

Computer Architecture: Cache Coherence

Prof. Onur Mutlu
Carnegie Mellon University

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.
- Laudon and Lenoski, “The SGI Origin: a ccNUMA highly scalable server,” ISCA 1997.

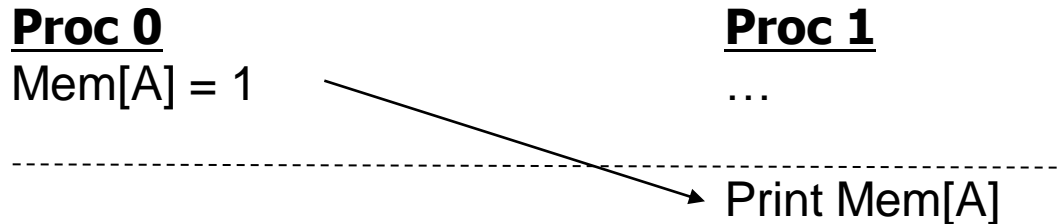
■ Recommended

- Censier and Feautrier, “A new solution to coherence problems in multicache systems,” IEEE Trans. Comput., 1978.
- Goodman, “Using cache memory to reduce processor-memory traffic,” ISCA 1983.
- Lenoski et al, “The Stanford DASH Multiprocessor,” IEEE Computer, 25(3):63-79, 1992.
- 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.

Cache Coherence

Shared Memory Model

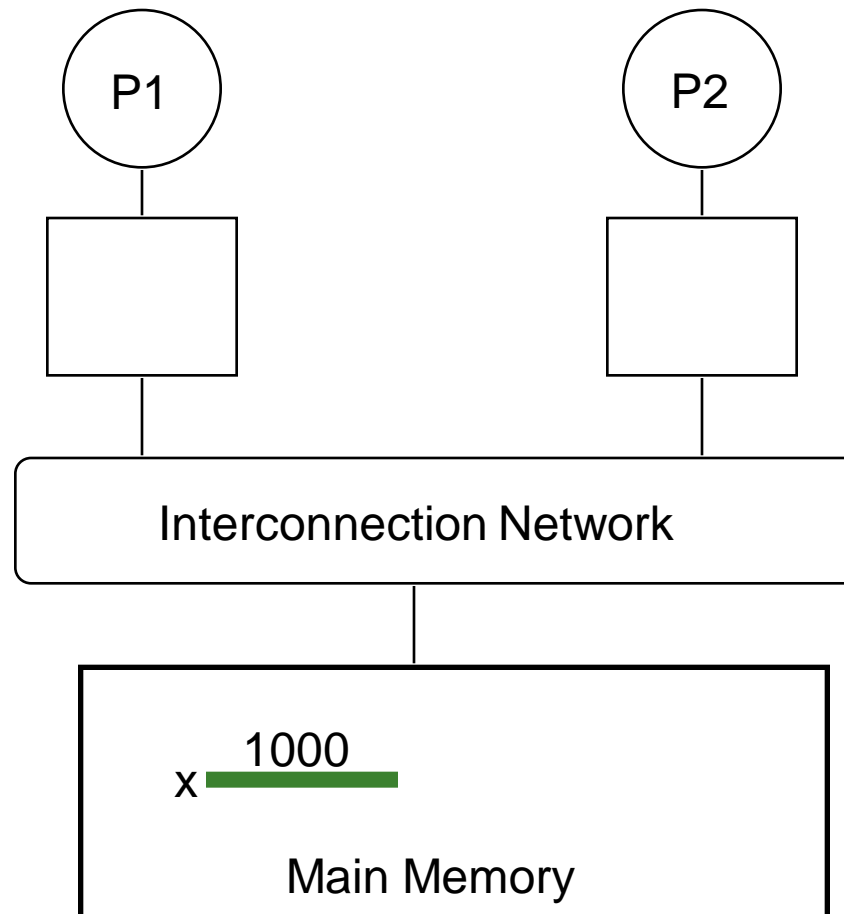
- Many parallel programs communicate through *shared memory*
- Proc 0 writes to an address, followed by Proc 1 reading
 - This implies communication between the two



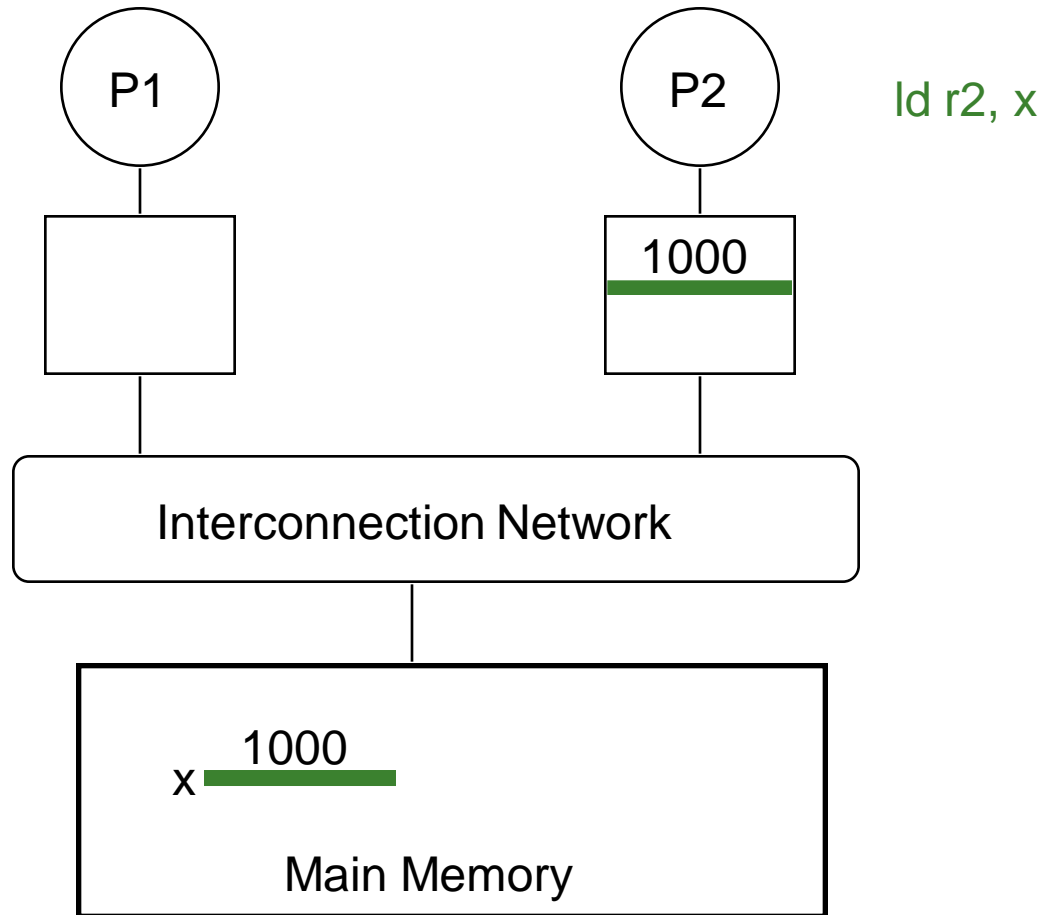
- Each read should receive the value last written by anyone
 - This requires synchronization (what does last written mean?)
- What if Mem[A] is cached (at either end)?

Cache Coherence

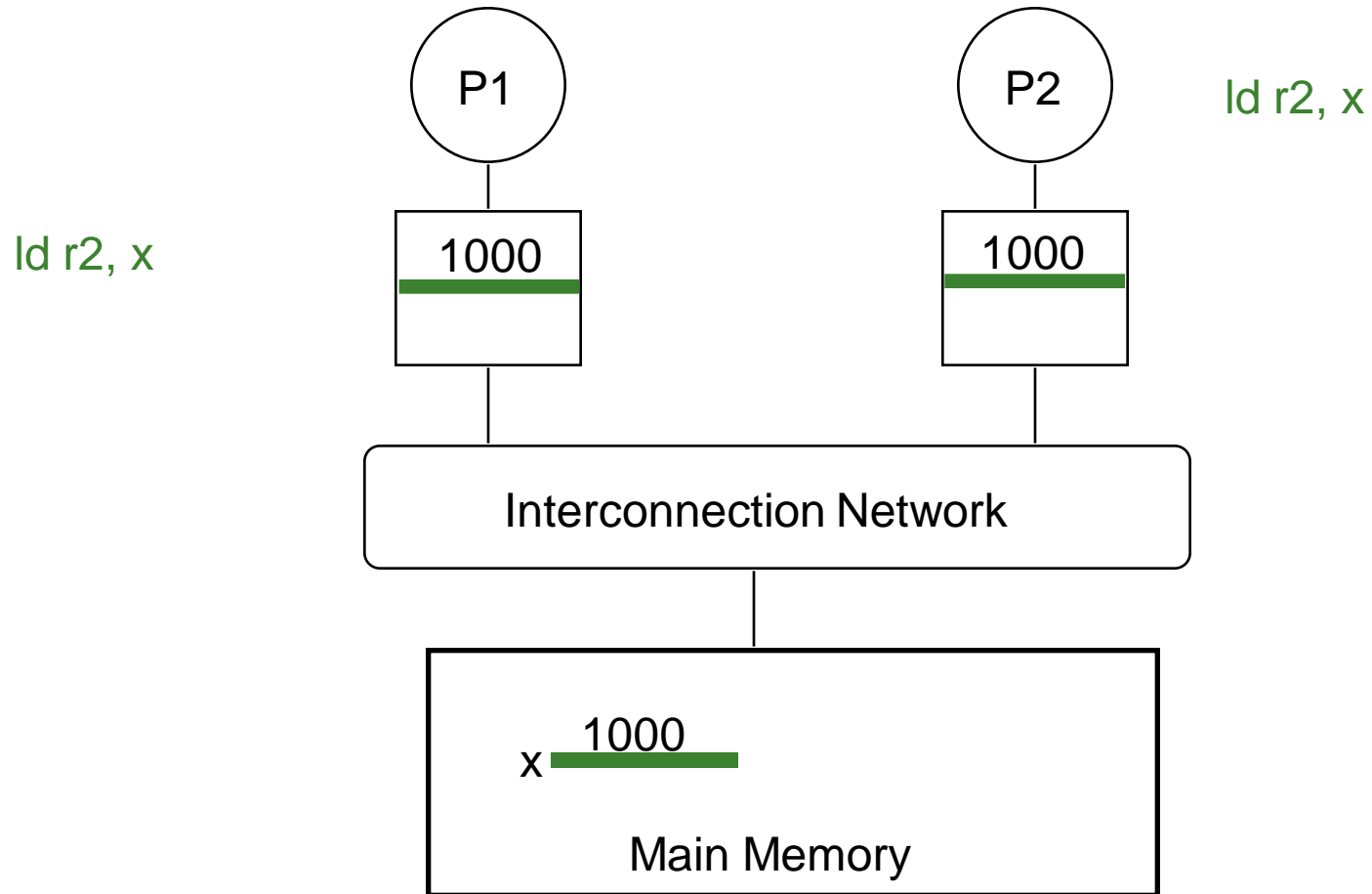
- Basic question: If multiple processors cache the same block, how do they ensure they all see a consistent state?



