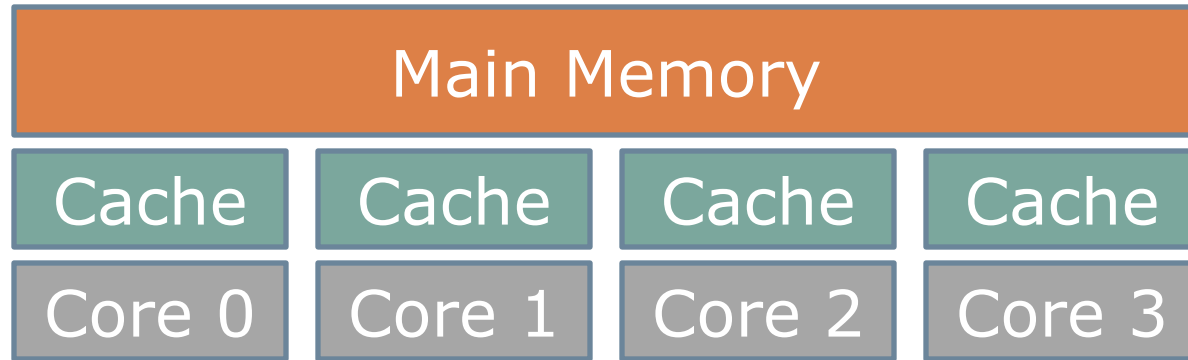


Cache Coherence

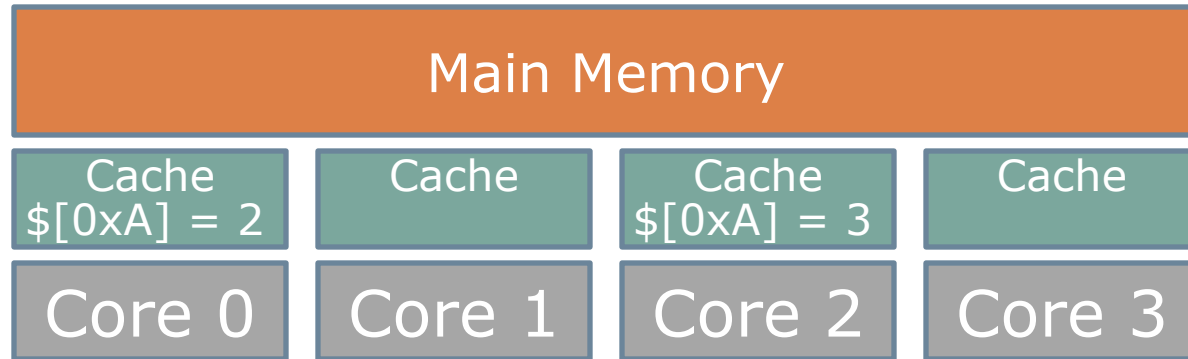
Multicores



- Modern microprocessors usually have 2 to 8 cores where each core has a **private cache** for performance
- Cores can be used cooperatively to speed up an application
- Cores communicate with each other via memory

Cache Coherence Avoids Stale Data

- Need to provide the illusion of a **single shared memory** even though multicores have multiple private caches
- Problem:



- 1 LD 0xA → 2
- 2 ST 3 → 0xA
- 3 LD 0xA → 2 (stale!)

- Solution: A **cache coherence protocol** controls cache contents to avoid stale lines
 - e.g., invalidate core 0's copy of A before letting core 2 write to it

Maintaining Coherence

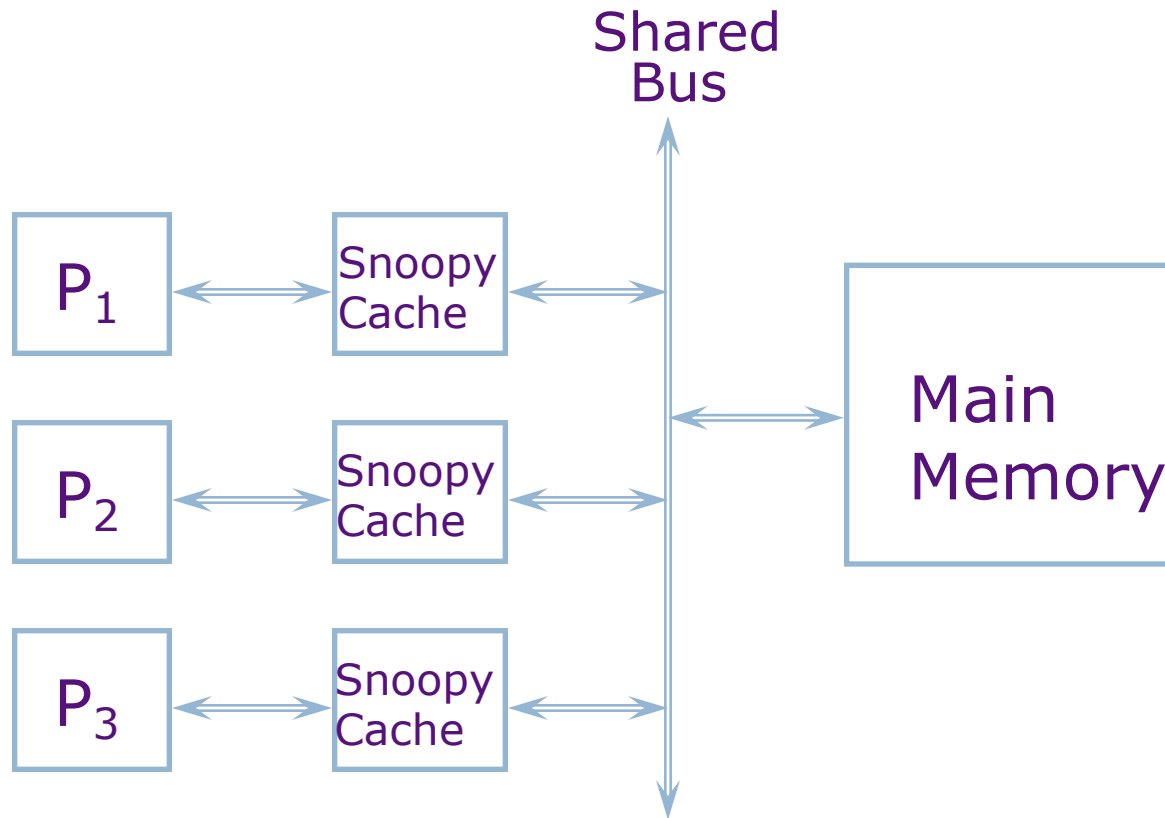
- In a *coherent memory* all loads and stores can be placed in a global order
 - multiple copies of an address in various caches can cause this property to be violated
- This property can be ensured if:
 - Only one cache at a time has the write permission for an address
 - No cache can have a stale copy of the data after a write to the address has been performed

Implementing Cache Coherence

- Coherence protocols must enforce two rules:
 - **Write propagation:** Writes eventually become visible to all processors
 - **Write serialization:** Writes to the same location are serialized (all processors see them in the same order)
- How to ensure write propagation?
 - **Write-invalidate protocols:** Invalidate all other cached copies before performing the write
 - **Write-update protocols:** Update all other cached copies after performing the write
- How to ensure write serialization?
 - **Snooping-based protocols:** All caches observe each other's actions through a shared bus
 - **Directory-based protocols:** A coherence directory tracks contents of private caches and serializes requests

