

18-447

Computer Architecture

Lecture 29: Consistency & Coherence

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Midterm II Next Week

- April 23, in class, 12:30-2:30pm
- Closed book, closed notes (same as Midterm I)
- Two cheat sheets allowed (2X the same sheet as Midterm I)
- Scope: Any topic we have covered so far in the course:
 - Lectures, labs, HWs, readings, review sessions, recitations, ...
 - Material after Midterm I will have higher weight on the exam

Suggestions for Midterm II

- Solve past midterms (and finals) on your own...
 - And, check your solutions vs. the online solutions
 - Questions will be similar in spirit
- http://www.ece.cmu.edu/~ece447/s14/doku.php?id=exam_s
- http://www.ece.cmu.edu/~ece447/s13/doku.php?id=exam_s
- Do Homework 7
- Study and internalize the lecture material well. Study hard.
- Do the readings that are required.

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

Readings: Memory Consistency

■ Required

- ❑ Lamport, "How to Make a Multiprocessor Computer That Correctly Executes Multiprocess Programs," IEEE Transactions on Computers, 1979

■ Recommended

- ❑ Gharachorloo et al., "Memory Consistency and Event Ordering in Scalable Shared-Memory Multiprocessors," ISCA 1990.
- ❑ Gharachorloo et al., "Two Techniques to Enhance the Performance of Memory Consistency Models," ICPP 1991.
- ❑ Ceze et al., "BulkSC: bulk enforcement of sequential consistency," ISCA 2007.

Memory Ordering in Multiprocessors

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 → high performance
- Disadvantage: Order can change across runs of the same program → 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?

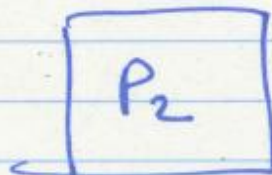
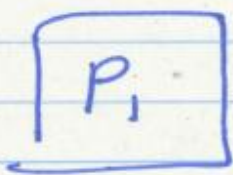
- When protecting shared data

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
 - Reading: Dijkstra, “[Cooperating Sequential Processes](#),” 1965.
 - <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



Protecting Shared Data

$F_1 = \emptyset$



A $F_1 = 1$

B IF ($F_2 = \emptyset$) THEN
 {Critical section}
 $F_1 \neq \emptyset$

ELSE
 {...}

$F_2 = \emptyset$



X $F_2 = 1$

Y IF ($F_1 = \emptyset$) THEN
 {Critical section}

ELSE
 {...}

Only P_1 or
 P_2 should
be in this
section
at any given
time,
not both

Assume P_1 is in critical section.

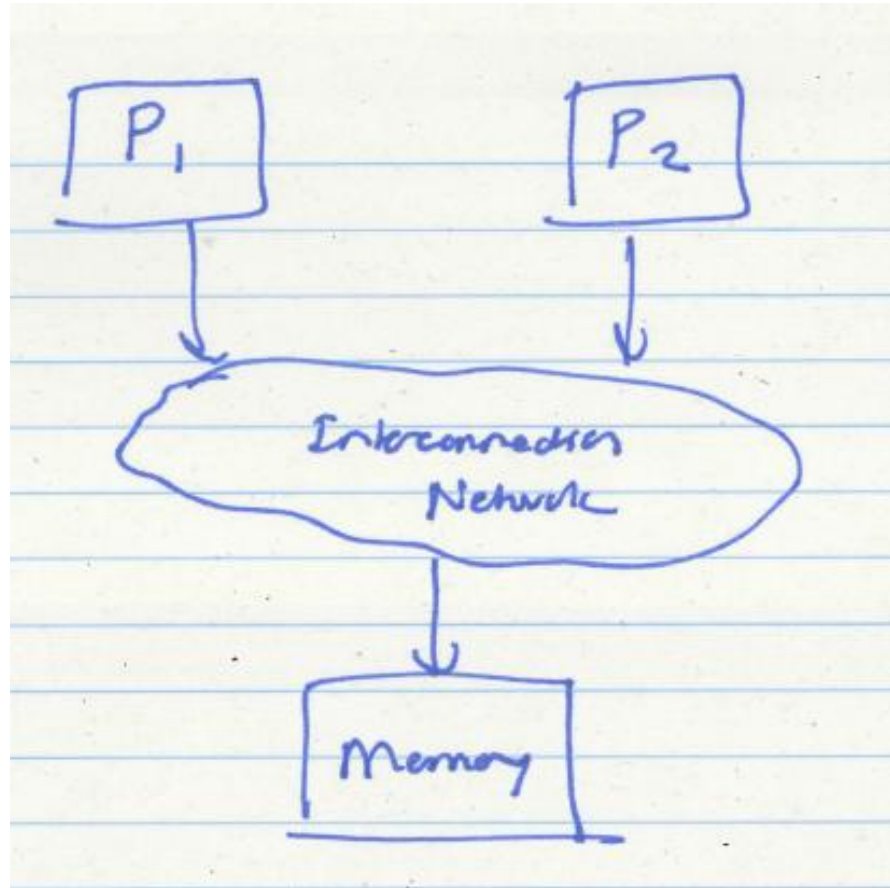
Intuitively, it must have executed A,

which means F_1 must be 1 (as A happens before B),

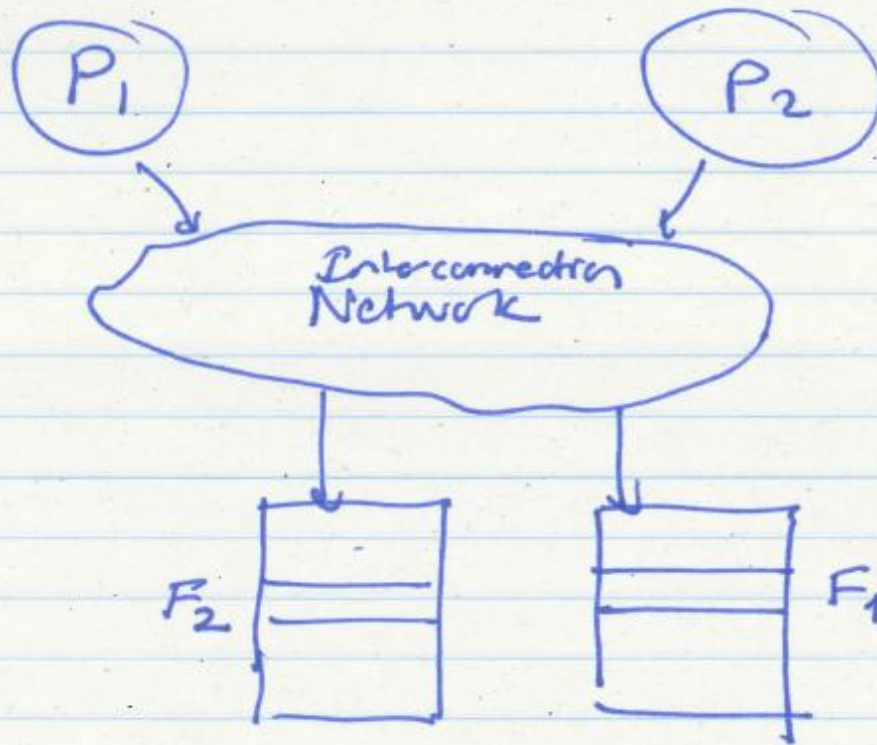
which means P_2 should not enter the critical section.

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 $F_1 = 1$) $S + F_1$ complete
A is sent to memory (from P_1 's view)

P_2 executes X
(set $F_2 = 1$) $S + F_2$ complete
X is sent to memory (from P_2 's view)

Both Processors in Critical Section

time 0: P_1 executes A
(set $F_1 = 1$) st F_1 complete (from P_1 's view)
A is sent to memory

P_2 executes X
(set $F_2 = 1$) st F_2 complete (from P_2 's view)
X is sent to memory

time 1: P_1 executes B
(test $F_2 == 0$) ld F_2 started
B is sent to memory

P_2 executes Y
(test $F_1 == 0$) ld F_1 started
Y is sent to memory

time 50: Memory sends back to P_1
 $F_2 (0)$ ld F_2 complete

Memory sends back to P_2
 $(F_1 \neq 0)$ ld F_1 complete

time 51: P_1 is in critical section
~~execute~~

P_2 is in critical section

time 100: Memory completes A
 $F_1 = 1$ in memory
(too late!)

Memory completes ~~X~~
 $F_2 = 1$ in memory
(too late!)

What happened?

P₁'s view of mem. ops

A (F₁=1)
B (test F₂=0)
X (F₂=1)

P₂'s view

X (F₂=1)
Y (test₂ F₁=0)
A (F₁=1)

A appeared to happen
before X

X appeared to happen
before A



Problem!

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

How Can We Solve The Problem?

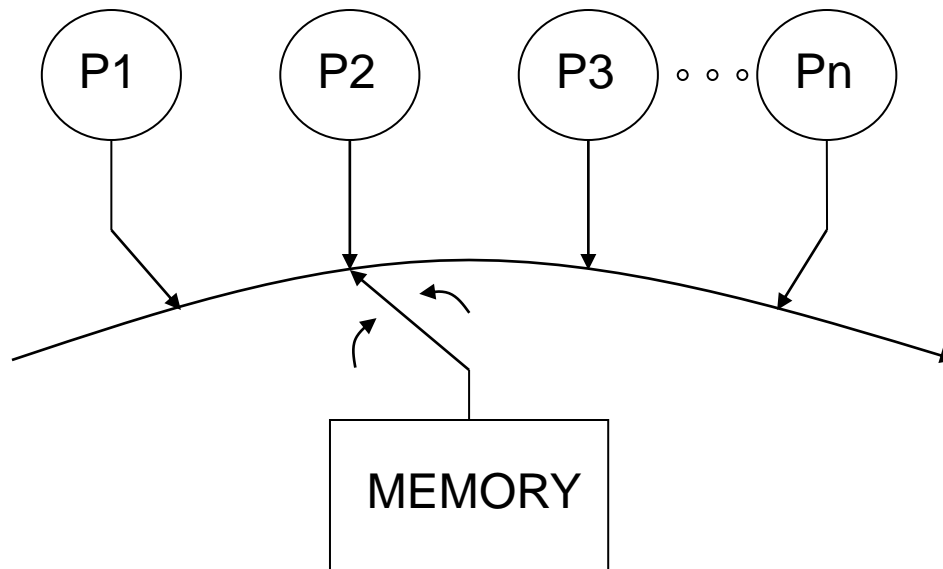
- Idea: Sequential consistency
- All processors see the same order of operations to memory
- i.e., all memory operations happen in an order (called the global total order) that is consistent across all processors
- Assumption: within this global order, each processor's operations appear in sequential order with respect to its own operations.