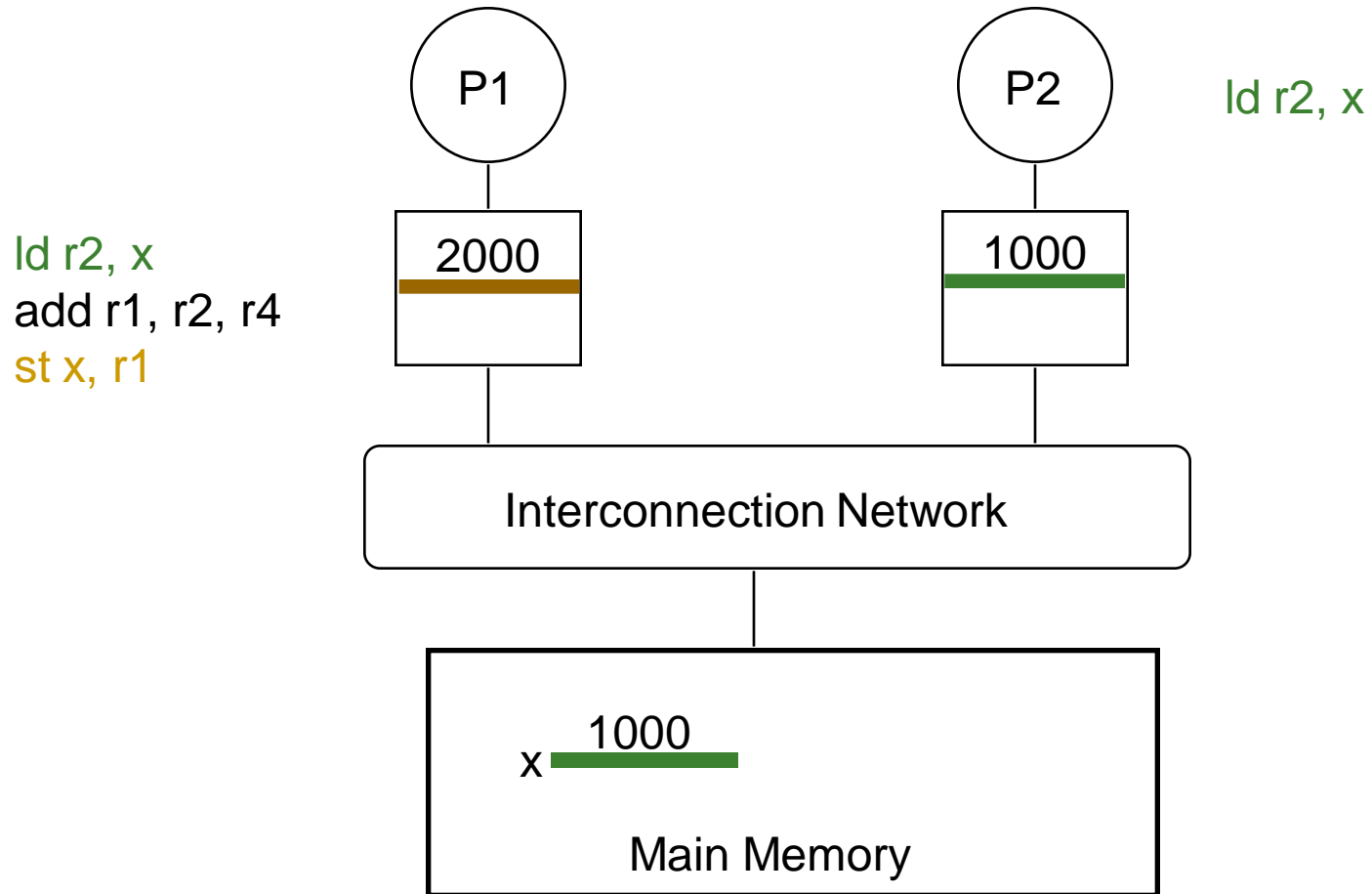
The Cache Coherence Problem



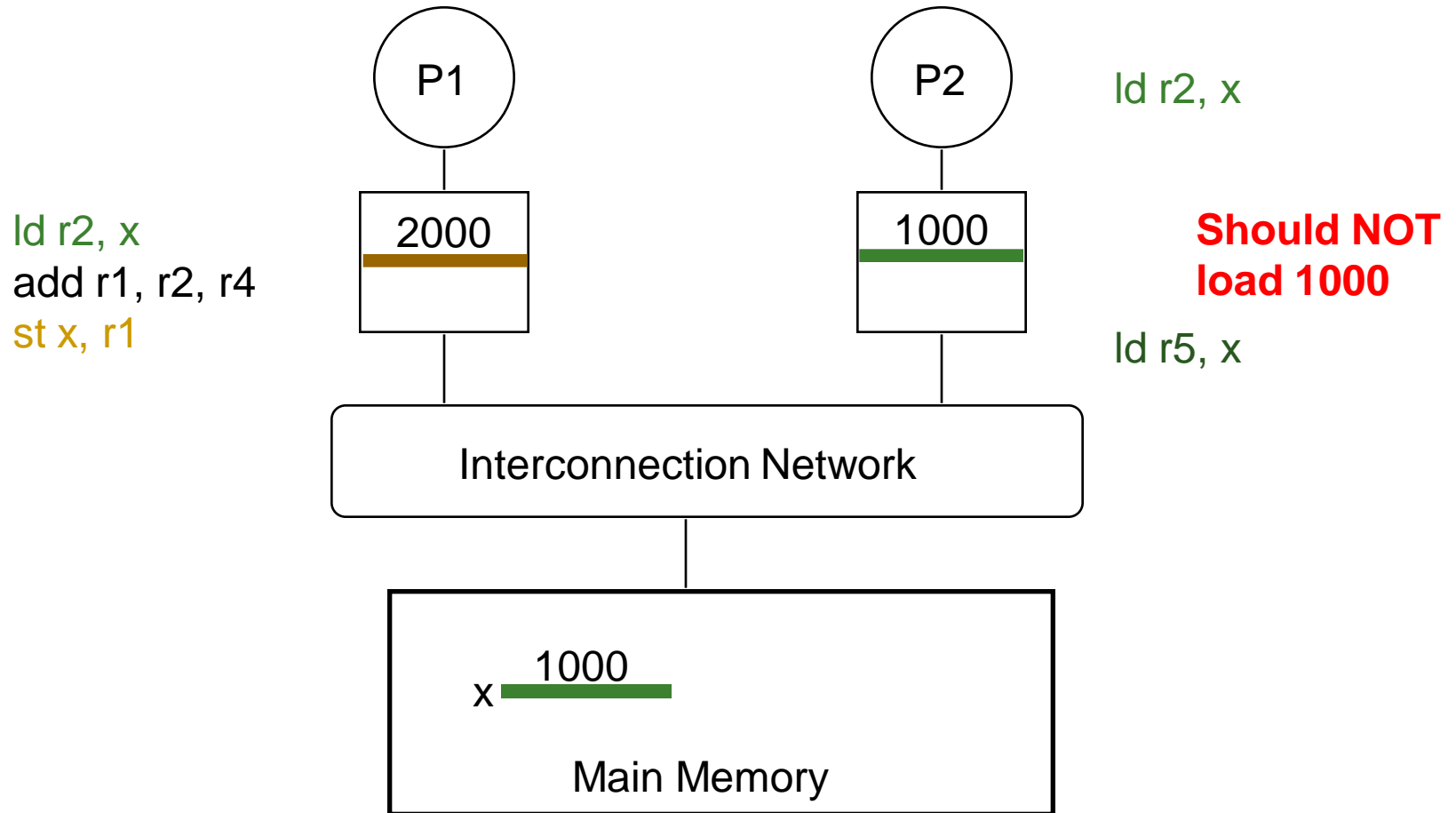
The Cache Coherence Problem



The Cache Coherence Problem



The Cache Coherence Problem



Cache Coherence: Whose Responsibility?

■ Software

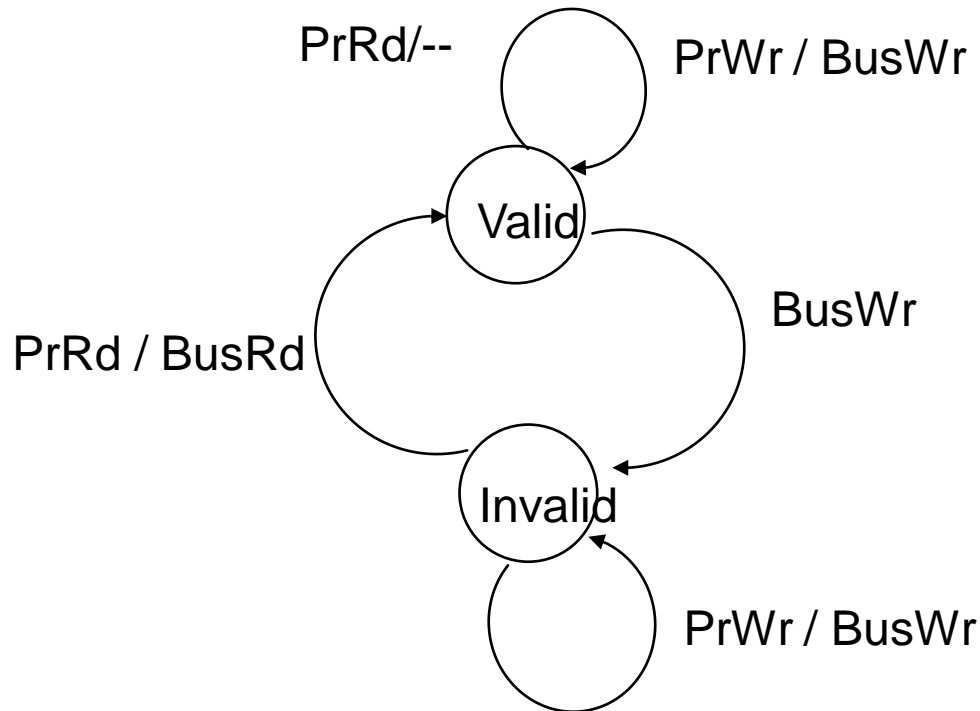
- Can the programmer ensure coherence if caches are invisible to software?
- What if the ISA provided a cache flush instruction?
 - FLUSH-LOCAL A: Flushes/invalidates the cache block containing address A from a processor's local cache.
 - FLUSH-GLOBAL A: Flushes/invalidates the cache block containing 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