Snooping-Based Coherence

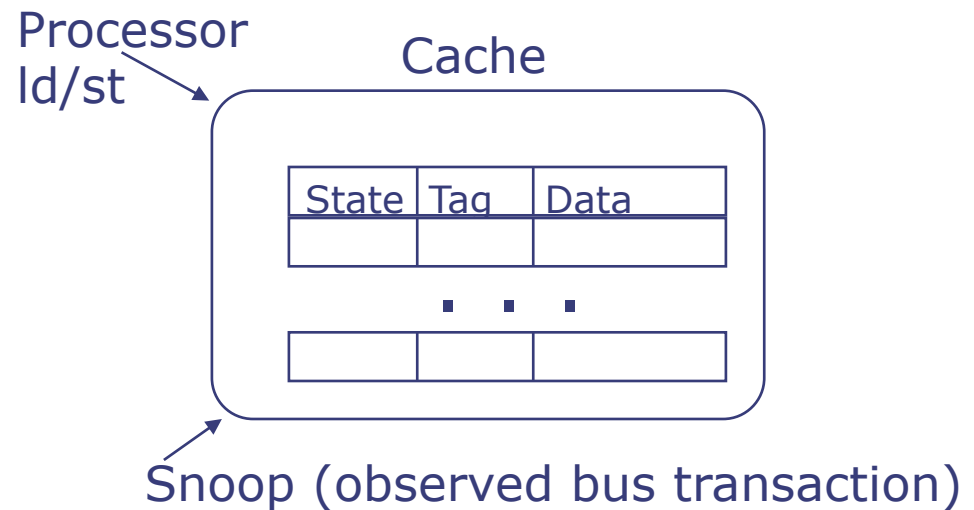
[Goodman 1983]



Caches watch (snoop on) bus to keep all processors' view of memory coherent

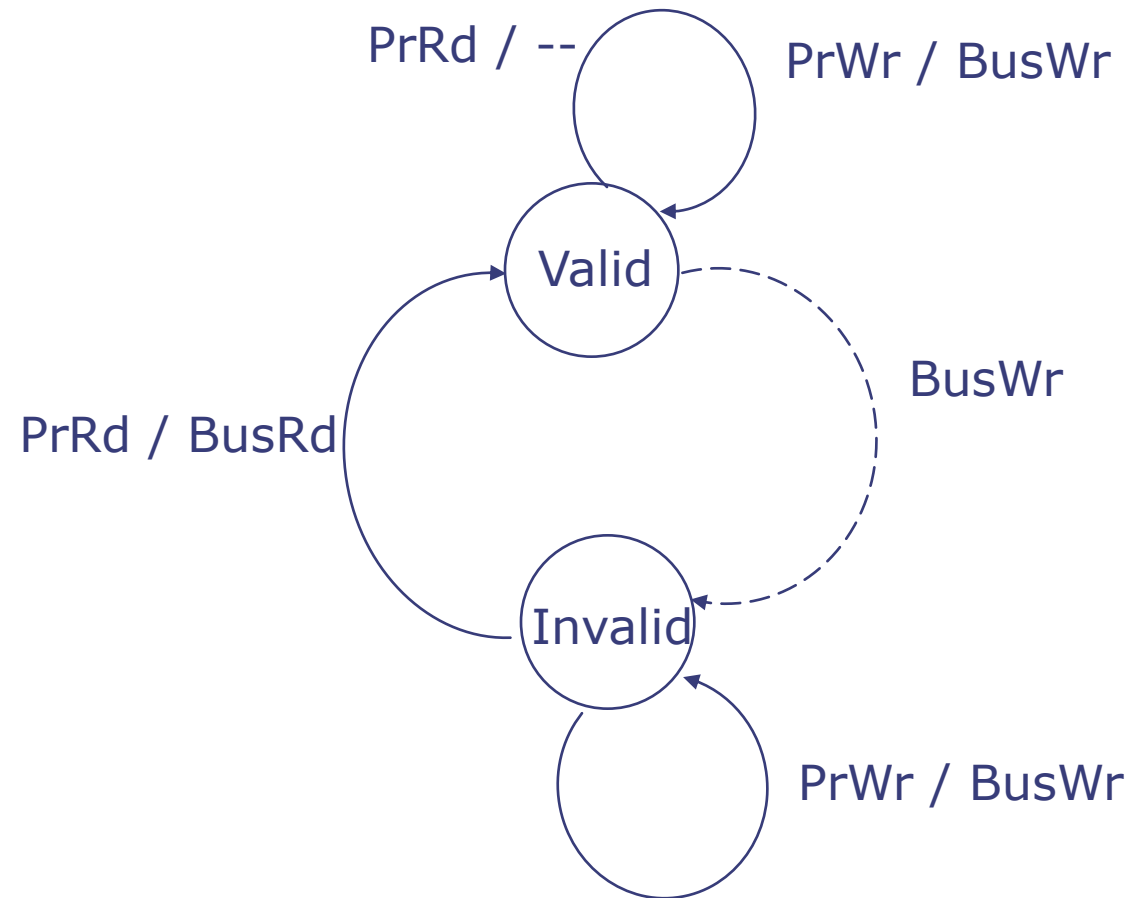
Snooping-Based Coherence

- Bus provides serialization point
 - Broadcast, totally **ordered**
 - Each cache controller “snoops” all bus transactions
 - Controller updates state of cache in response to processor and snoop events and generates bus transactions
- Snoopy protocol (FSM)
 - State-transition diagram
 - Actions



A Simple Protocol: Valid/Invalid (VI)

- Assume **write-through caches**



Actions

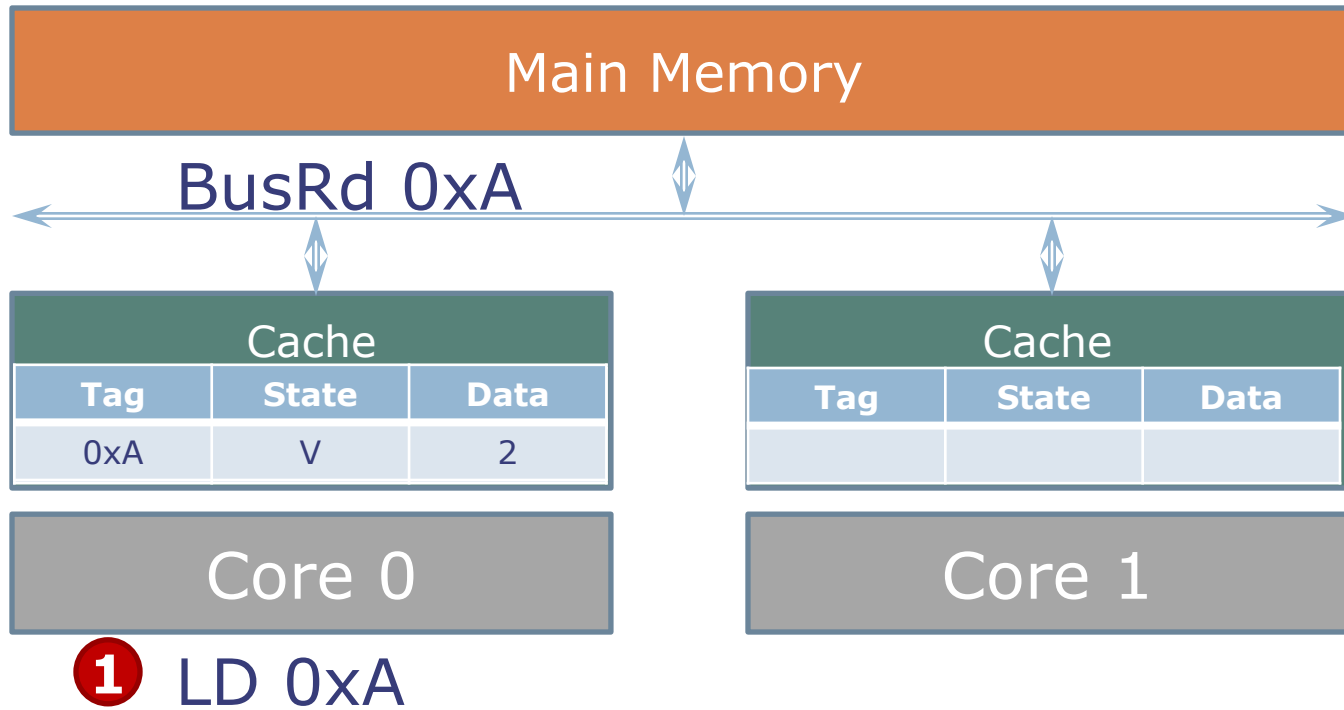
Processor Read (PrRd)