Sequential Consistency

- Lamport, "How to Make a Multiprocessor Computer That Correctly Executes Multiprocess Programs," IEEE Transactions on Computers, 1979
 - 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 → 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

Related Questions

- Question 4 in
 - <http://www.ece.cmu.edu/~ece447/s13/lib/exe/fetch.php?media=final.pdf>

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 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

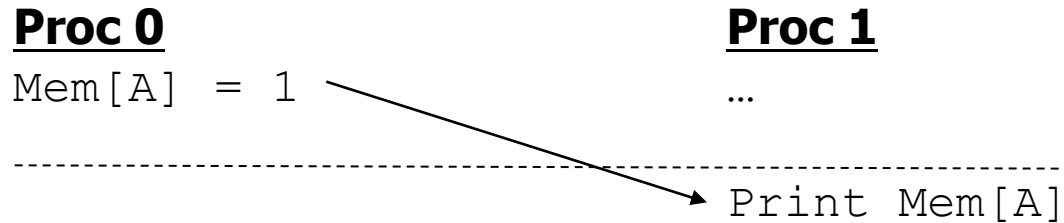
- Culler and Singh, *Parallel Computer Architecture*
 - Chapter 5.1 (pp 269 – 283), Chapter 5.3 (pp 291 – 305)
- P&H, *Computer Organization and Design*
 - Chapter 5.8 (pp 534 – 538 in 4th and 4th revised eds.)
- Papamarcos and Patel, “A low-overhead coherence solution for multiprocessors with private cache memories,” ISCA 1984.

■ Recommended

- Censier and Feautrier, “A new solution to coherence problems in multicache systems,” IEEE Trans. Computers, 1978.
- Goodman, “Using cache memory to reduce processor-memory traffic,” ISCA 1983.
- Laudon and Lenoski, “The SGI Origin: a ccNUMA highly scalable server,” ISCA 1997.
- Martin et al, “Token coherence: decoupling performance and correctness,” ISCA 2003.
- Baer and Wang, “On the inclusion properties for multi-level cache hierarchies,” ISCA 1988.

Shared Memory Model

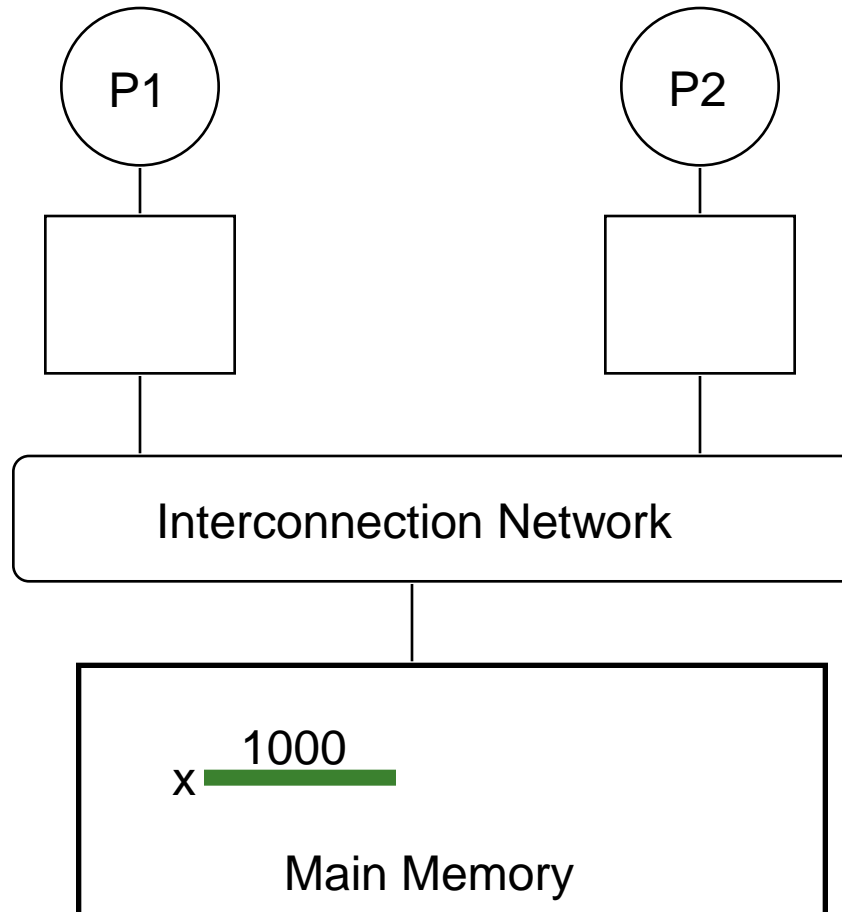
- Many parallel programs communicate through *shared memory*
- Proc 0 writes to an address, followed by Proc 1 reading
 - This implies communication between the two



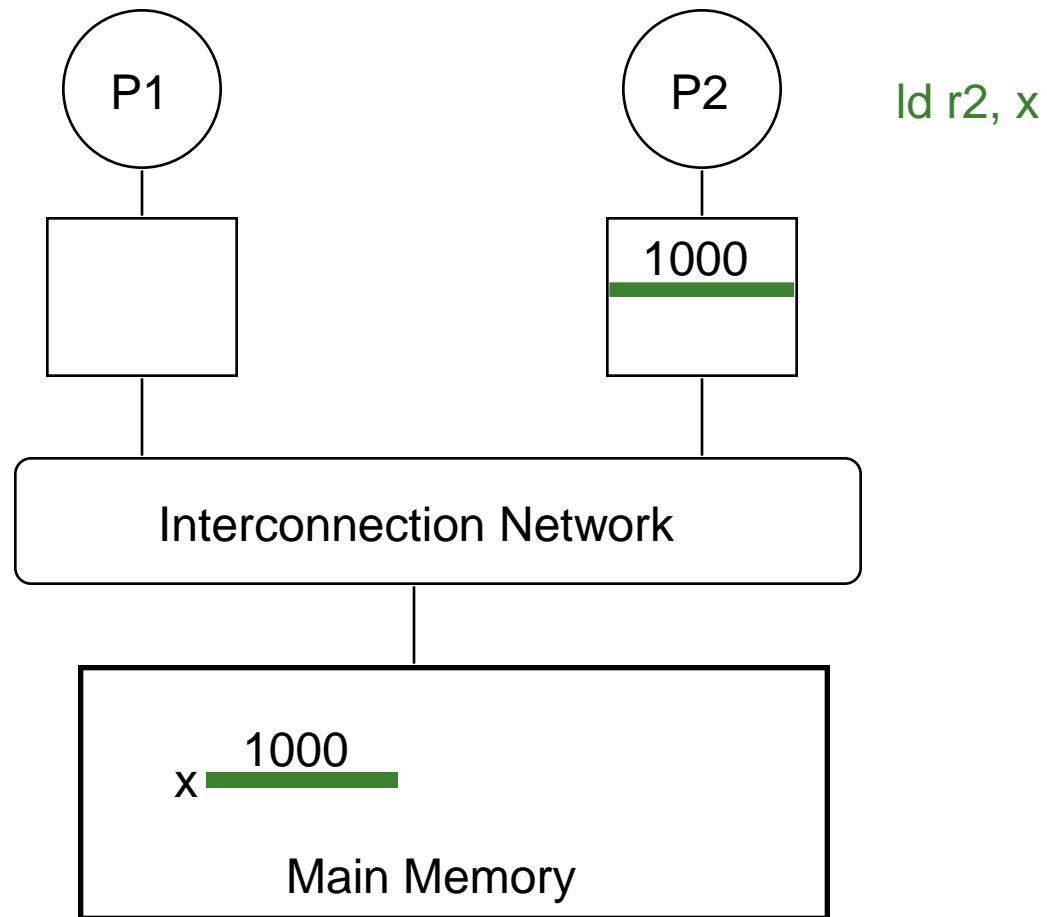
- Each read should receive the value last written by anyone
 - This requires synchronization (what does last written mean?)
- What if `Mem[A]` is cached (at either end)?