- Caches “snoop” (observe) each other’s write/read operations. If a processor writes to a block, all others invalidate it from their caches.
- A simple protocol:



- Write-through, no-write-allocate cache
- Actions: PrRd, PrWr, 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
- **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 isn't valid, 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 to sharers
- (Other nodes update their caches if data was present)

Invalidate Protocol:

- Write to block, and simultaneously broadcast invalidation of address to sharers
- (Other nodes clear block from cache)

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 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 ownership (sharer set) for each block
 - Directory coordinates invalidation appropriately
 - ❑ E.g.: P1 asks directory for exclusive copy, directory asks P0 to invalidate, waits for ACK, then responds to P1

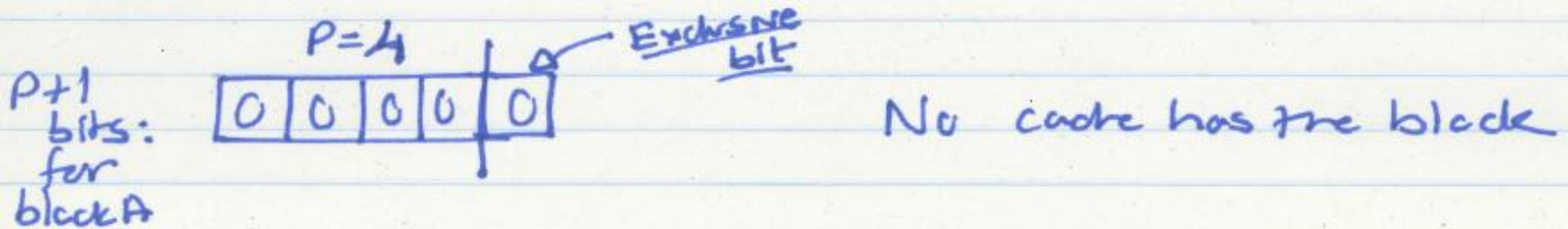
Directory Based Cache Coherence

Directory Based Coherence

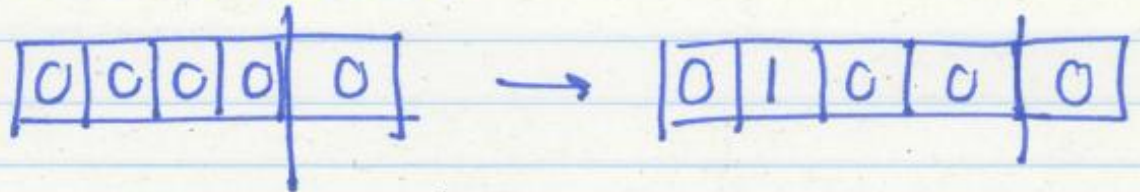
- Idea: A logically-central directory keeps track of where the copies of each cache block reside. Caches consult this directory to ensure coherence.
- An example mechanism:
 - For each cache block in memory, store $P+1$ bits in directory
 - One bit for each cache, indicating whether the block is in cache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

Directory Based Coherence Example (I)

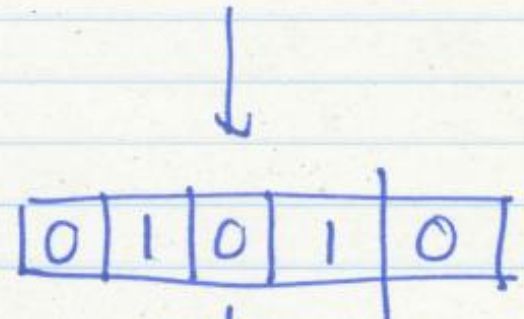
Example directory based scheme



① P_1 takes a read miss to block A



② P_3 takes a read miss



③ P₂ takes a write miss

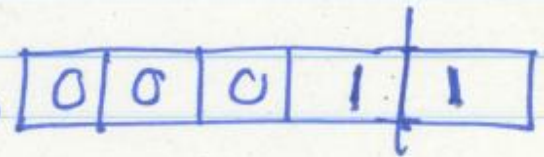
- invalidate P₁ & P₃'s caches
- write request → P₂ has the exclusive copy of the block now. Set the Exclusive bit



- 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

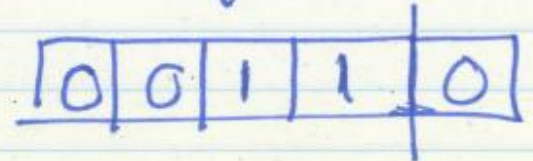
④ P₃ takes a write miss

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



⑤ P₂ takes a read miss

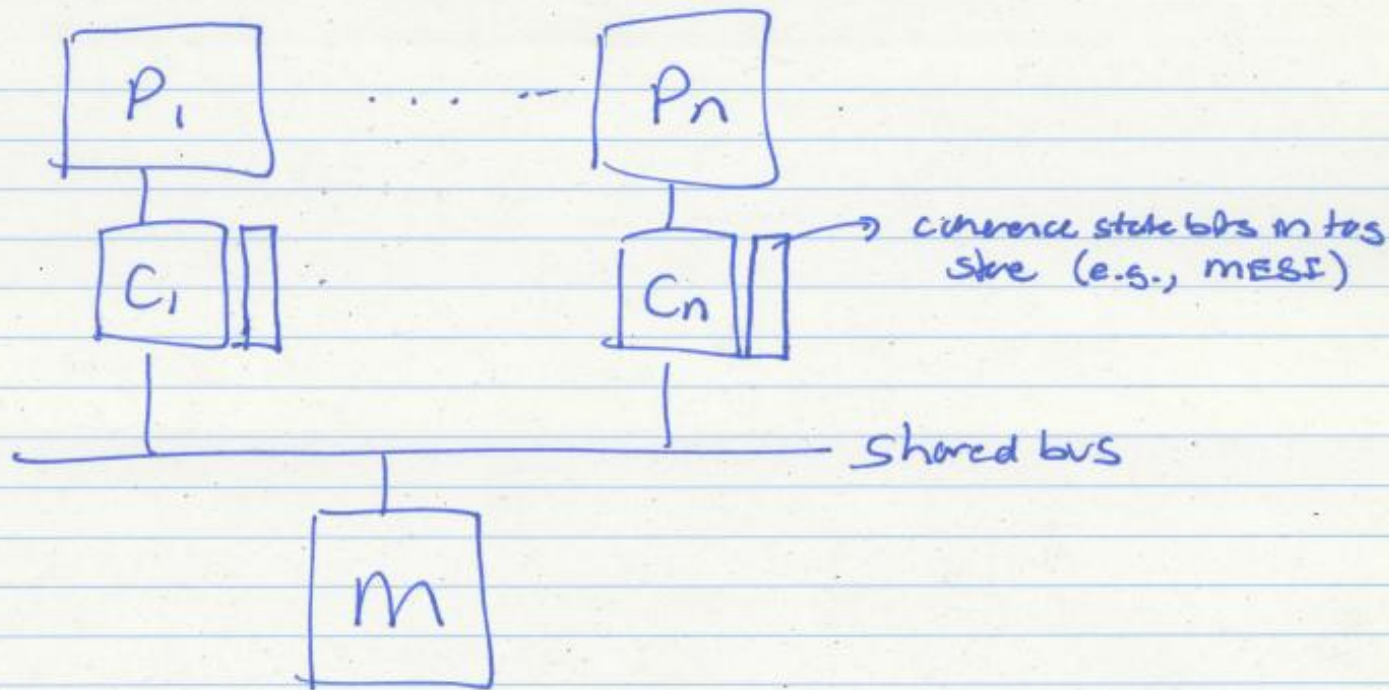
- P₃ supplies it



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

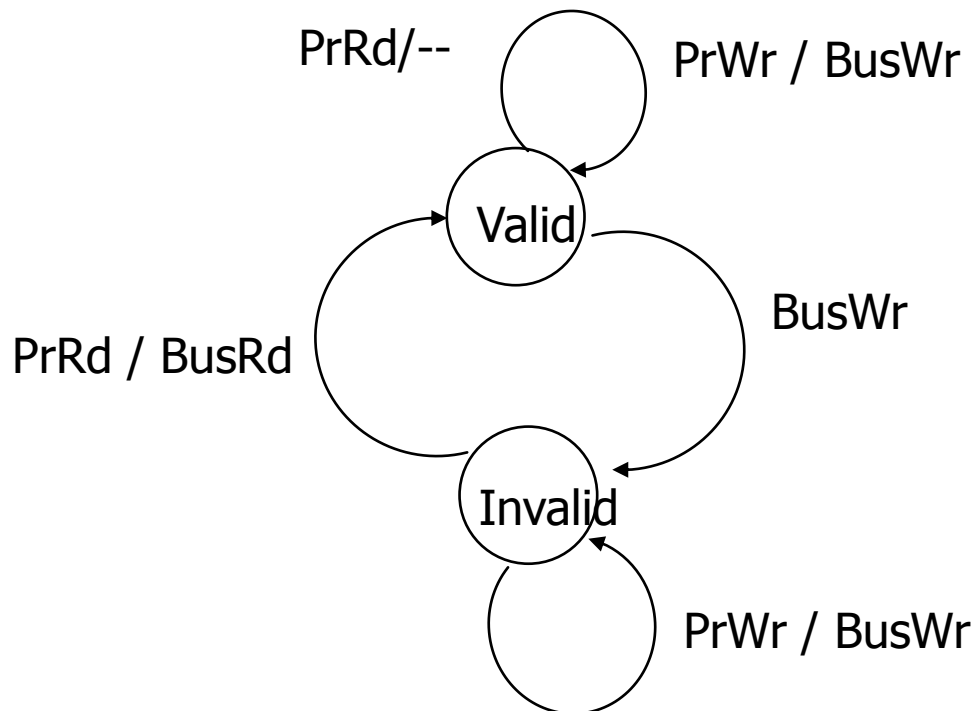
Processor actions to a block: PR (Proc. Read)
 RW (Proc. Write)

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:



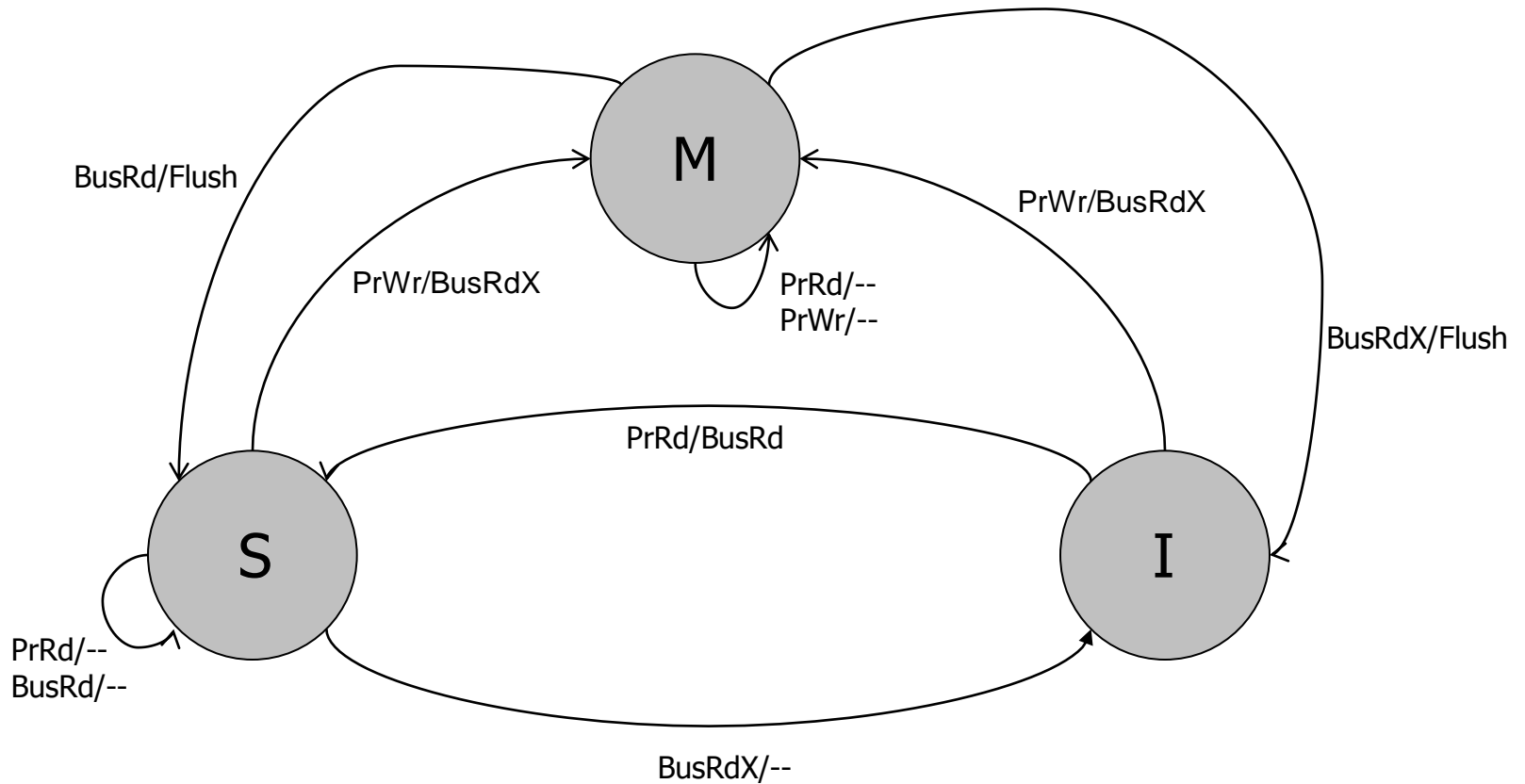
- Write-through, no-write-allocate cache
- Actions: PrRd, PrWr, BusRd, BusWr

A More Sophisticated Protocol: MSI

- Extend single valid bit per block to three states:
 - **M**(odified): cache line is only copy and is dirty
 - **S**(hared): cache line is one of several copies
 - **I**(nvalid): not present

- 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



ObservedEvent/Action

[Culler/Singh96]

The Problem with MSI

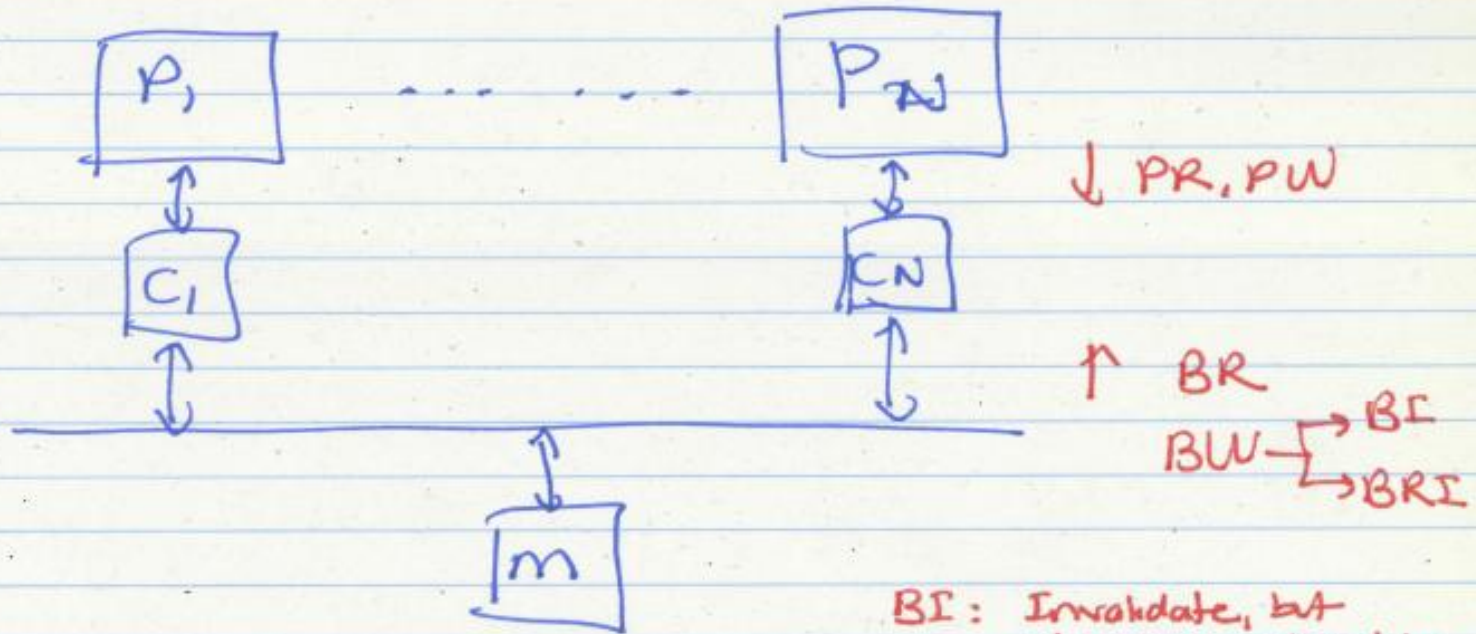
- A block is in no cache to begin with
- Problem: On a read, the block immediately goes to “Shared” state although it may be the only copy to be cached (i.e., no other processor will cache it)
- Why is this a problem?
 - Suppose the cache that read the block wants to write to it at some point
 - It needs 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, I SCA 1984

Illinois Protocol



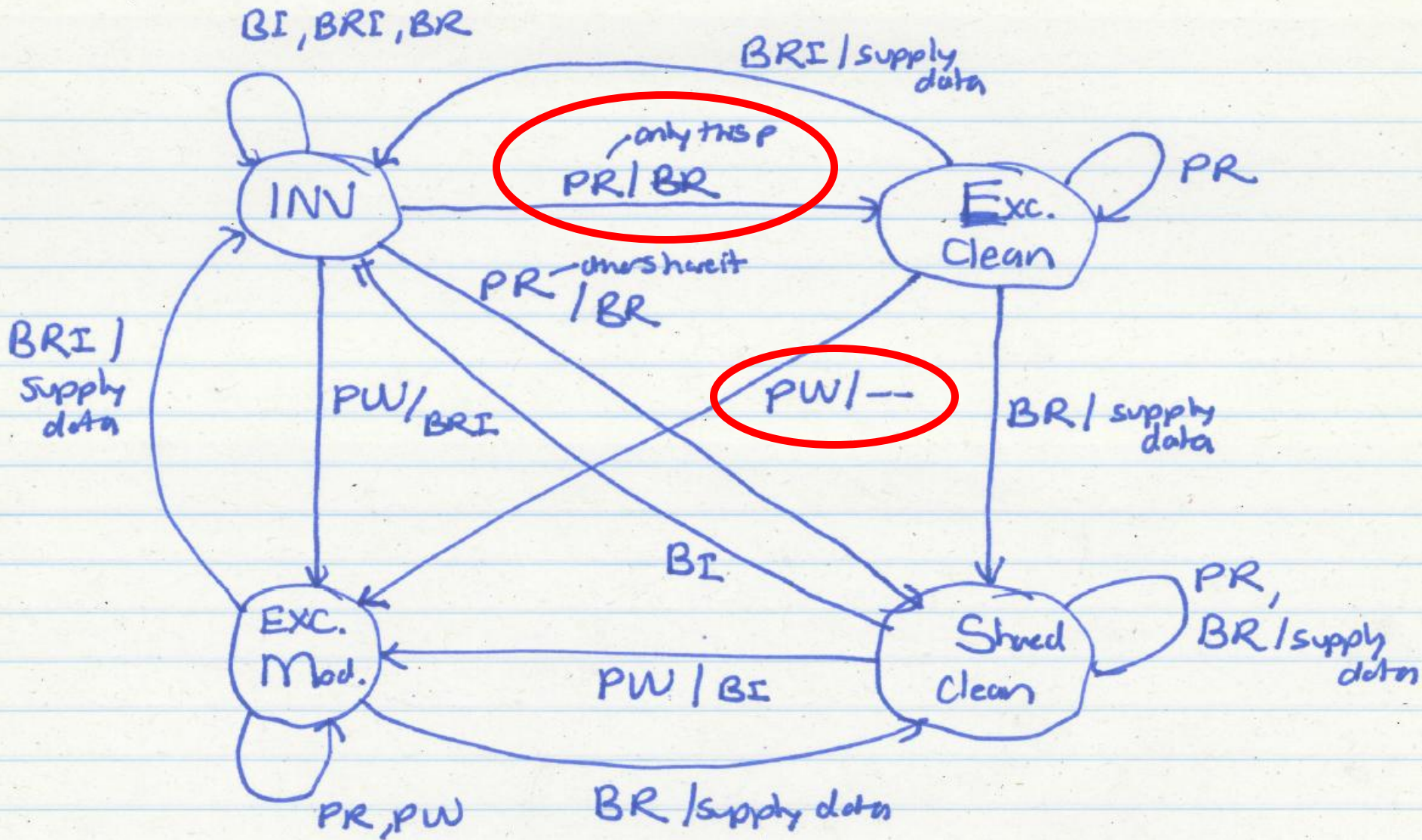
BI: Invalidate, but already have the data (do not supply it)