Processor Write (PrWr)

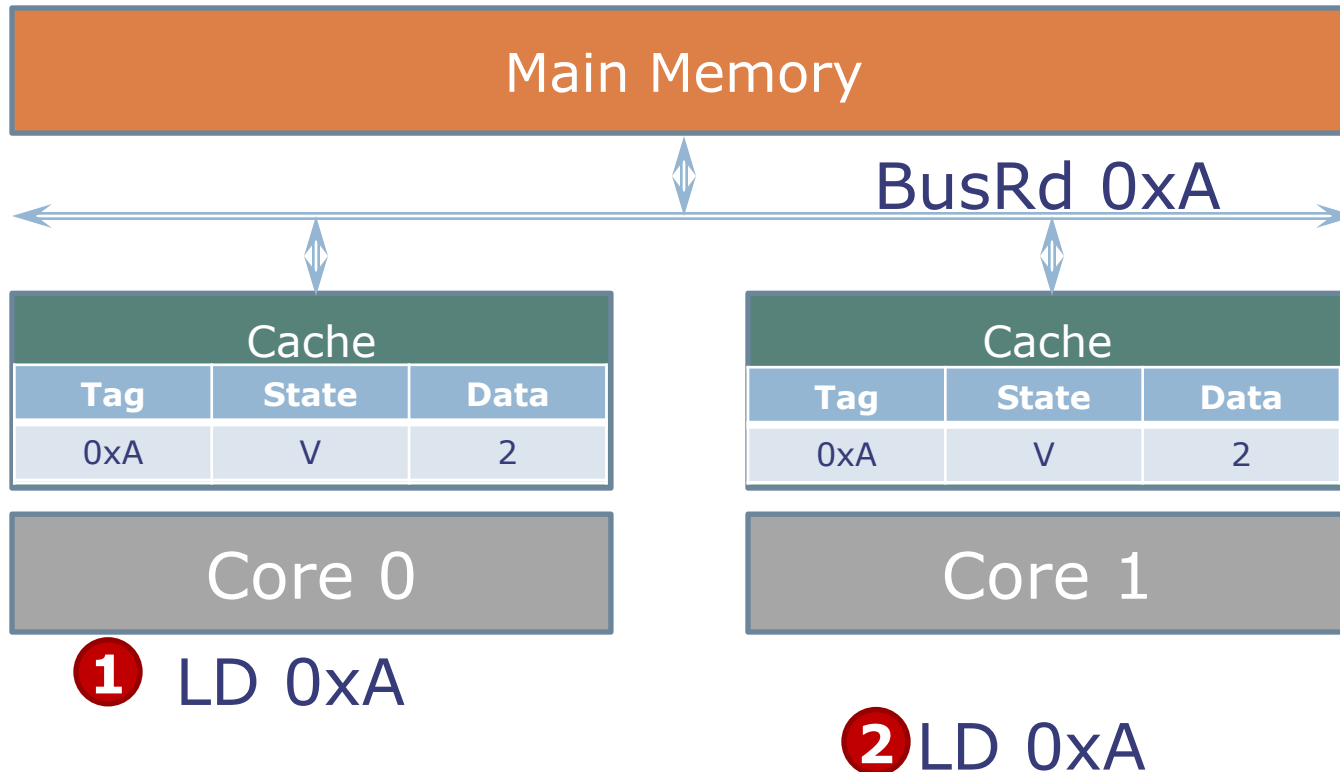
Bus Read (BusRd)

Bus Write (BusWr)