Cache Coherence

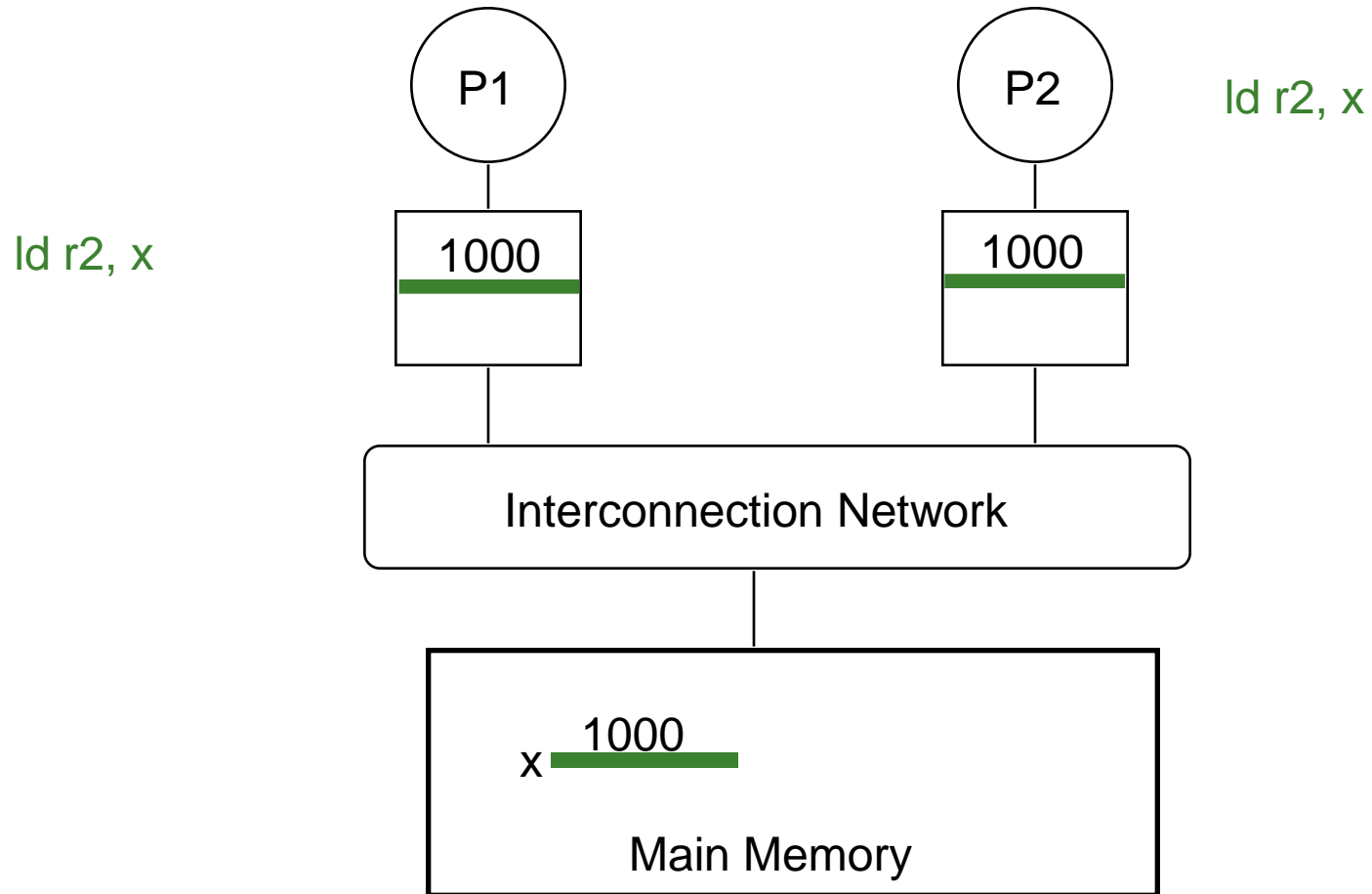
- Basic question: If multiple processors cache the same block, how do they ensure they all see a consistent state?



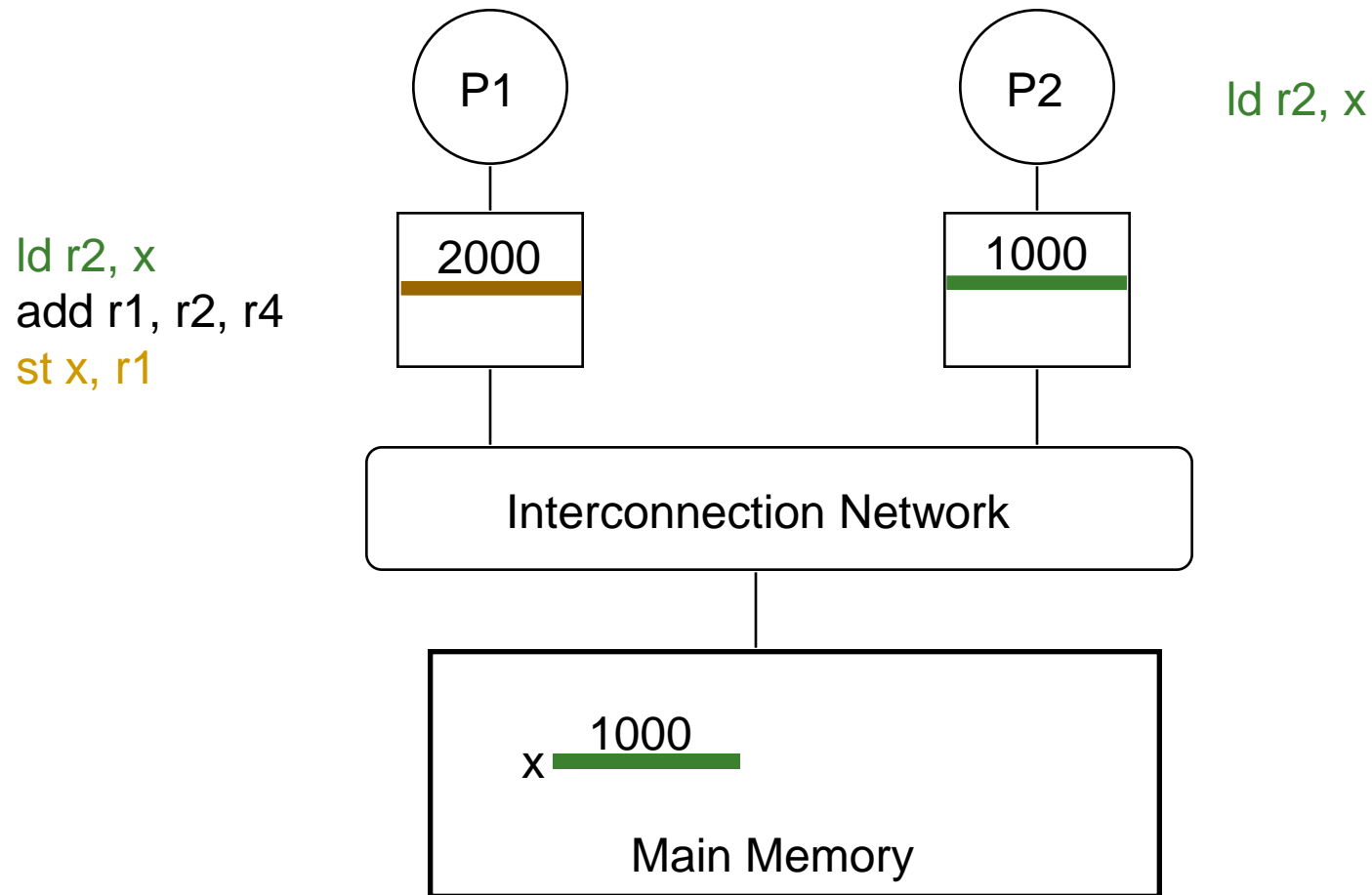
The Cache Coherence Problem



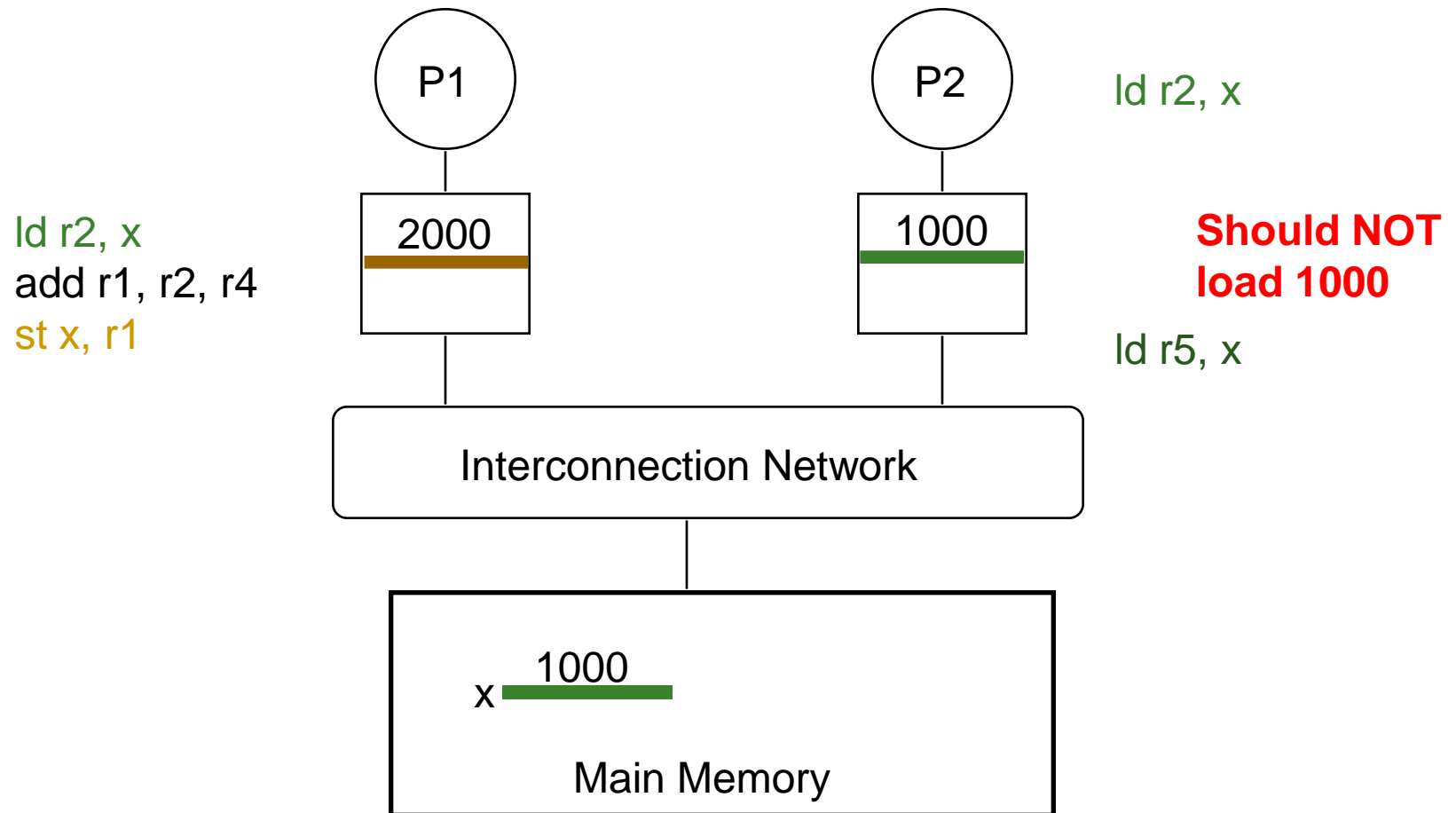
The Cache Coherence Problem



The Cache Coherence Problem



The Cache Coherence Problem



Cache Coherence: Whose Responsibility?