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

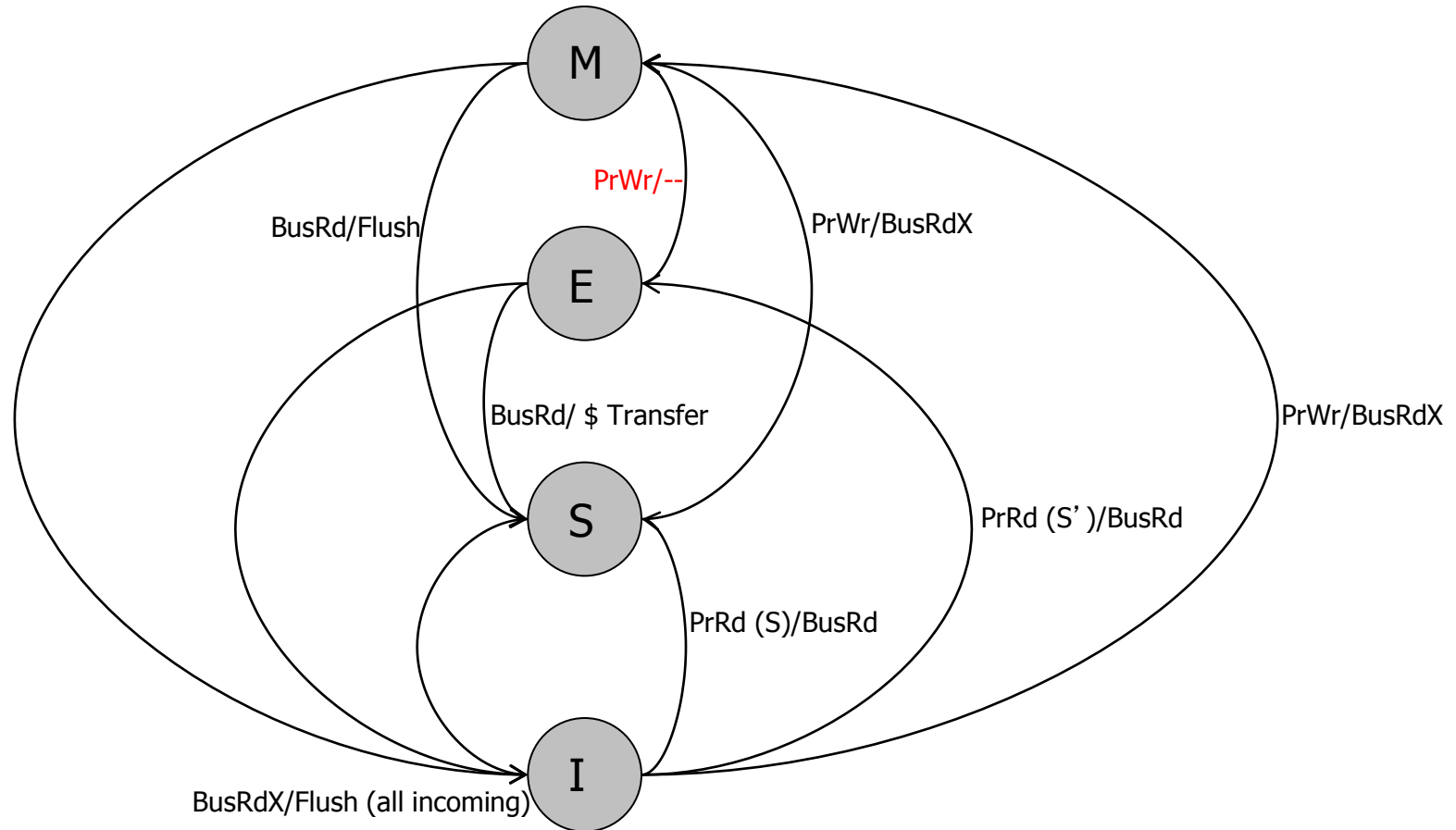
4 States

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

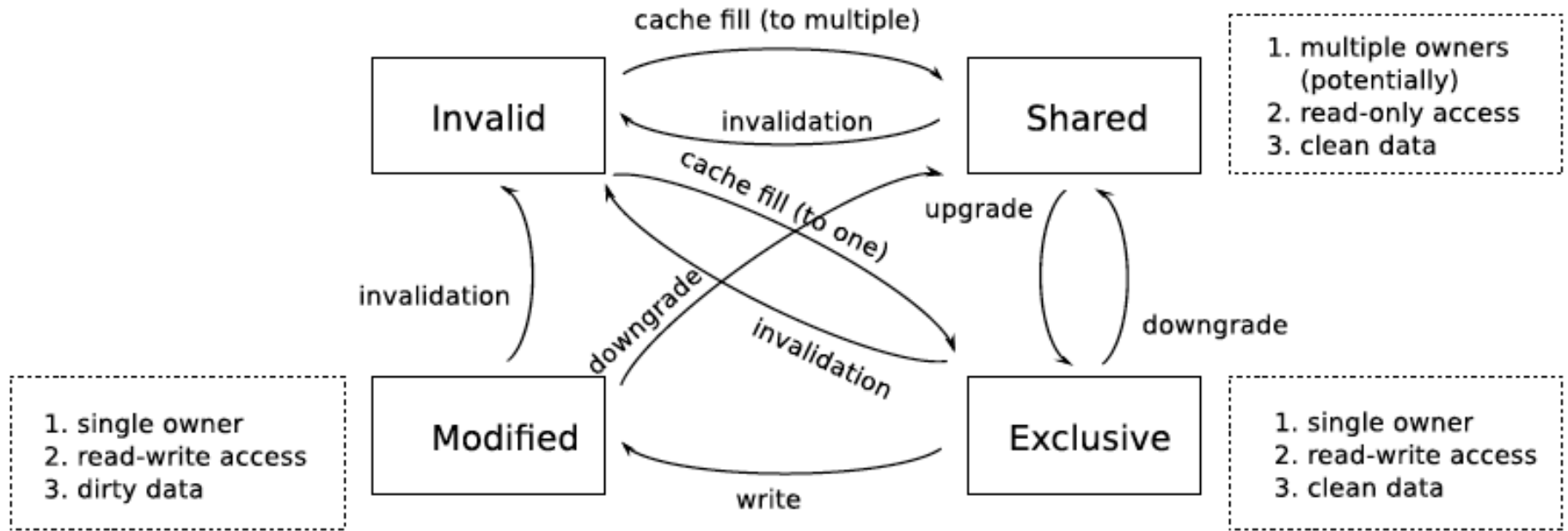
MESI State Machine



MESI State Machine



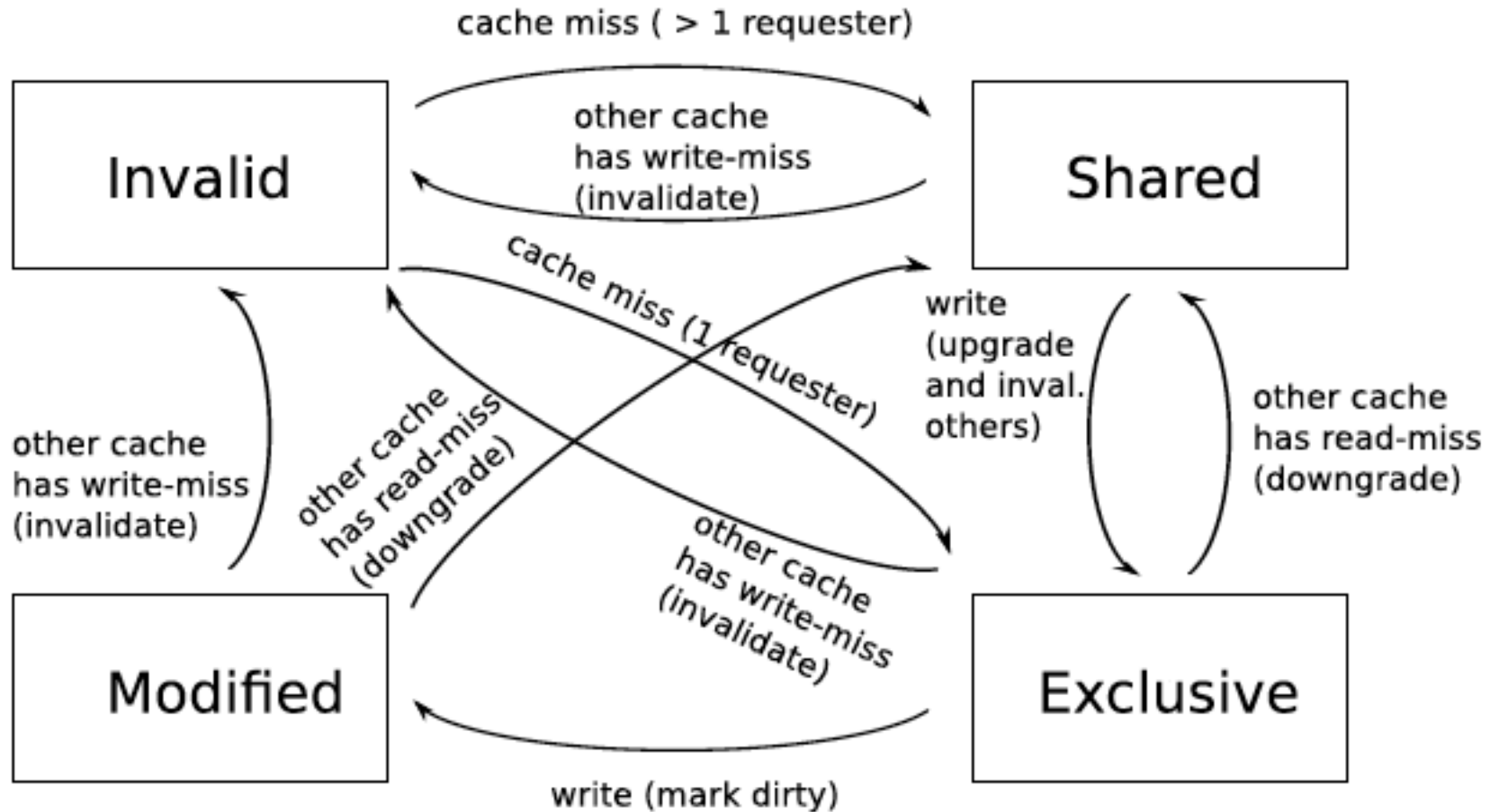
MESI State Machine from 18-447 Lab 7



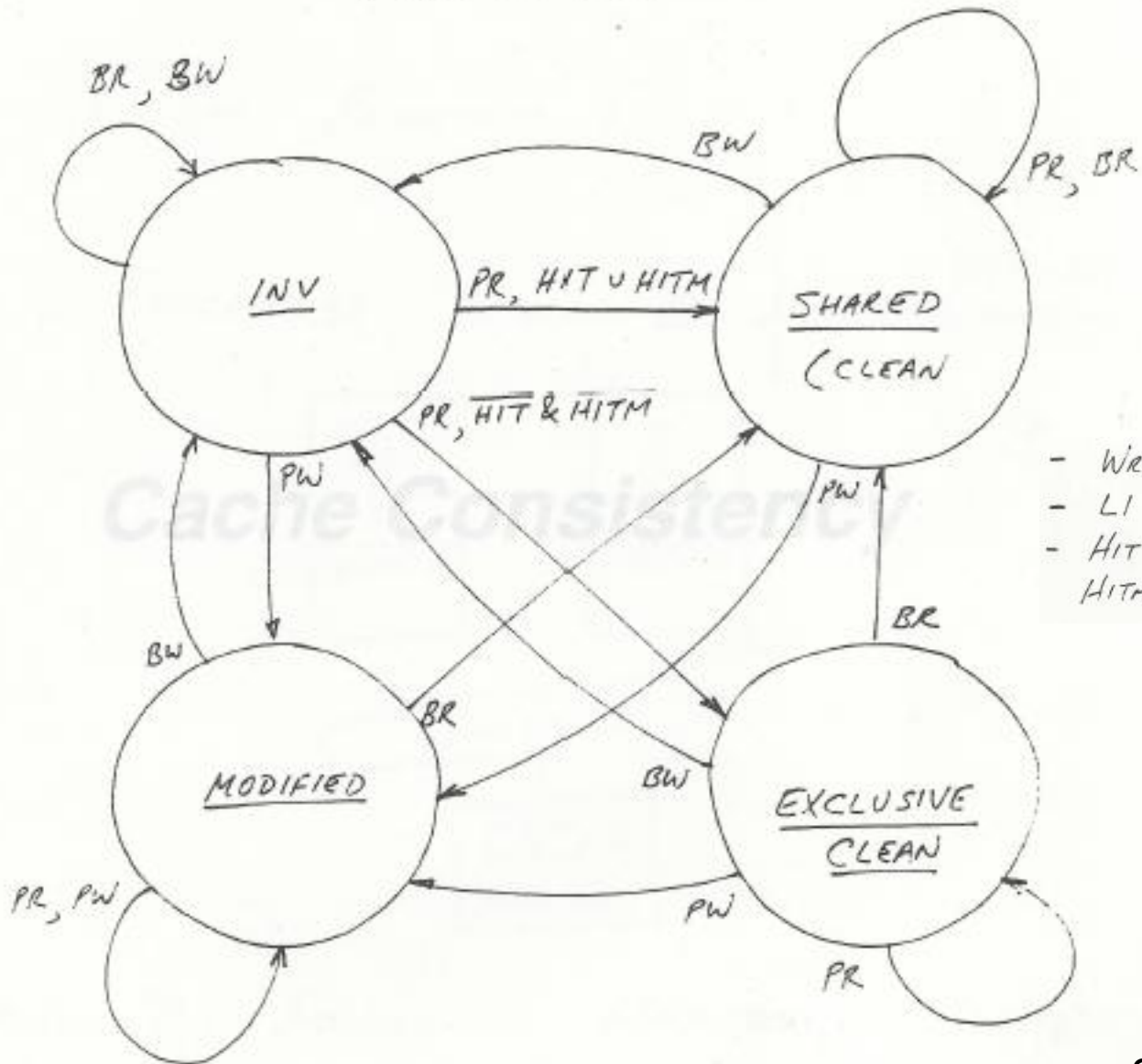
A transition from a single-owner state (Exclusive or Modified) to Shared is called a **downgrade**, because the transition takes away the owner's right to modify the data

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 18-447 Lab 7



Intel Pentium Pro



- WRITE ALLOCATE
- L1 CAN HAVE DATA NOT IN L2
- HIT : SOMEONE HAS IT CLEAN
- HITM : SOMEONE HAS IT DIRTY

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 cache has 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

- 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 while it is cached

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 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 ownership (sharer set) for each block
 - Directory coordinates invalidation appropriately
 - ❑ 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: miss → bus transaction to memory
- + Global serialization is easy: bus provides this already (arbitration)
- + Simple: 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)

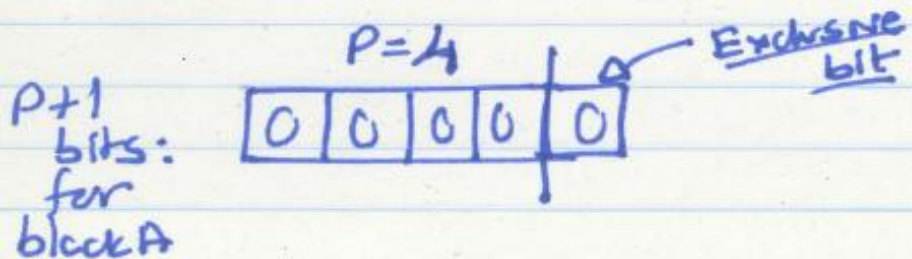