Valid/Invalid Example

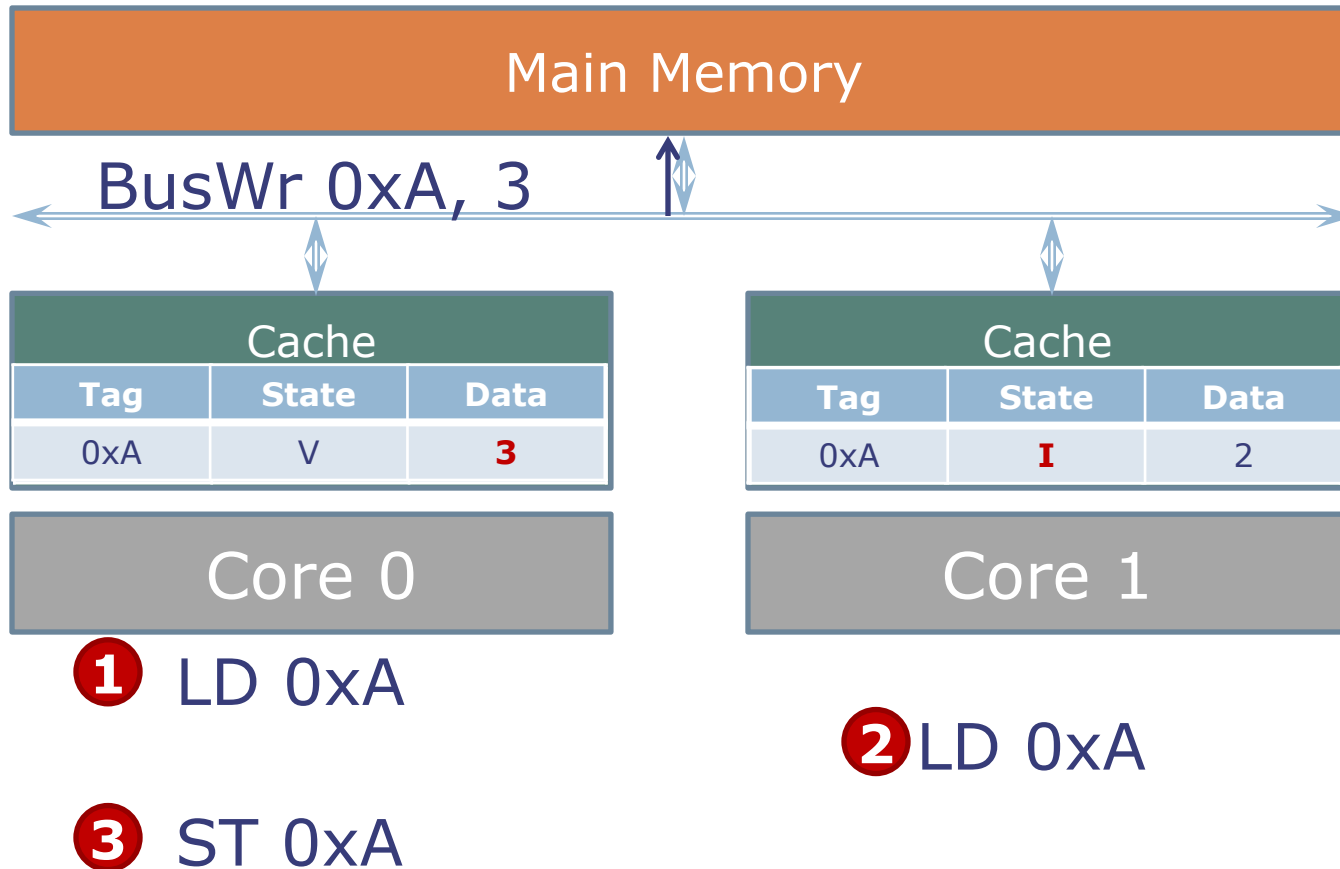


Valid/Invalid Example

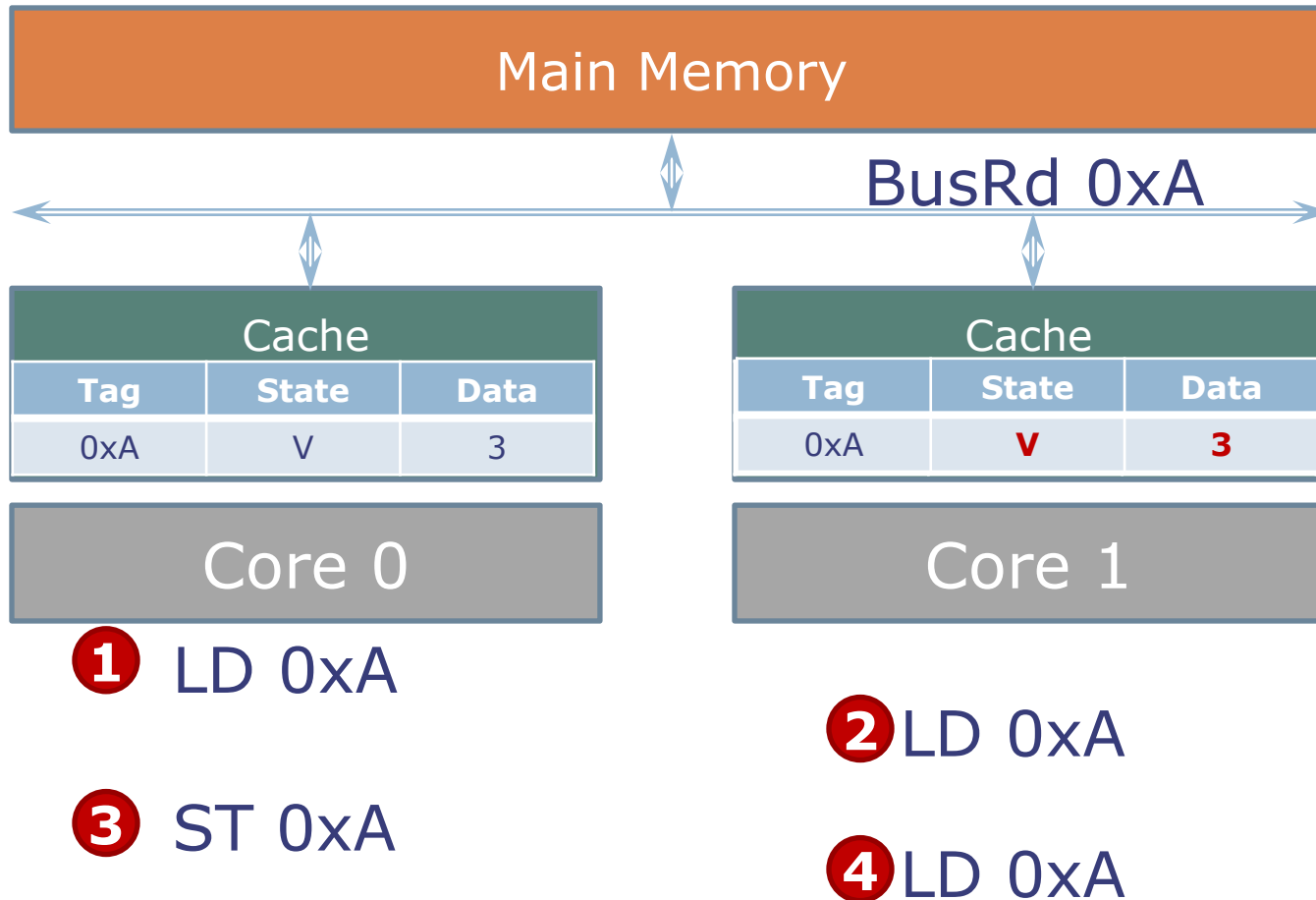


Additional loads satisfied locally, without BusRd

Valid/Invalid Example



Valid/Invalid Example



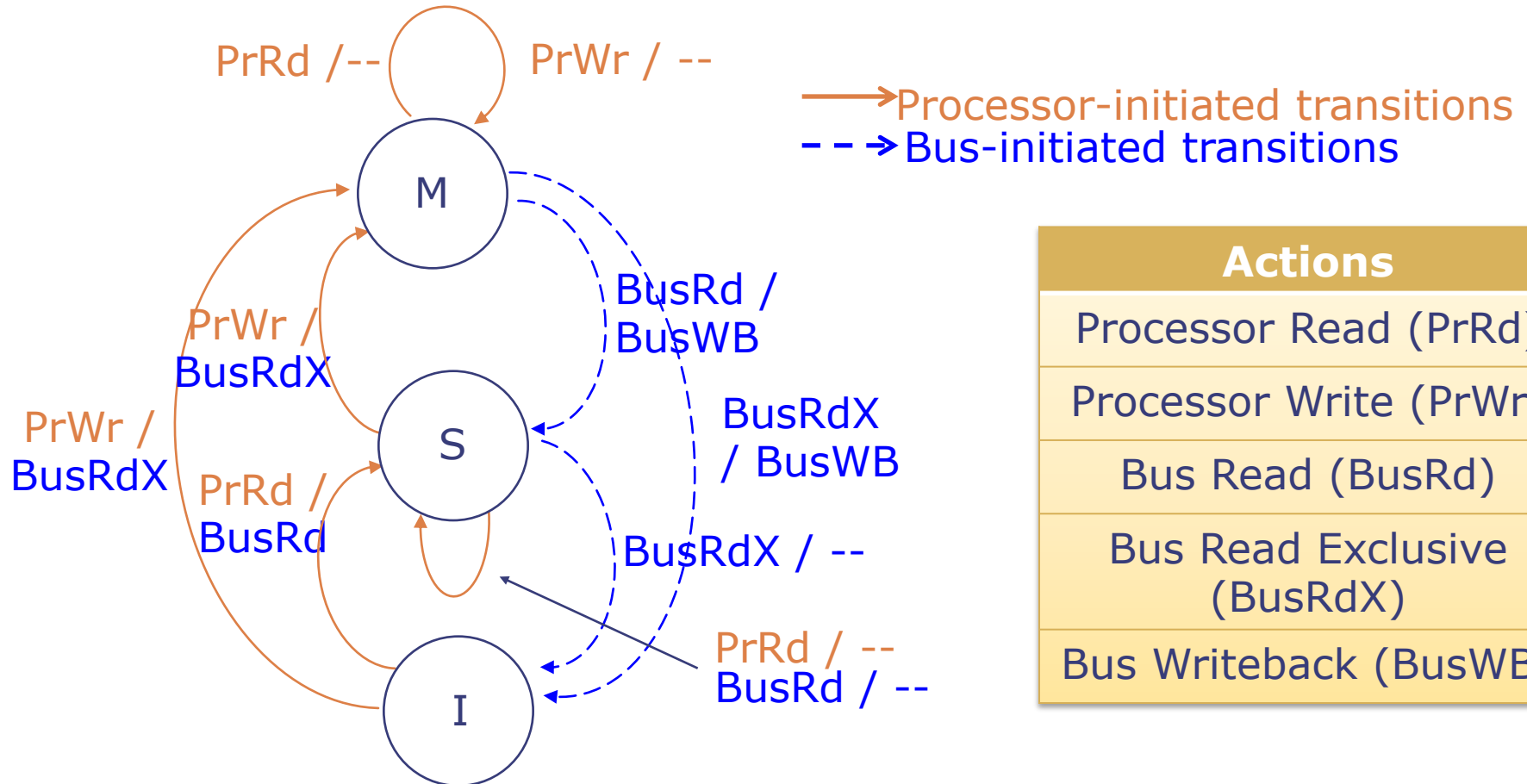
VI Problems? Every write updates main memory
Every write requires broadcast & snoop