■ Software

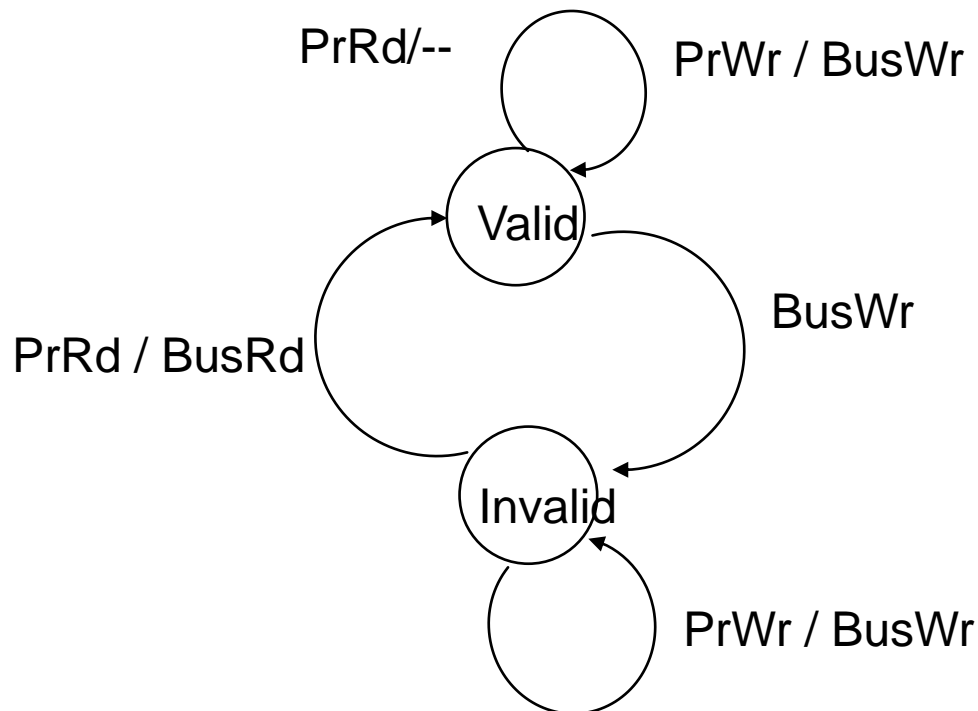
- ❑ Can the programmer ensure coherence if caches are invisible to software?
- ❑ What if the ISA provided a cache flush instruction?
 - FLUSH-LOCAL A: Flushes/invalidates the cache block containing address A from a processor's local cache.
 - FLUSH-GLOBAL A: Flushes/invalidates the cache block containing 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 global order seen by all processors
- 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-reacquire (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-ponging (rapid mutual invalidation-reacquire)

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

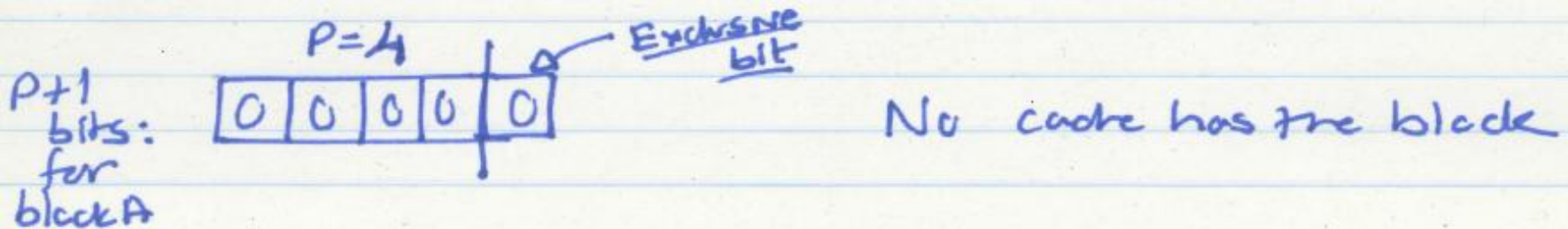
Directory Based Cache Coherence

Directory Based Coherence

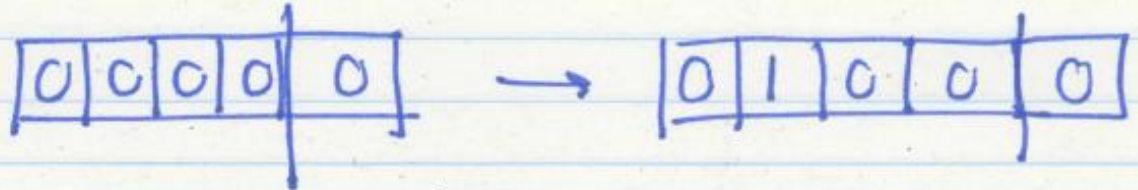
- Idea: A logically-central directory keeps track of where the copies of each cache block reside. Caches consult this directory to ensure coherence.
- An example mechanism:
 - For each cache block in memory, store $P+1$ bits in directory
 - One bit for each cache, indicating whether the block is in cache
 - 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)

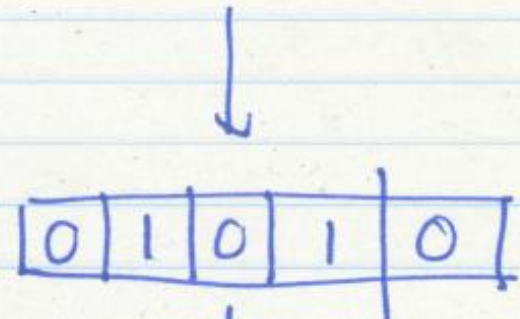
Example directory based scheme



① P_1 takes a read miss to block A



② P_3 takes a read miss



③ P₂ takes a write miss

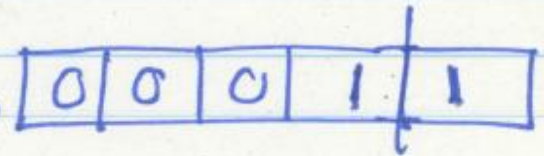
- invalidate P₁ & P₃'s caches
- write request → P₂ has the exclusive copy of the block now. Set the Exclusive bit



- 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 ~~the~~ block from P₂
- Mem Controller gives block to P₃
- P₂ invalidates its copy



