snoopy Cache vs. Directory Coherence

**Snoopy Cache**
+ Miss latency (critical path) is short: request → bus transaction to mem.
+ Global serialization is easy: bus provides this already (arbitration)
+ Simple: can adapt bus-based uniprocessors easily
  - Relies on broadcast messages to be seen by all caches (in same order):
    → single point of serialization (bus): *not scalable*
    → *need a virtual bus (or a totally-ordered interconnect)*

**Directory**
- Adds indirection to miss latency (critical path): request → dir. → mem.
- Requires extra storage space to track sharer sets
  - Can be approximate (false positives are OK for correctness)
- Protocols and race conditions are more complex (for high-performance)
+ Does not require broadcast to all caches
+ Exactly as scalable as interconnect and directory storage
  
  *(much more scalable than bus)*
Revisiting Directory-Based Cache Coherence
Remember: Directory Based Coherence

- Idea: A logically-central directory keeps track of where the copies of each cache block reside. Caches consult this directory to ensure coherence.

- An example mechanism:
  - For each cache block in memory, store $P+1$ bits in directory
    - One bit for each cache, indicating whether the block is in cache
    - Exclusive bit: indicates that the cache that has the only copy of the block and can update it without notifying others
  - On a read: set the cache’s bit and arrange the supply of data
  - On a write: invalidate all caches that have the block and reset their bits
  - Have an “exclusive bit” associated with each block in each cache
Remember: Directory Based Coherence

Example directory based scheme

$p + 1$ bits: for block $A$

$p = 4$ 

Exclusive bit

No cache has the block

$P_1$ takes a read miss to block $A$

$000000 \rightarrow 010000$

$P_3$ takes a read miss

$\downarrow$

$010100$
Directory-Based Protocols

- Required when scaling past the capacity of a single bus
- Distributed, but:
  - Coherence still requires single point of serialization (for write serialization)
  - Serialization location can be different for every block (striped across nodes/memory-controllers)

- We can reason about the protocol for a single block: one server (directory node), many clients (private caches)

- Directory receives Read and ReadEx requests, and sends Invl requests: invalidation is explicit (as opposed to snoopy buses)
Directory: Data Structures

- Required to support invalidation and cache block requests
- Key operation to support is *set inclusion test*
  - False positives are OK: want to know which caches *may* contain a copy of a block, and spurious invalidations are ignored
  - False positive rate determines *performance*
- Most accurate (and expensive): full bit-vector
- Compressed representation, linked list, Bloom filters are all possible

<table>
<thead>
<tr>
<th>0x00</th>
<th>Shared: {P0, P1, P2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x04</td>
<td>---</td>
</tr>
<tr>
<td>0x08</td>
<td>Exclusive: P2</td>
</tr>
<tr>
<td>0x0C</td>
<td>---</td>
</tr>
</tbody>
</table>
Directory: Basic Operations

- Follow *semantics* of snoop-based system
  - but with explicit request, reply messages

- Directory:
  - Receives *Read, ReadEx, Upgrade* requests from nodes
  - Sends *Inval/Downgrade* messages to sharers if needed
  - Forwards request to memory if needed
  - Replies to requestor and updates sharing state

- Protocol design is flexible
  - Exact forwarding paths depend on implementation
  - For example, do cache-to-cache transfer?
P0 acquires an address for reading:

1. Read

2. DatEx (DatShr)
RdEx with Former Owner

1. RdEx

P0 -> Home

2. Inv

Home -> Owner

3a. Rev

Owner -> Home

3b. DatEx
Contestion Resolution (for Write)

1a. RdEx
4. InvI
5a. Rev

2a. DatEx

3. RdEx
1b. RdEx

5b. DatEx

2b. NACK
Issues with Contention Resolution

- Need to escape race conditions by:
  - NACKing requests to busy (pending invalidate) entries
    - Original requestor retries
  - OR, queuing requests and granting in sequence
  - (Or some combination thereof)

- Fairness
  - Which requestor should be preferred in a conflict?
  - Interconnect delivery order, and distance, both matter

- Ping-ponging is a higher-level issue
  - With solutions like combining trees (for locks/barriers) and better shared-data-structure design
Scaling the Directory: Some Questions

- How large is the directory?
- How can we reduce the access latency to the directory?
- How can we scale the system to thousands of nodes?
- Can we get the best of snooping and directory protocols?
  - Heterogeneity
  - E.g., token coherence [Martin+, ISCA 2003]
Advancing Coherence
Motivation: Three Desirable Attributes

- Low-latency cache-to-cache misses
- No bus-like interconnect
- Bandwidth efficient

Dictated by workload and technology trends
Workload Trends

- **Commercial workloads**
  - Many cache-to-cache misses
  - Clusters of small multiprocessors

- **Goals:**
  - Direct cache-to-cache misses
    (2 hops, not 3 hops)
  - Moderate scalability

Workload trends → snooping protocols
Workload Trends

Low-latency cache-to-cache misses

No bus-like interconnect  Bandwidth efficient
Workload Trends ▶ Snooping Protocols

Low-latency cache-to-cache misses
(Yes: direct request/response)

No bus-like interconnect
(No: requires a “virtual bus”)

Bandwidth efficient
(No: broadcast always)
Technology Trends

• High-speed point-to-point links
  – No (multi-drop) busses

• Increasing design integration
  – “Glueless” multiprocessors
  – Improve cost & latency

• Desire: low-latency interconnect
  – Avoid “virtual bus” ordering
  – Enabled by directory protocols

Technology trends → unordered interconnects
Technology Trends

Low-latency cache-to-cache misses

No bus-like interconnect  Bandwidth efficient
Technology Trends Directory Protocols

Low-latency cache-to-cache misses

(No: indirection through directory)

No bus-like interconnect
(Yes: no ordering required)

Bandwidth efficient
(Yes: avoids broadcast)
Goal: All Three Attributes

Low-latency cache-to-cache misses

No bus-like interconnect

Bandwidth efficient

Step#1

Step#2
Token Coherence: Key Insight

• Goal of invalidation-based coherence
  – Invariant: many readers -or- single writer
  – Enforced by globally coordinated actions

• Enforce this invariant directly using tokens
  – Fixed number of tokens per block
  – One token to read, all tokens to write

• Guarantees safety in all cases
  – Global invariant enforced with only local rules
  – Independent of races, request ordering, etc.