Modified/Shared/Invalid (MSI) Protocol

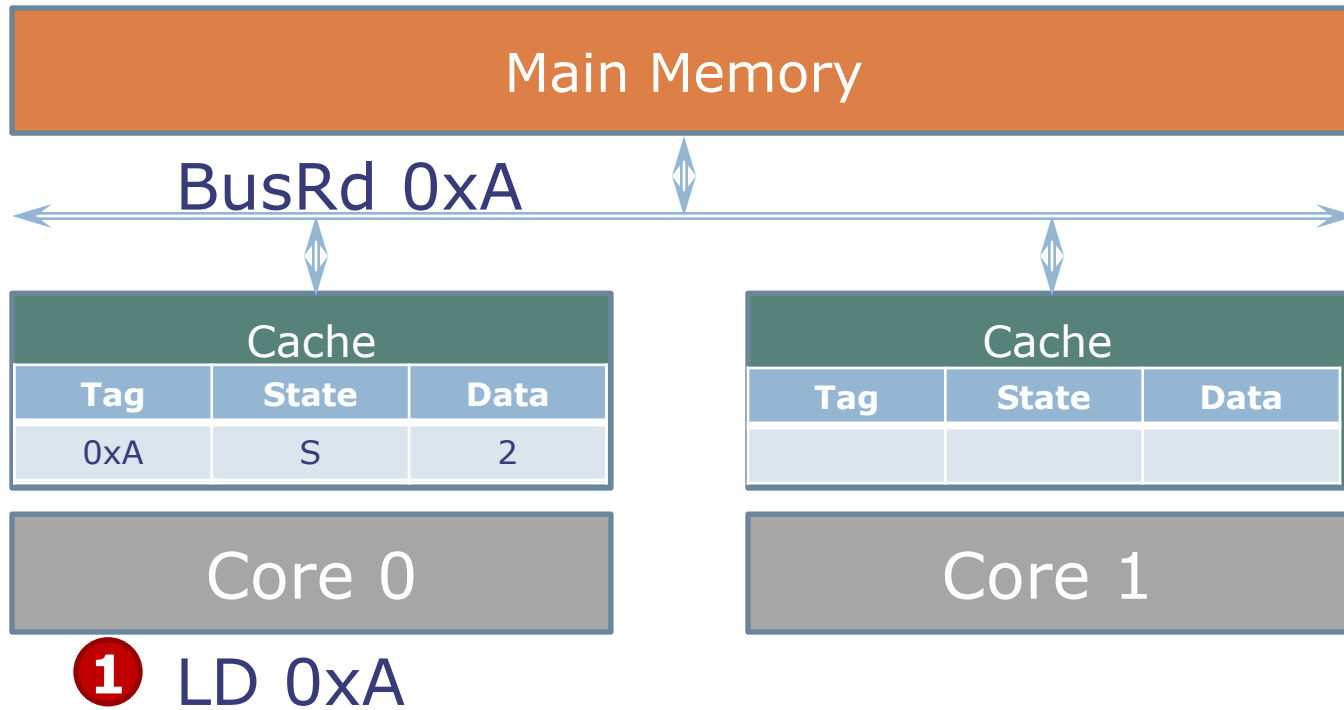
- Each line in each cache maintains MSI state:
 - I - cache doesn't contain the address
 - S - cache has the address but so may other caches; hence it can only be read
 - M - only this cache has the address; hence it can be read and written
 - any other cache that had this address got invalidated

MSI Protocol FSM

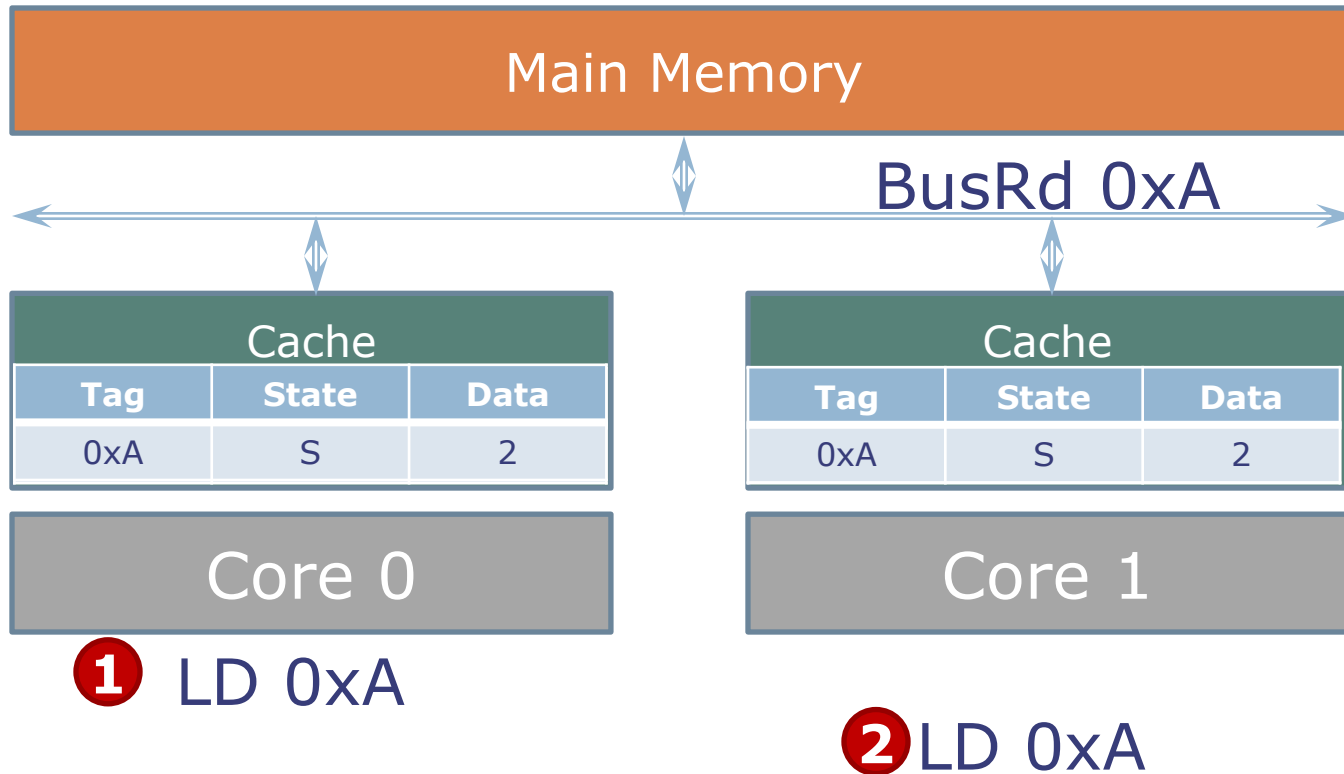
- VI Drawbacks: Every write updates main memory, and every write requires broadcast & snoop
- MSI: Allows writeback caches + satisfies writes locally