⑤ P₂ takes a read miss

- P₃ supplies it

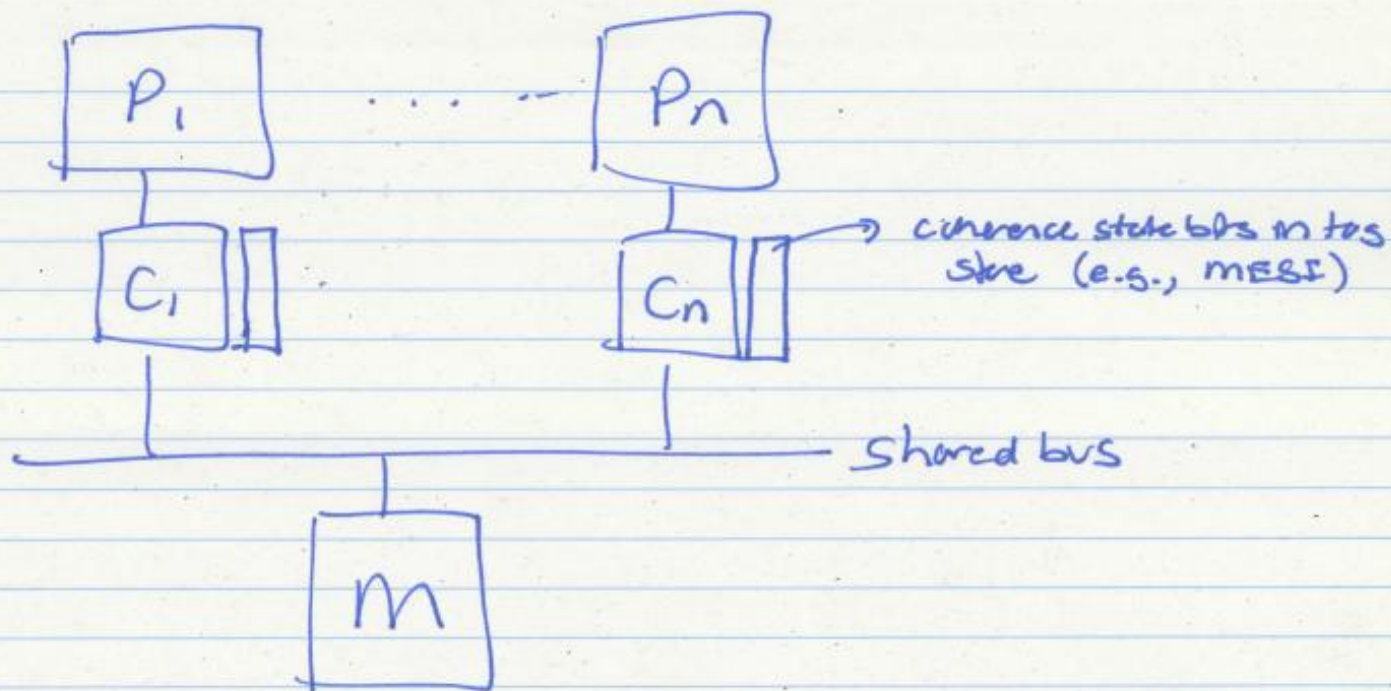


Snoopy Cache Coherence

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

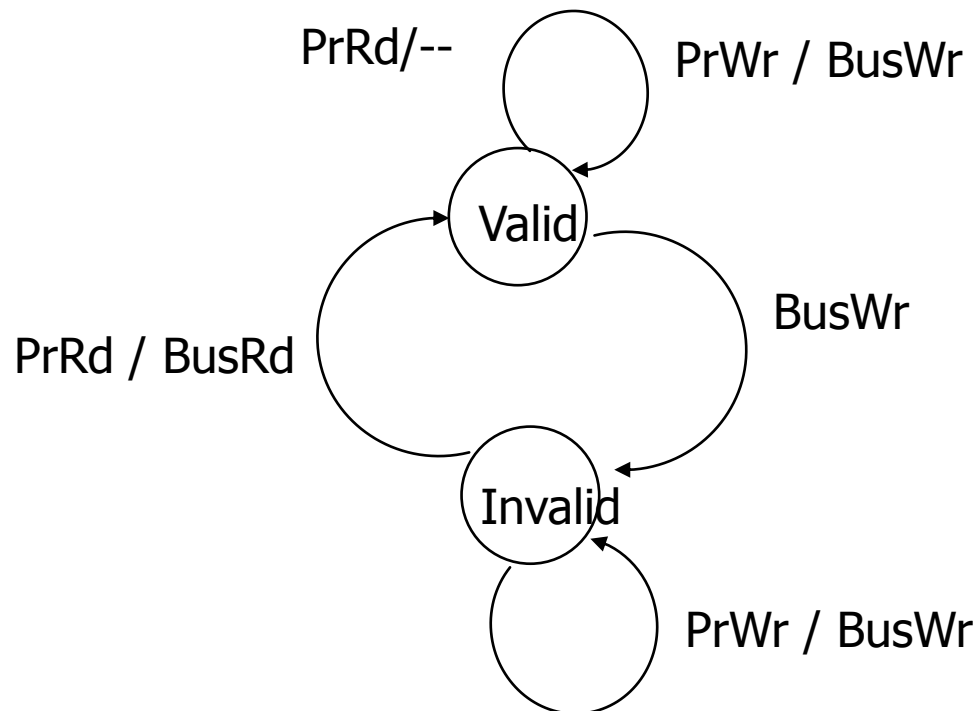
Processor actions to a block: PR (Proc. Read)
 RW (Proc. Write)

Bus actions to a block : BR (Bus Read)
 (coming from another processor) BW (Bus Write)

or BRx (Bus Read Exclusive)

A Simple Snoopy Cache Coherence Protocol

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

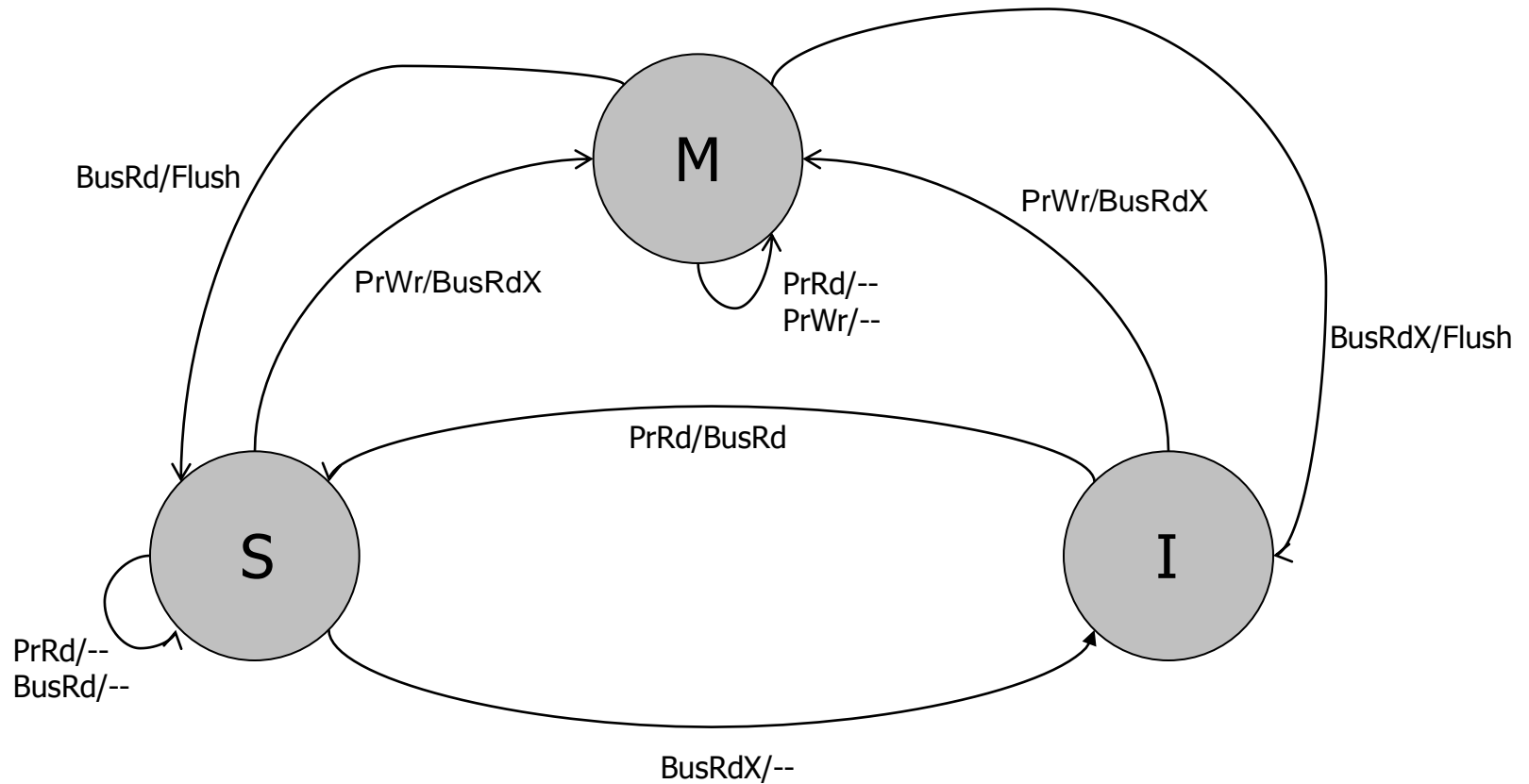


- Write-through, no-write-allocate cache
- Actions of the local processor on the cache block: PrRd, PrWr,
- Actions that are broadcast on the bus for the block: BusRd, BusWr

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)
- $S \rightarrow M$ *upgrade* can be made without re-reading data from memory (via *Invalidations*)

MSI State Machine



ObservedEvent/Action

[Culler/Singh96]

The Problem with MSI

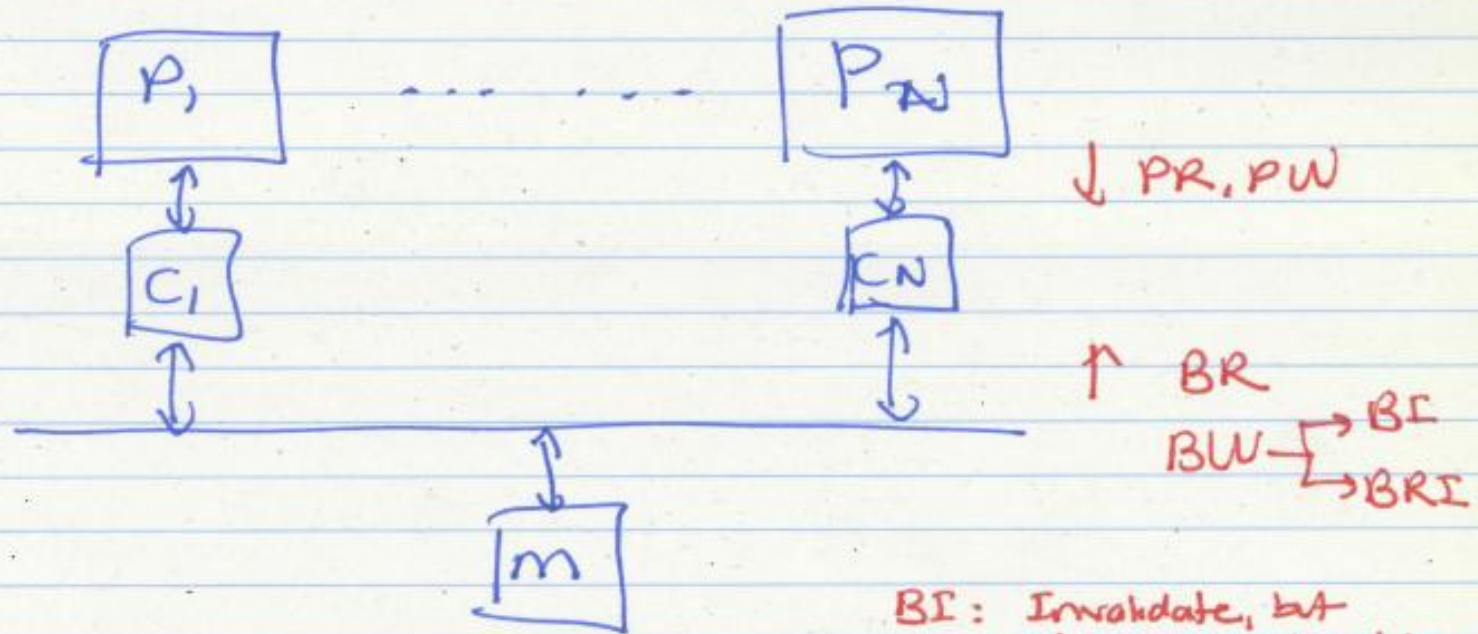
- A block is in no cache to begin with
- Problem: On a read, the block immediately goes to “Shared” state although it may be the only copy to be cached (i.e., no other processor will cache it)
- Why is this a problem?
 - Suppose the cache that read the block wants to write to it at some point
 - It needs 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*→*Modified* is possible on write!
- MESI is also called the *Illinois protocol*
 - Papamarcos and Patel, “A low-overhead coherence solution for multiprocessors with private cache memories,” ISCA 1984.