Revisiting Directory-Based Cache Coherence

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:
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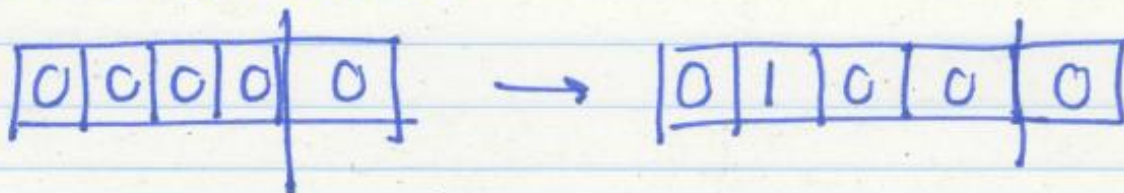
Remember: Directory Based Coherence

Example directory based scheme

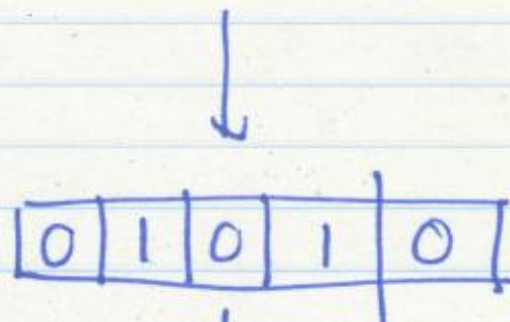


No cache has the block

① P_1 takes a read miss to block A



② P_3 takes a read miss



Directory-Based Protocols

- Especially desirable when scaling the system 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: Data Structures

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

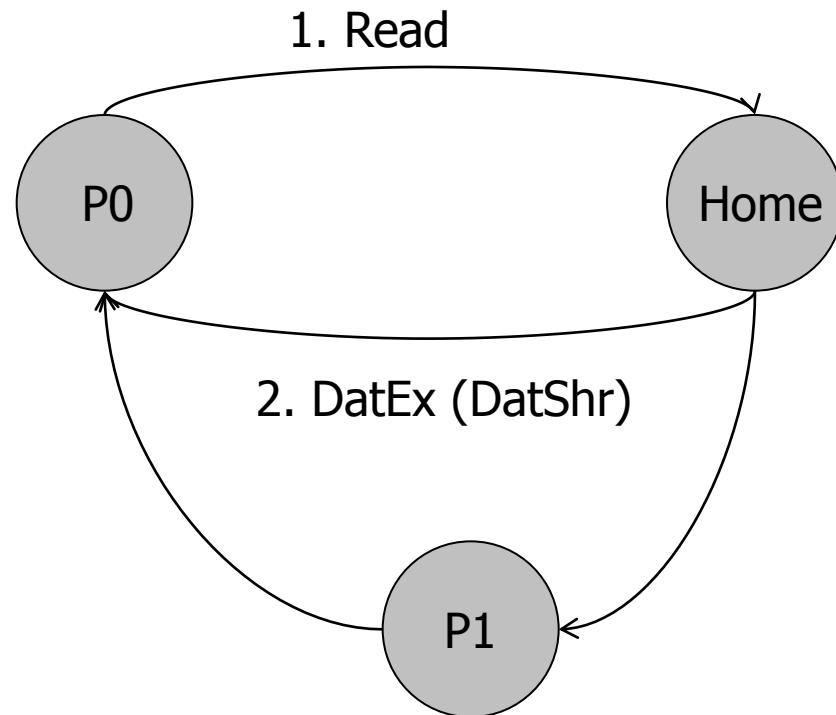
- Key operation to support is *set inclusion test*
 - False positives are OK: want to know which caches *may* contain a copy of a block, and spurious invalidations are ignored
 - False positive rate determines *performance*
- Most accurate (and expensive): full bit-vector
- Compressed representation,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

Directory: Basic Operations

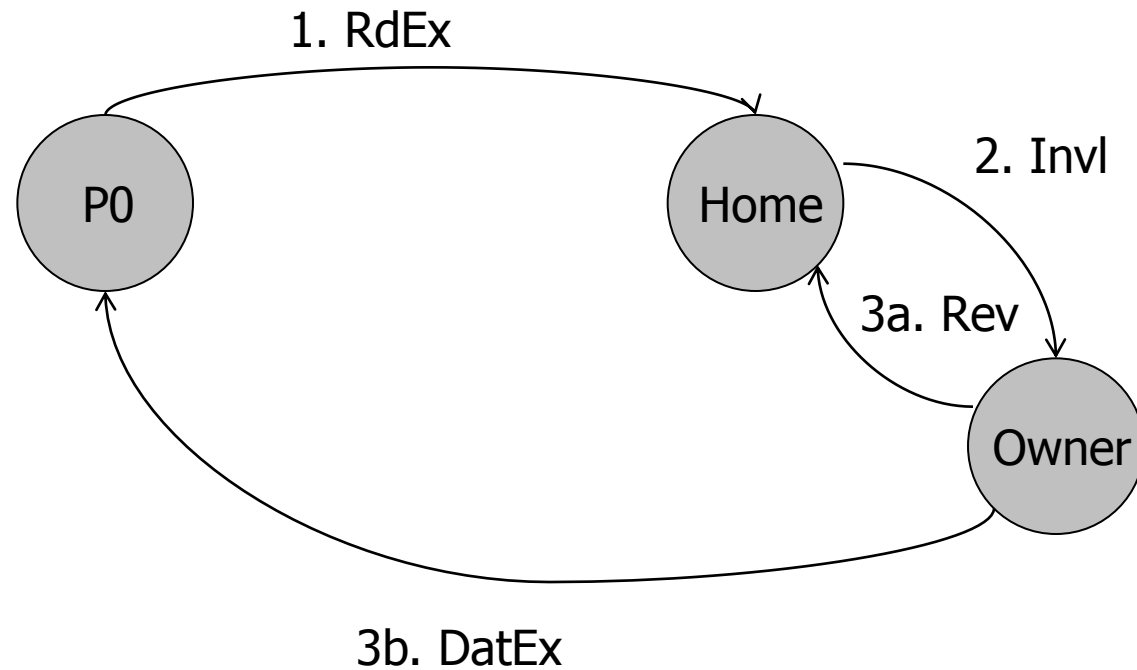
- Follow *semantics* of snoop-based system
 - but with explicit request, reply messages
- Directory:
 - Receives *Read, ReadEx, Upgrade* requests from nodes
 - Sends *Inval/Downgrade* messages to sharers if needed
 - Forwards request to memory if needed
 - Replies to requestor and updates sharing state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