MSI Example

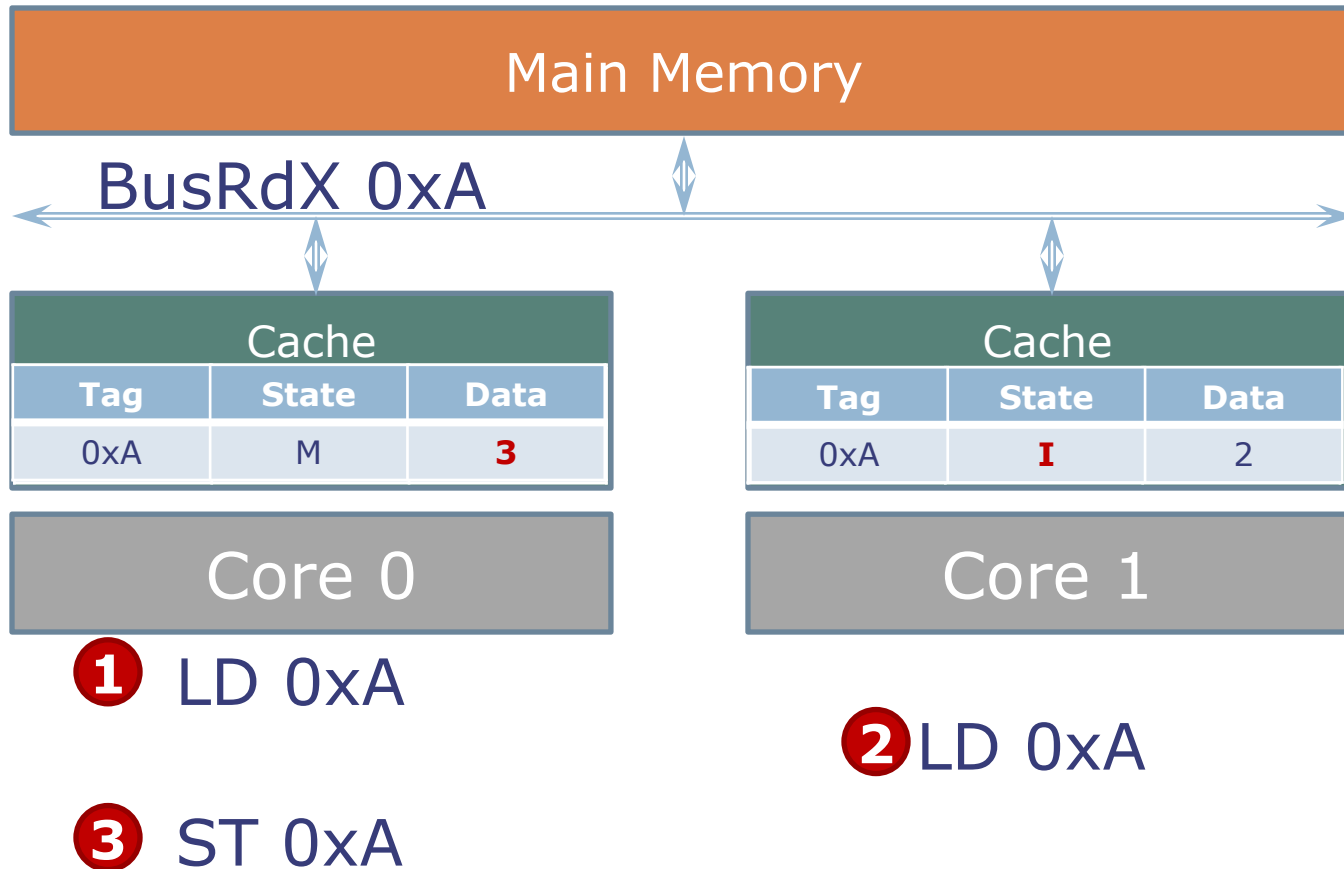


MSI Example



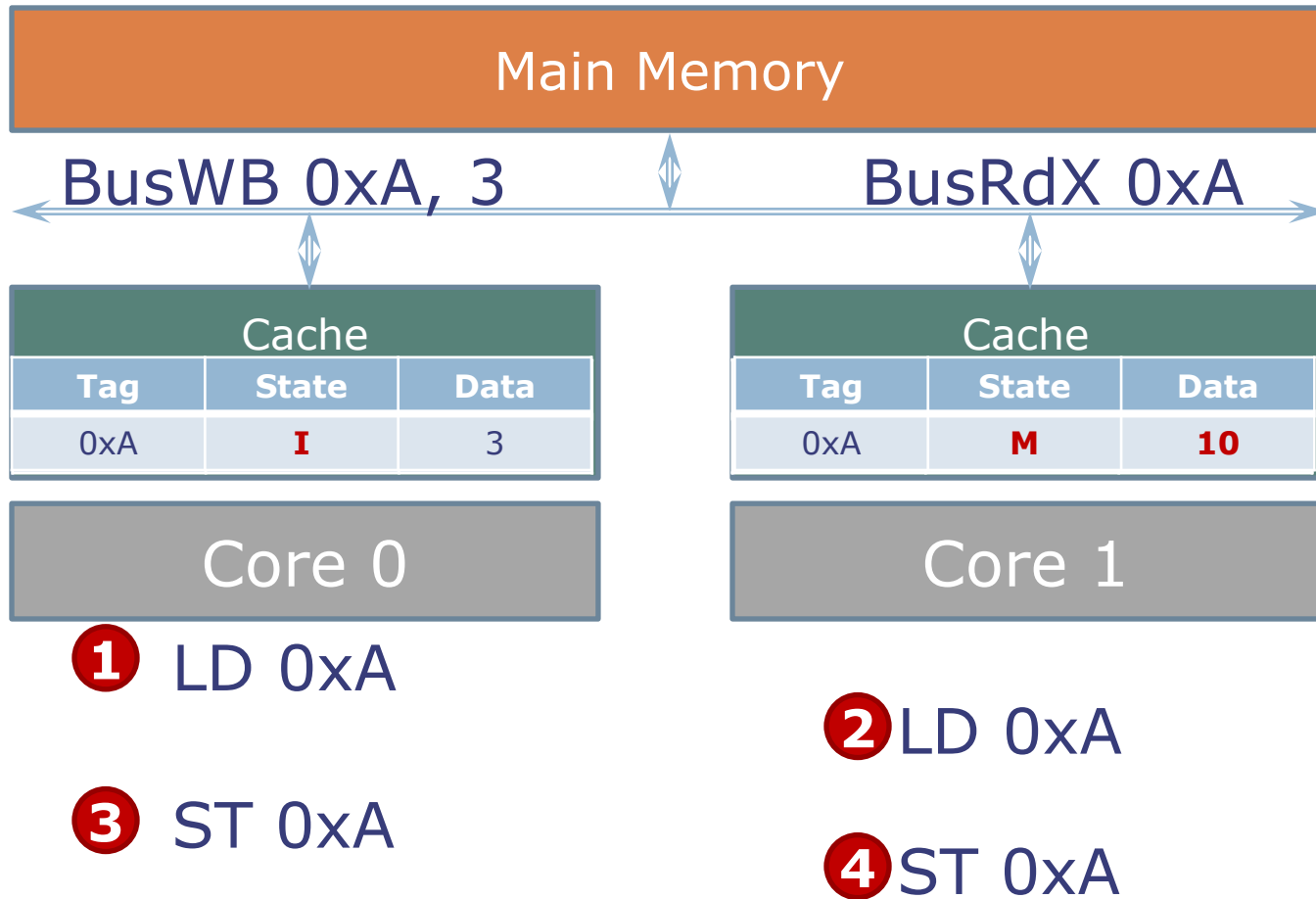
Additional loads satisfied locally, without BusRd
(like in VI)