Papamarcos & Patel, ISCA 1984

Illinois Protocol



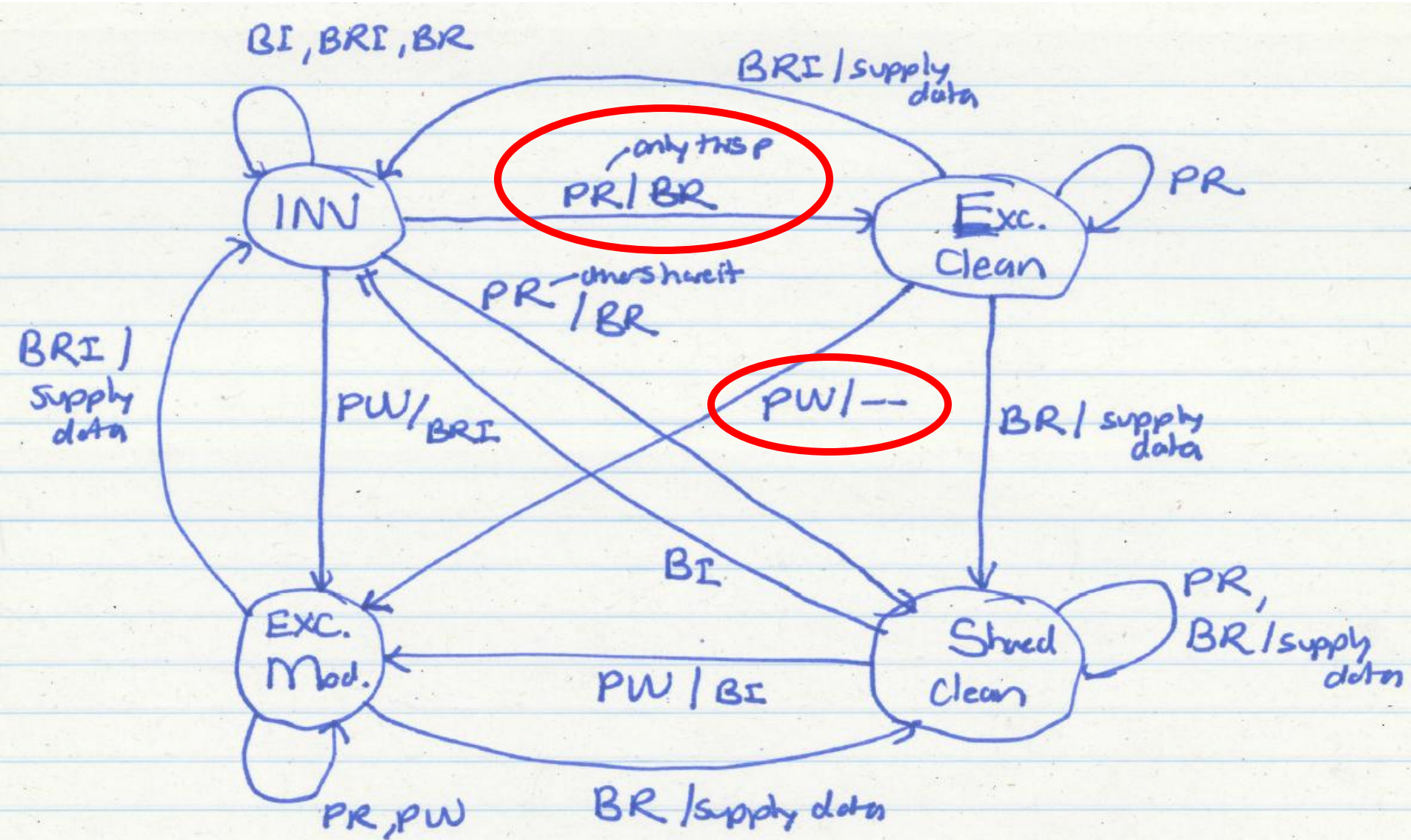
BI: Invalidate, but
already have the data
(do not supply it)

BRI: Invalidate, but
also need the data
(supply it)

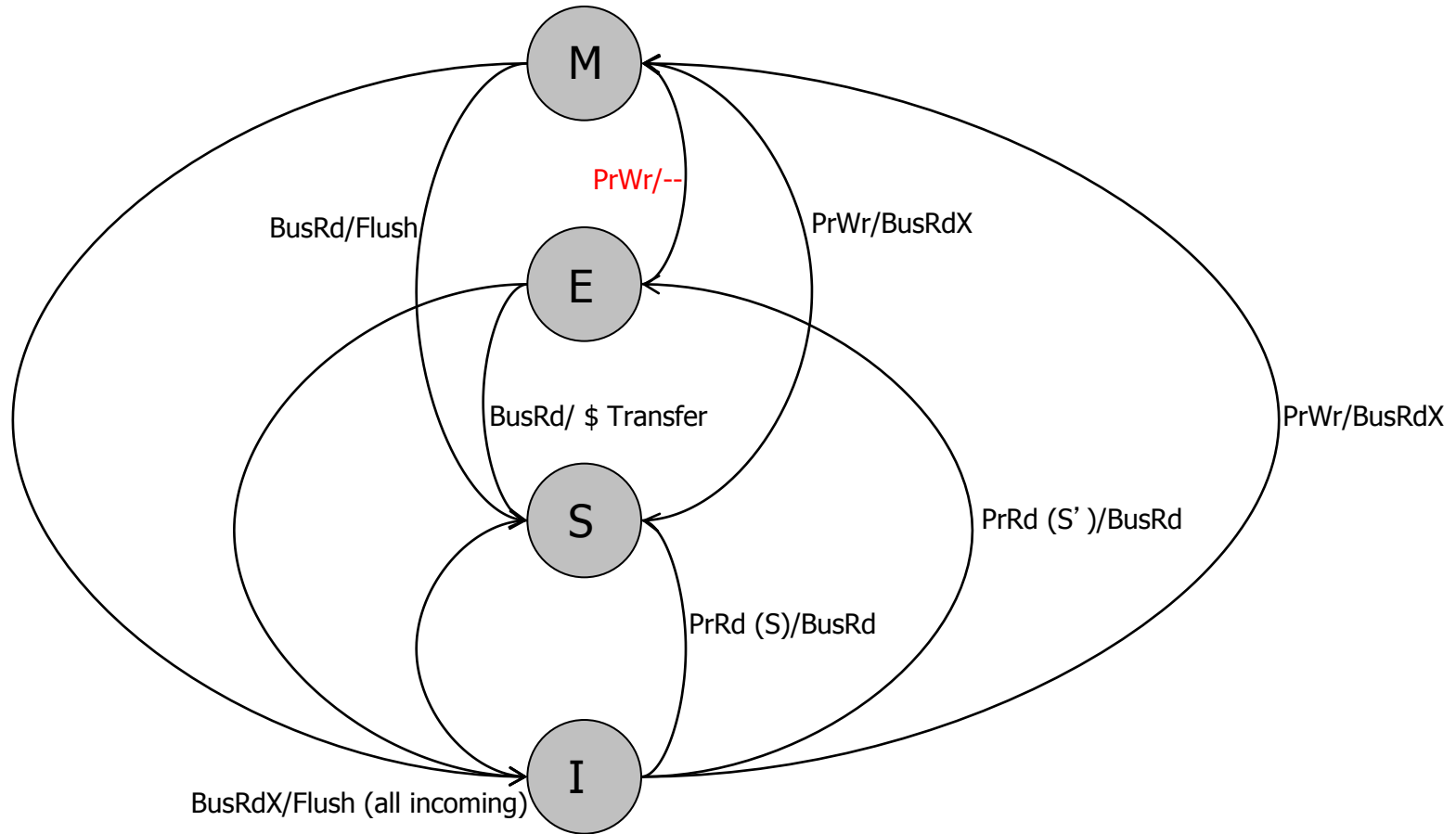
4 States

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

MESI State Machine

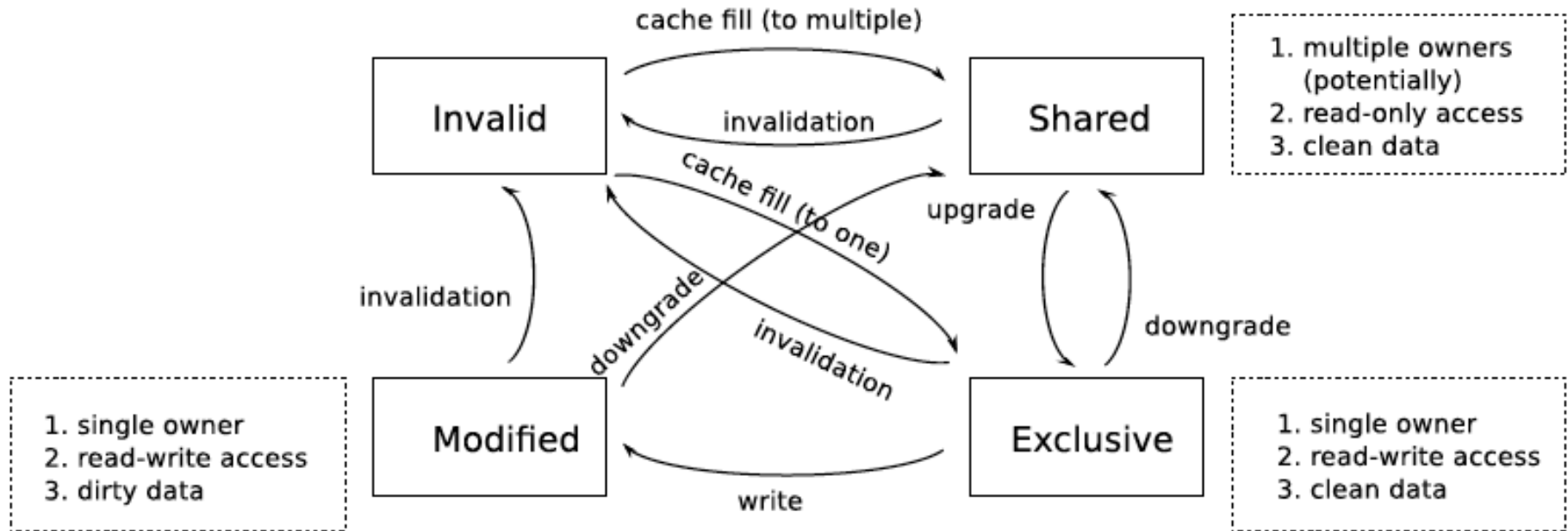


MESI State Machine



[Culler/Singh96]