MESI Directory Transaction: Read

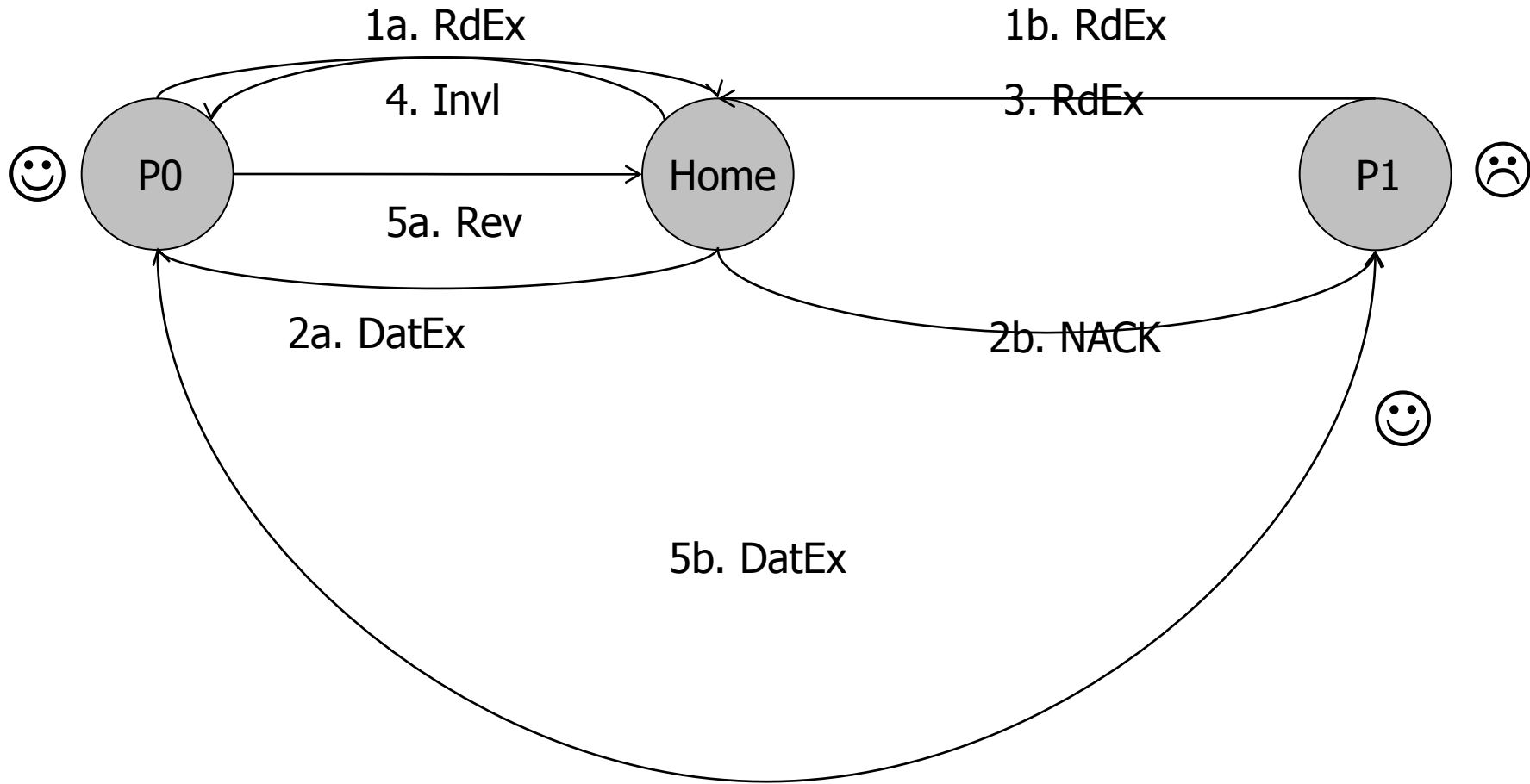
P0 acquires an address for reading:



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]

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Backup slides

Referenced Readings

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- 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.

Other Recommended Readings (Research)

- Kelm et al., “WAYPOINT: scaling coherence to thousand-core architectures,” PACT 2010.
- Kelm et al., “Cohesion: a hybrid memory model for accelerators,” ISCA 2010.
- Martin et al, “Token coherence: decoupling performance and correctness,” ISCA 2003.

Related Videos

- Multiprocessor Correctness and Cache Coherence
 - <http://www.youtube.com/watch?v=U-VZKMgItDM>
 - <http://www.youtube.com/watch?v=6xEpbFVgnf8&list=PL5PHm2jkkXmidJOd59REog9jDnPDTG6IJ&index=33>

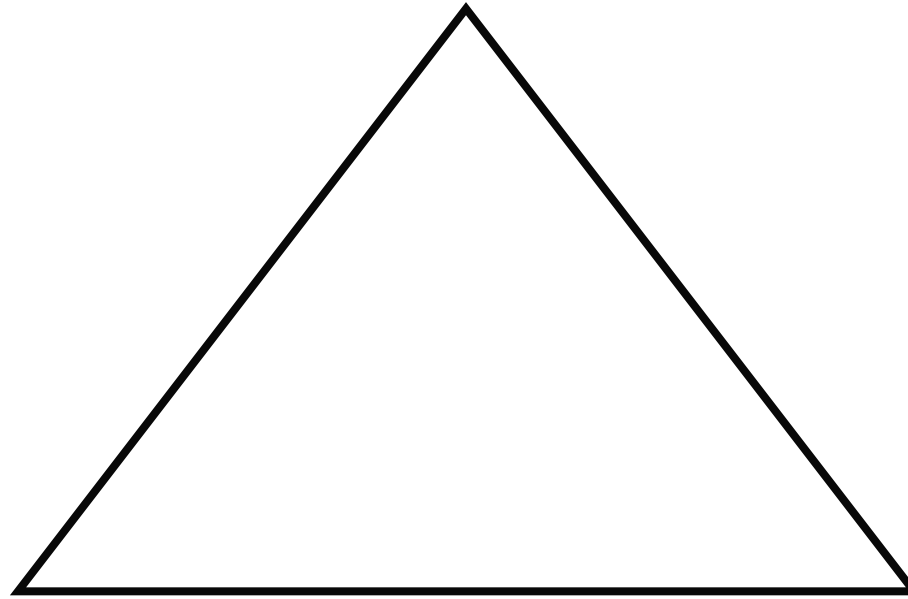
Related Exam Questions

- Question 5 in
 - <http://www.ece.cmu.edu/~ece447/s13/lib/exe/fetch.php?media=final.pdf>

- Question I-11 in
 - <http://www.ece.cmu.edu/~ece447/s12/lib/exe/fetch.php?media=wiki:18447-final.pdf>

Motivation: Three Desirable Attributes

Low-latency cache-to-cache misses



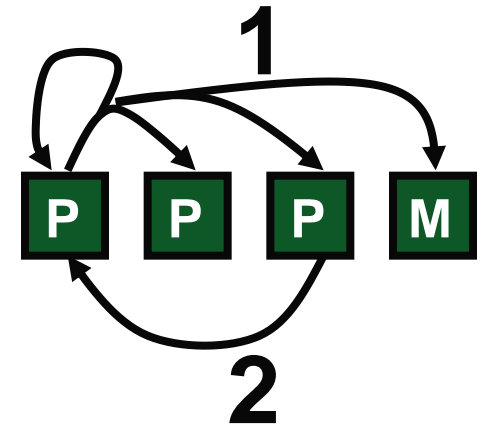
No bus-like interconnect

Bandwidth efficient

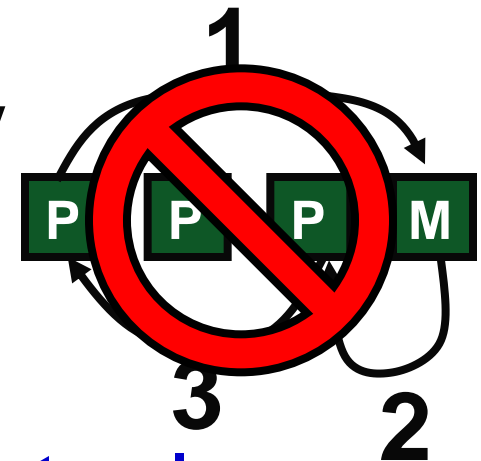
Dictated by workload and technology trends