MSI Example

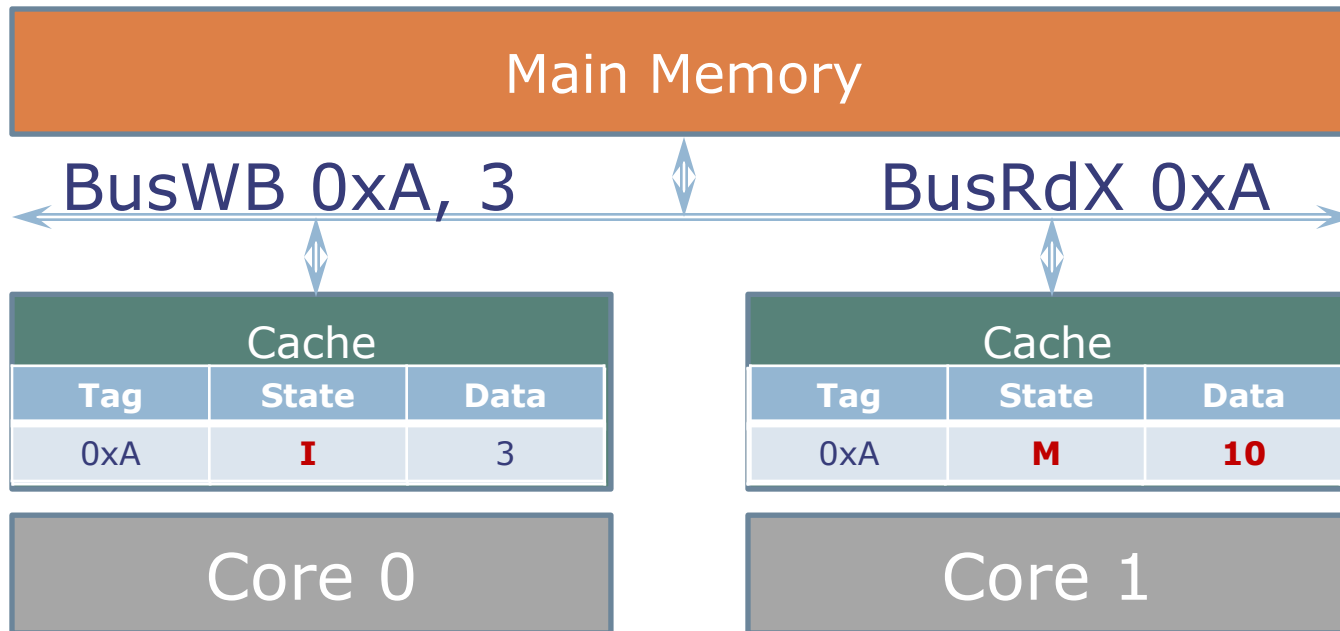


Additional loads *and* stores from core 0 satisfied locally, without bus transactions (unlike in VI)

MSI Example

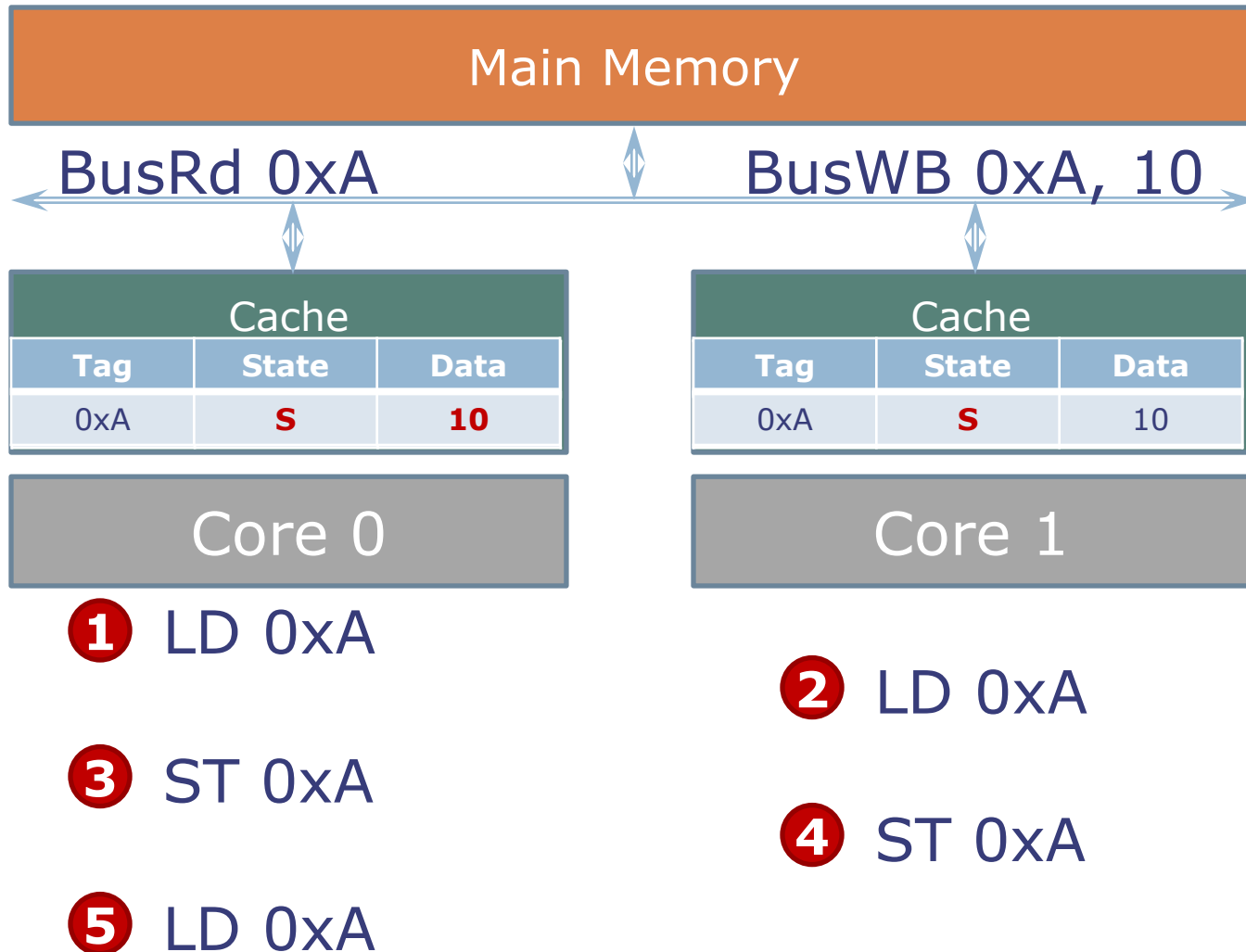


Cache Interventions



- MSI lets caches serve writes without updating memory, so main memory can have stale data
 - Core 0's cache needs to supply data
 - But main memory may also respond!
- Cache must override response from main memory

MSI Example



MSI Optimizations: Exclusive State

- Observation: Doing read-modify-write sequences on private data is common
 - What's the problem with MSI?