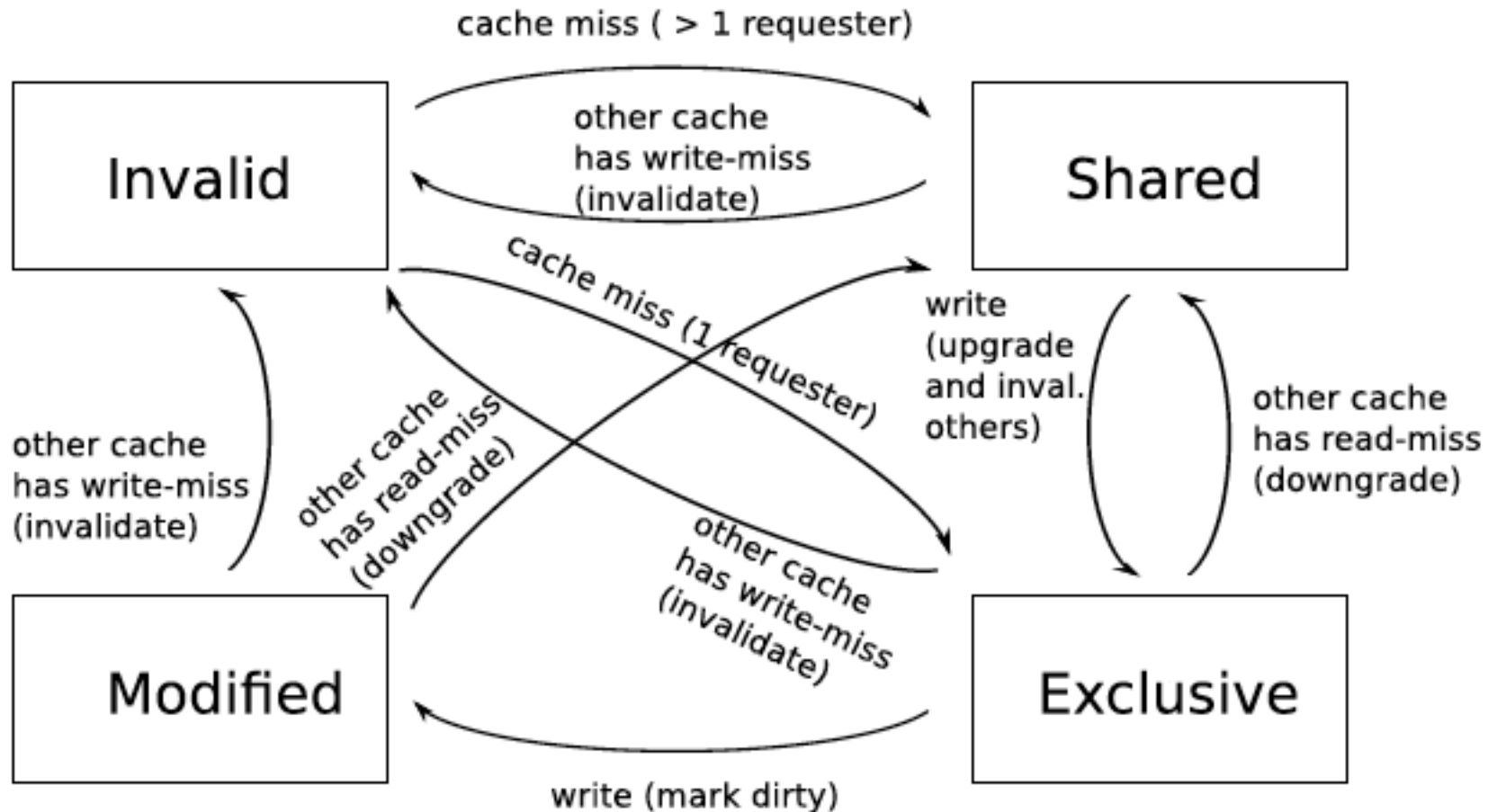
MESI State Machine from Lab 7



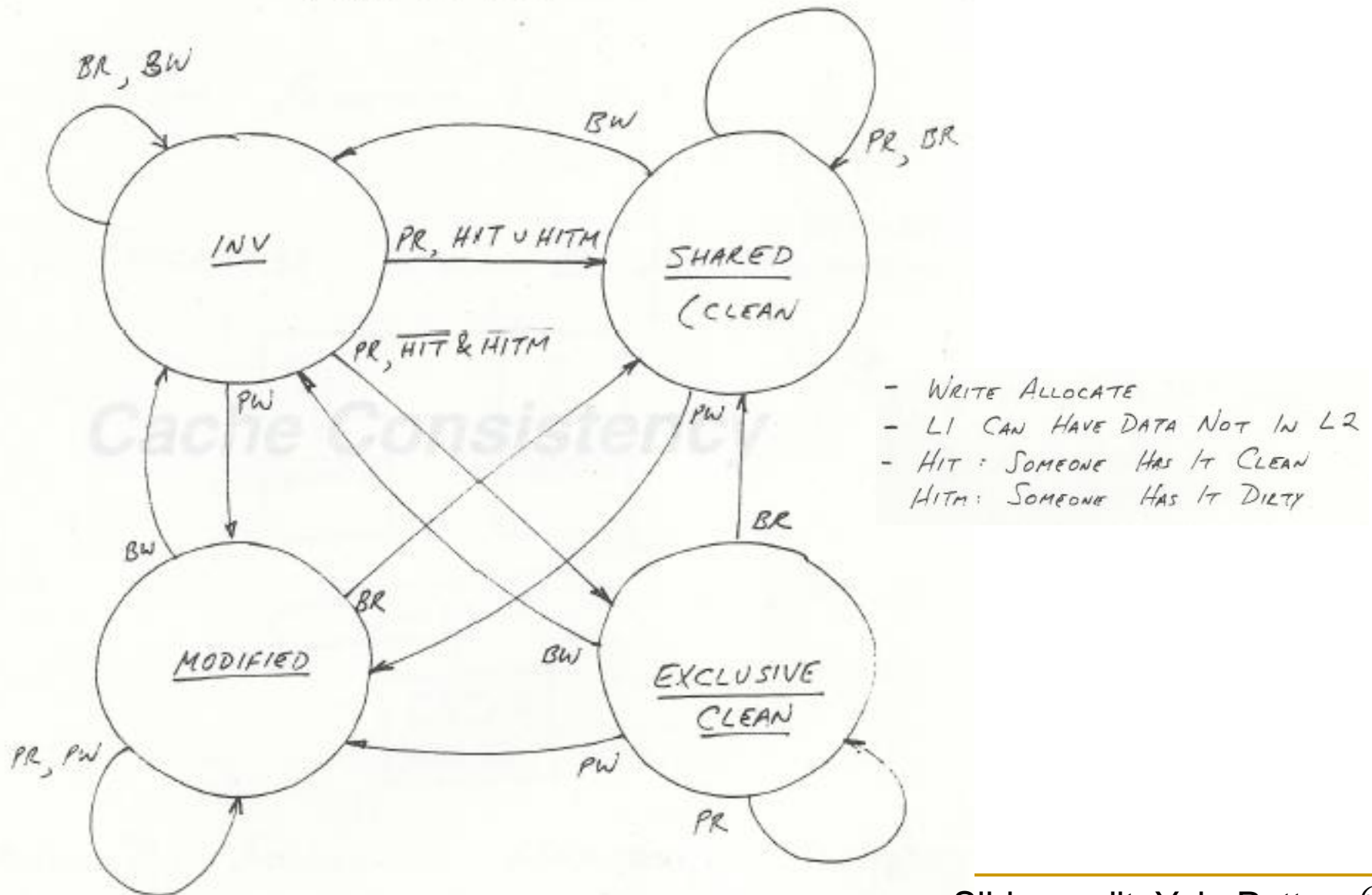
A transition from a single-owner state (Exclusive or Modified) to Shared is called a **downgrade**, because the transition takes away the owner's right to modify the data

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 Lab 7



Intel Pentium Pro



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 $M \rightarrow S$ on a BusRd. Invalidate the copy and supply the modified block to the requesting processor directly without updating memory
- Idea 2: Transition from $M \rightarrow S$, 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)
- 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)

We did not cover the following slides. They are for your benefit.

Revisiting Directory-Based Cache Coherence

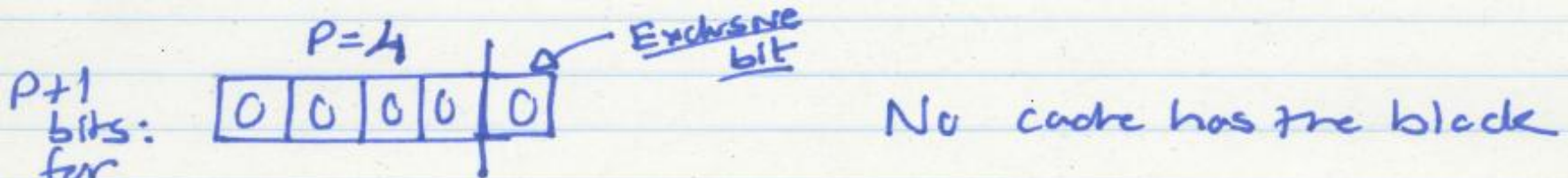
Remember: Directory Based Coherence

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

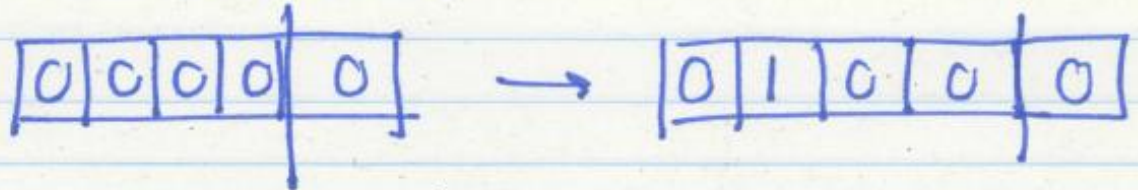
- An example mechanism:
 - For each cache block in memory, store $P+1$ bits in directory
 - One bit for each cache, indicating whether the block is in cache
 - Exclusive bit: indicates that the cache that has the only copy of the block and can update it without notifying others
 - On a read: set the 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