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



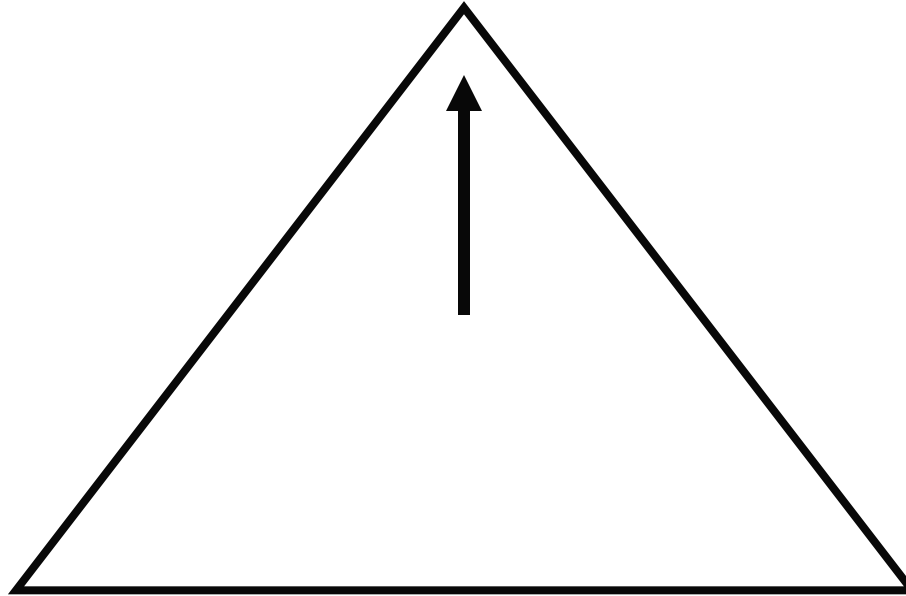
Directory Protocol



Workload trends → snooping protocols

Workload Trends

Low-latency cache-to-cache misses



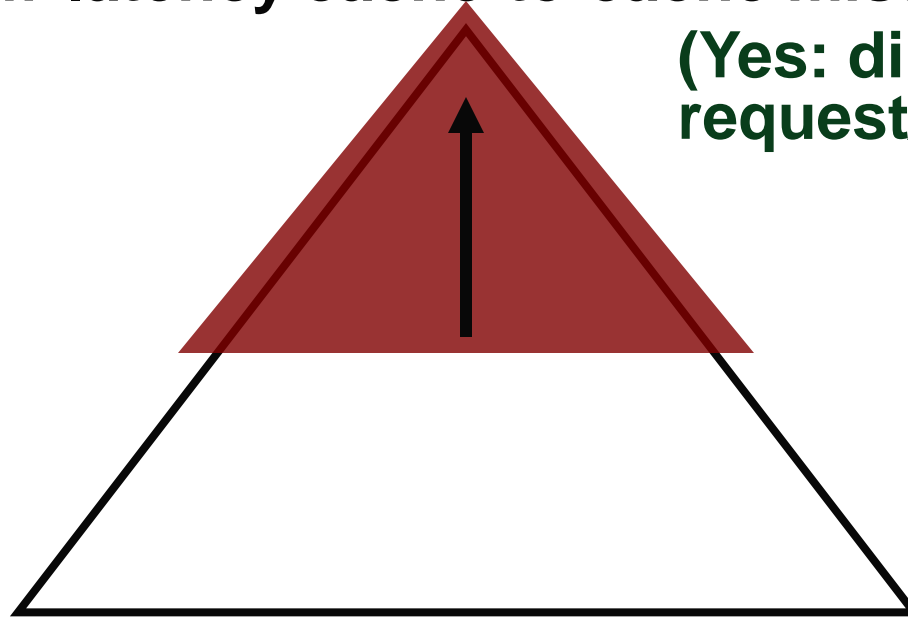
No bus-like interconnect

Bandwidth efficient

Workload Trends Snooping Protocols

Low-latency cache-to-cache misses

(Yes: direct request/response)



No bus-like interconnect

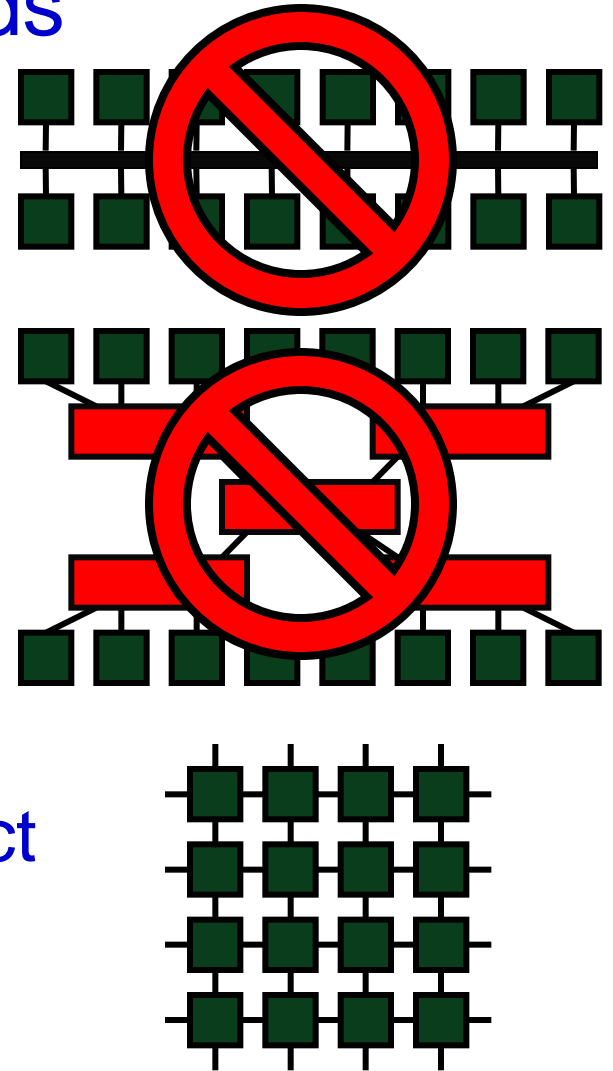
(No: requires a “virtual bus”)

Bandwidth efficient

(No: broadcast always)

Technology Trends

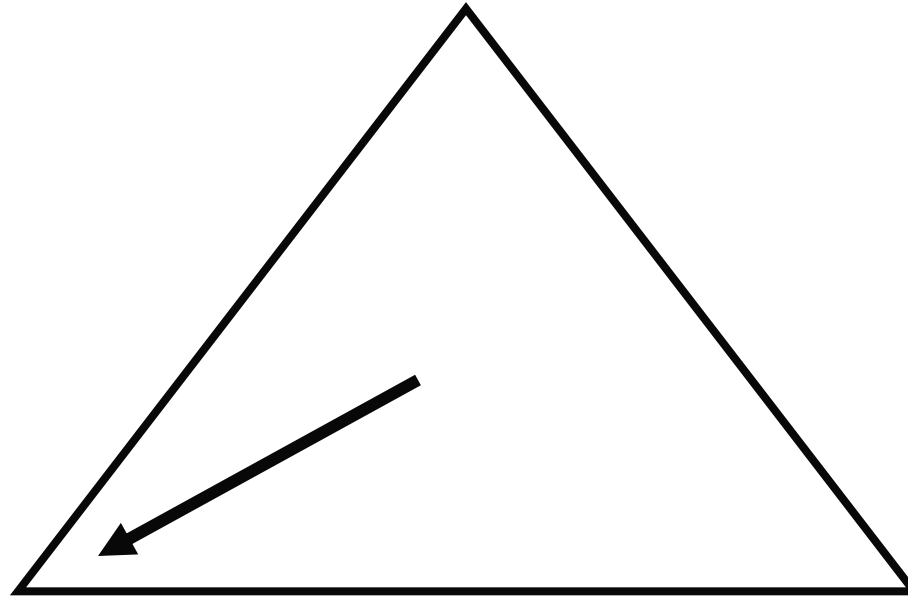
- High-speed point-to-point links
 - No (multi-drop) busses
- Increasing design integration
 - “Glueless” multiprocessors
 - Improve cost & latency
- Desire: low-latency interconnect
 - Avoid “virtual bus” ordering
 - Enabled by directory protocols



Technology trends → unordered interconnects

Technology Trends

Low-latency cache-to-cache misses



No bus-like interconnect

Bandwidth efficient

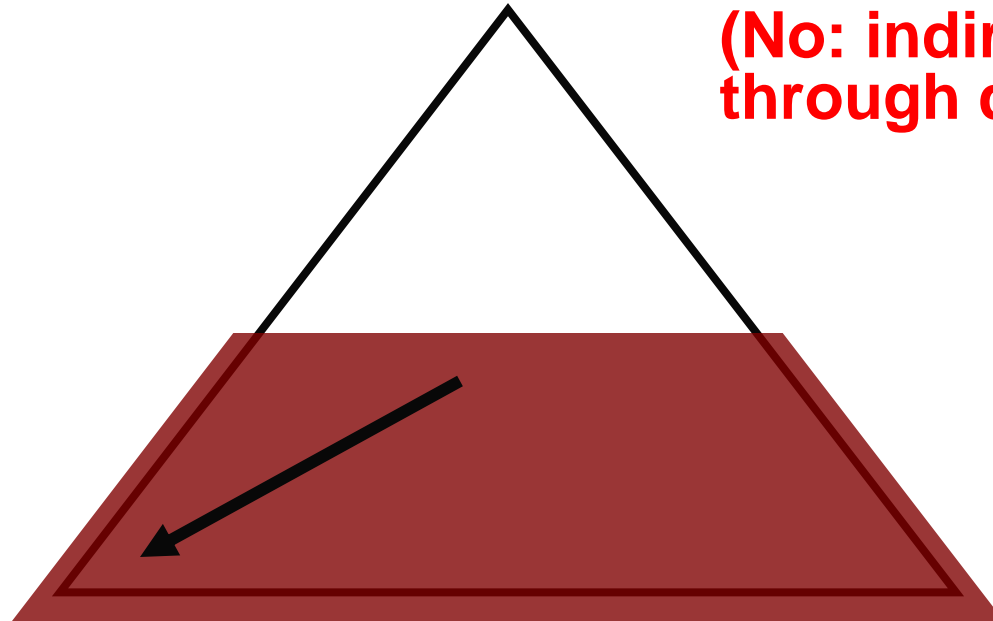
Technology Trends □ Directory Protocols

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

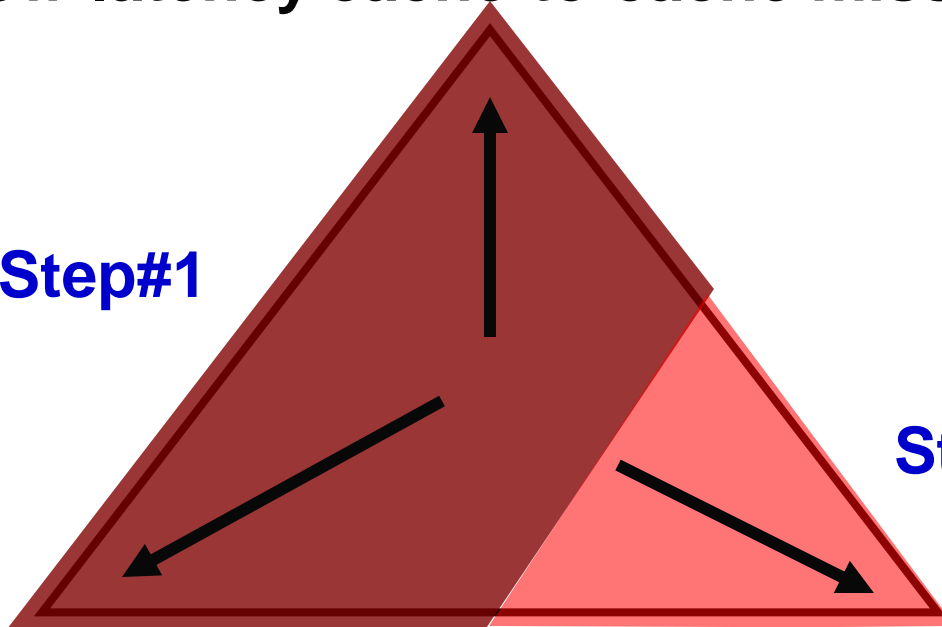
Low-latency cache-to-cache misses

Step#1

Step#2

No bus-like interconnect

Bandwidth efficient



Token Coherence: Key Insight

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

Key insight

- 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.

Token Coherence: Contributions

1. **Token counting** rules for enforcing safety
2. **Persistent requests** for preventing starvation
3. **Decoupling correctness and performance** in cache coherence protocols
 - Correctness Substrate
 - Performance Policy
4. **Exploration of three performance policies**