2 bus transactions for every read-modify-write of private data.

- Solution: E state (exclusive, clean)
 - If no other sharers, a read acquires line in E instead of S
 - Writes silently cause $E \rightarrow M$ (exclusive, dirty)

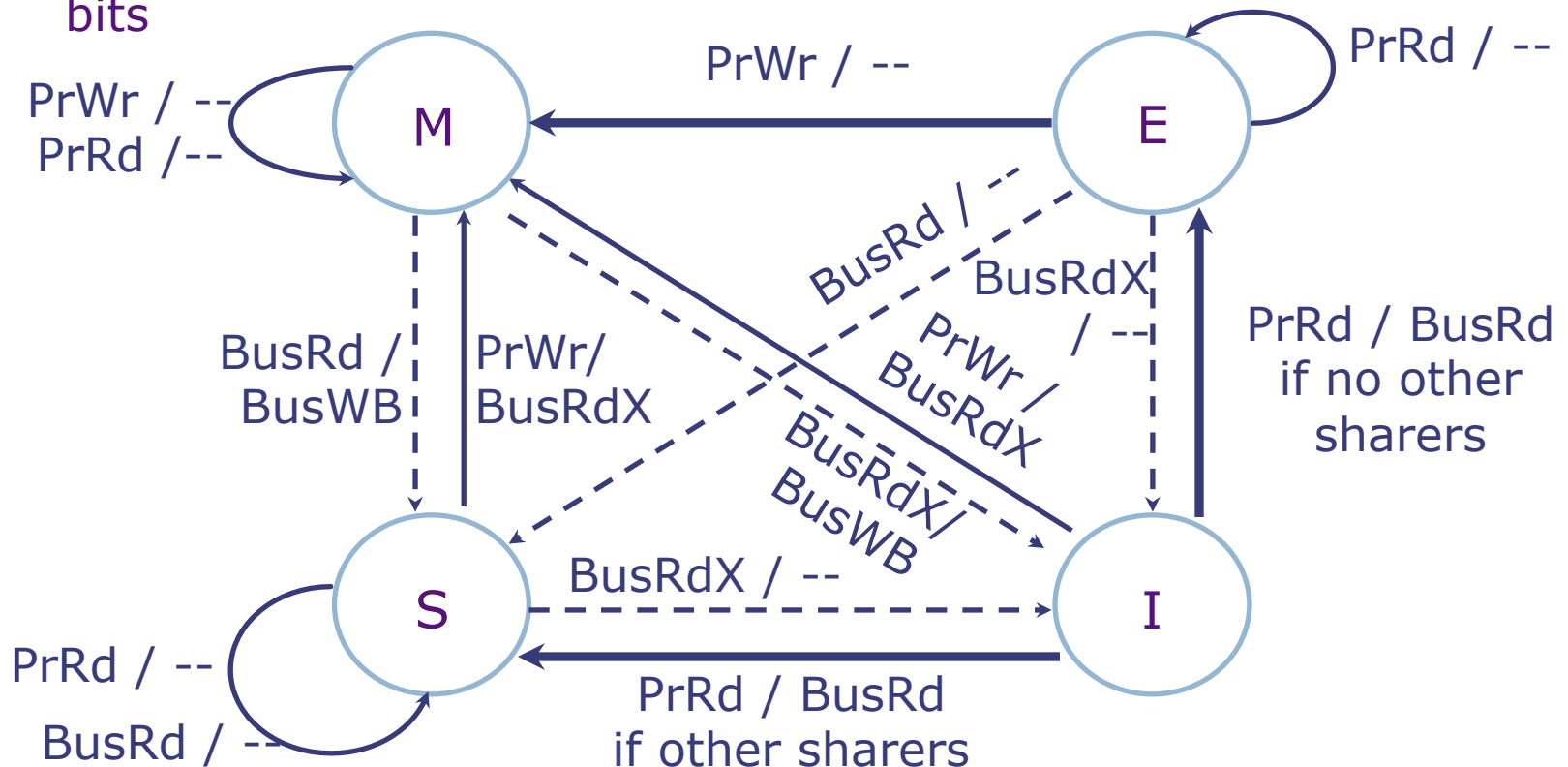
MESI: An Enhanced MSI protocol

increased performance for private read-write data

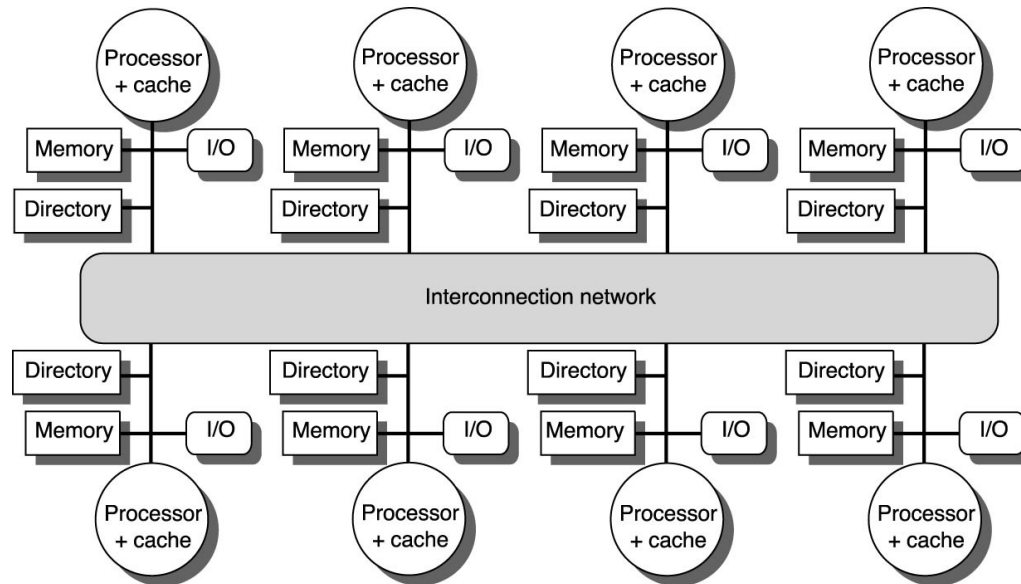
Each cache line has a tag



M: Modified Exclusive
E: Exclusive, unmodified
S: Shared
I: Invalid



Directory-Based Coherence



- Route all coherence transactions through a directory
 - Tracks contents of private caches → No broadcasts
 - Serves as ordering point for conflicting requests → Unordered networks

Cache Coherence and False Sharing

Performance Issue #1

- A cache line contains more than one word, and cache coherence is done at line granularity



- Suppose P_1 writes word_i and P_2 writes word_k and both words have the same line address
- What can happen?

The line may be invalidated (ping-pong)
many times unnecessarily because
addresses are in the same line.

Thank you!

Next lecture: Modern
Processor Architecture