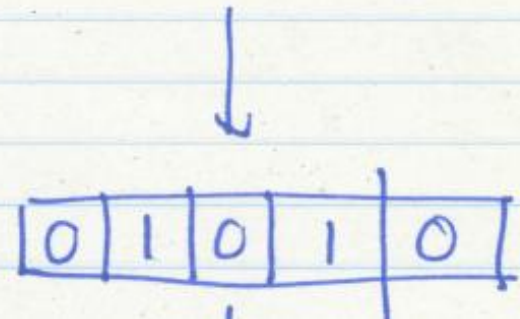
Example directory based scheme



① P_1 takes a read miss to block A



② P_3 takes a read miss



Directory-Based Protocols

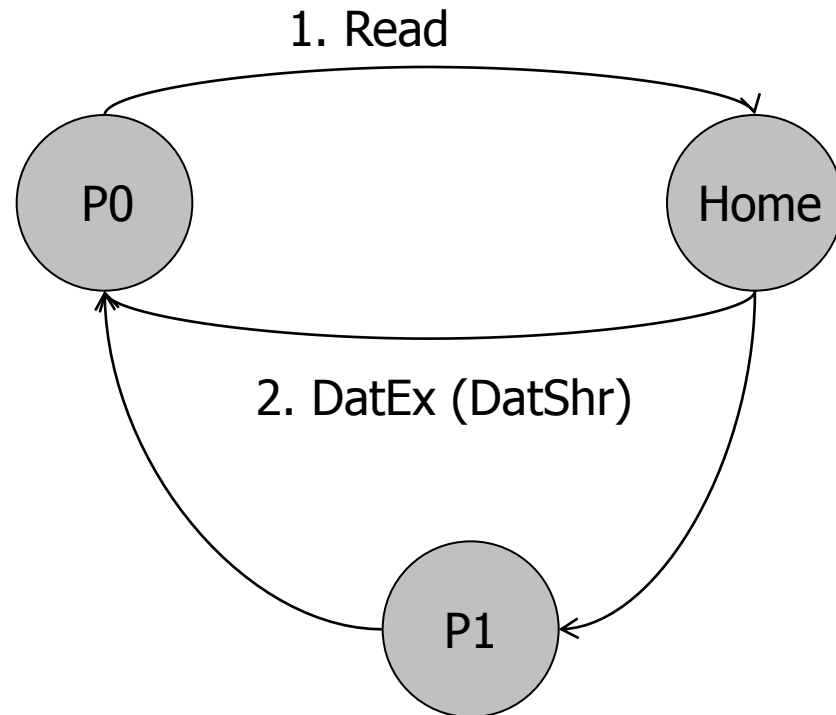
- Required when scaling past the capacity of a single bus
- Distributed, *but*:
 - Coherence still requires single point of serialization (for write serialization)
 - Serialization location can be different for every block (striped across nodes)
- We can reason about the protocol for a single block: one *server* (directory node), many *clients* (private caches)
- Directory receives *Read* and *ReadEx* requests, and sends *Inv!* requests: invalidation is explicit (as opposed to snoopy buses)

Directory: Basic Operations

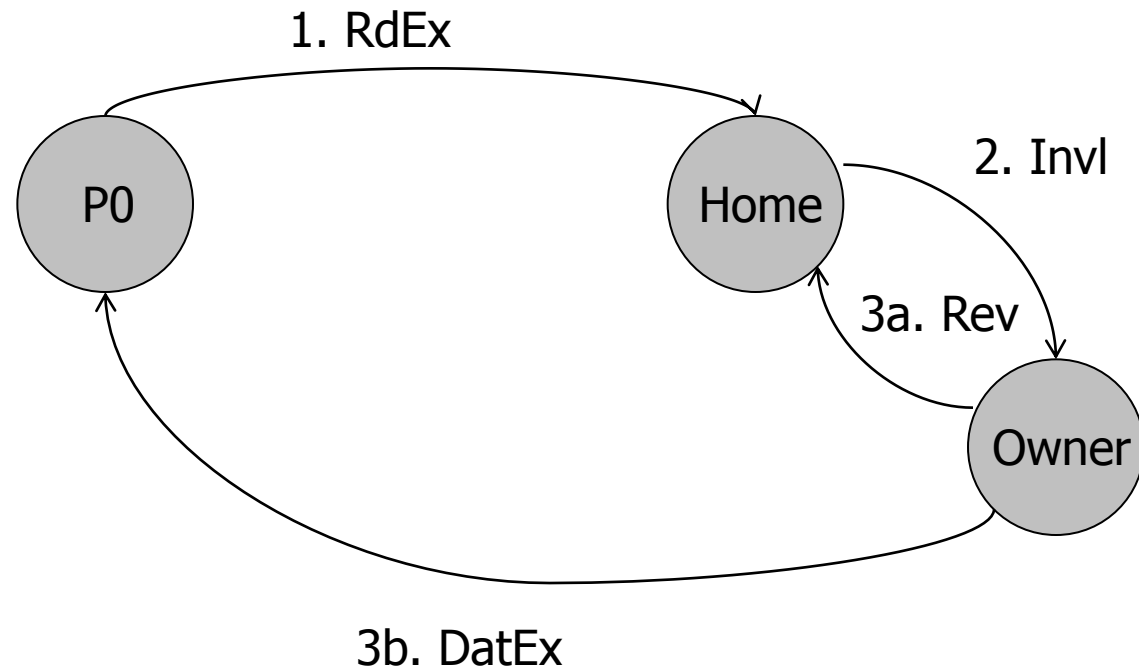
- Follow *semantics* of snoop-based system
 - but with explicit request, reply messages
- Directory:
 - Receives *Read*, *ReadEx*, *Upgrade* requests from nodes
 - Sends *Inval/Downgrade* messages to sharers if needed
 - Forwards request to memory if needed
 - Replies to requestor and updates sharing state
- Protocol design is flexible
 - Exact forwarding paths depend on implementation
 - For example, do cache-to-cache transfer?

MESI Directory Transaction: Read

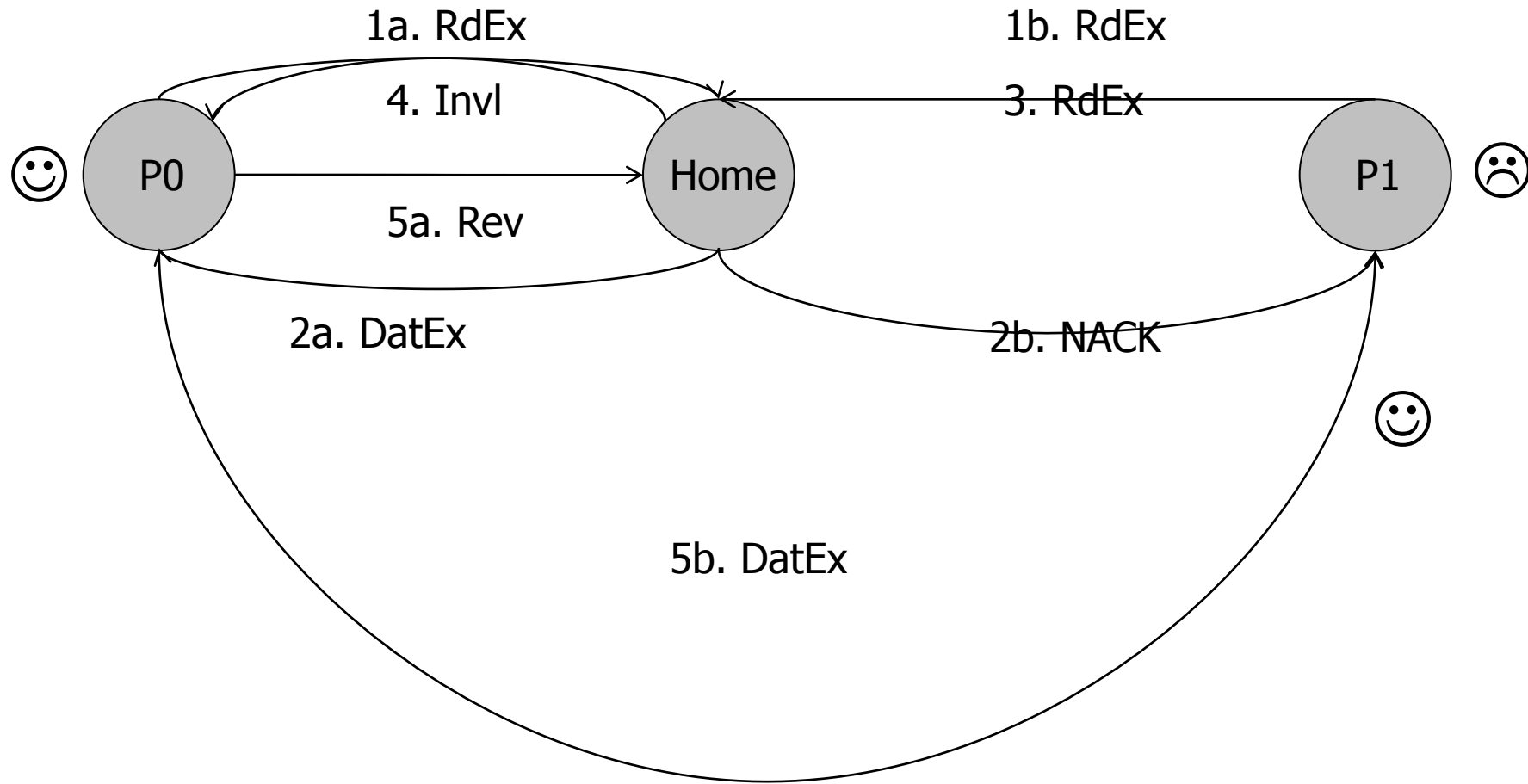
P0 acquires an address for reading:



RdEx with Former Owner



Contention Resolution (for Write)



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]

Directory: Data Structures

0x00	Shared: {P0, P1, P2}
0x04	---
0x08	Exclusive: P2
0x0C	---
...	---

- 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