Cache Coherency

The issue:

- must guarantee that all processors see correct data despite multiple readers & writers
- in a nutshell, how to make writes by one processor show up in other processor caches

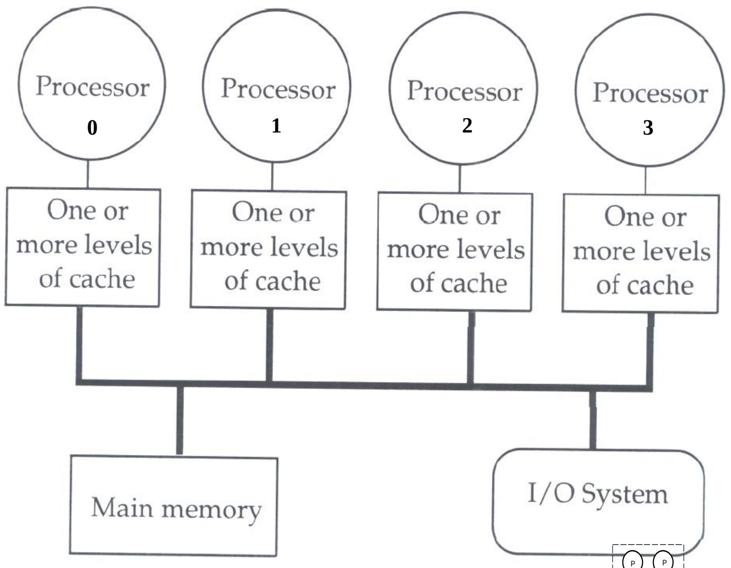
Cache coherent processors

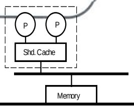
- all reading processors must get the most current value
- most current value for an address is the last write (in program order)

Cache coherency problem

- update from a writing processor is not known to other processors

A Low-end MP


Processor 0
Processor 1
Processor 2
Processor 3
One or more levels of cache
One or more levels of cache
One or more levels of cache
One or more levels of cache
Main memory
I/O System



Cache Coherency

Cache coherency protocols

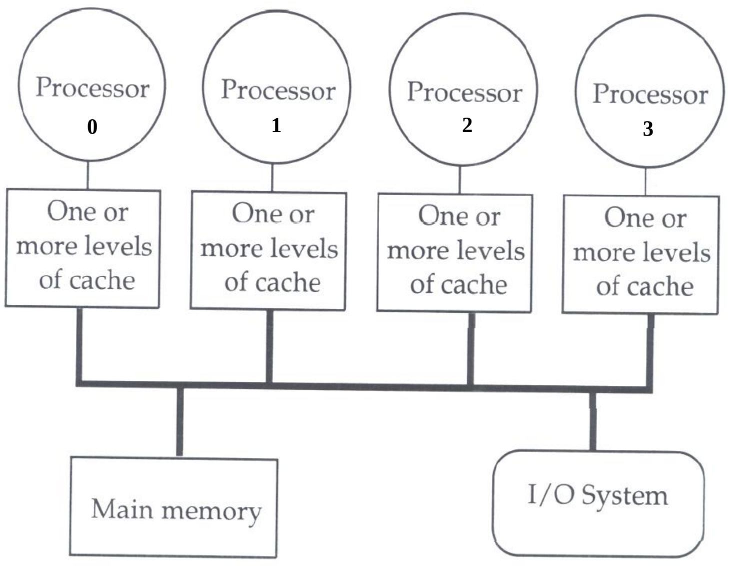
- (usually) hardware mechanism for maintaining cache coherency
- coherency state associated with a cache block of data
- operations on shared data change the state
  - for the processor that initiates an operation
  - for other processors that have the data of that operation resident in their caches
- two general types
  - snooping with a bus
  - directory with a multi-path interconnect

- In sum, hardware implementation for:
  - sharing state of each cache block
  - rules for changing this state in response to memory operations
  - implemented as a state transition diagram

Write-Invalidate Protocols

- Processor obtains exclusive access for writes (becomes the "**owner**") by invalidating data in other processors' caches
- When those other processors, access the data, they incur a **coherency miss** (invalidation miss)
- **Cache-to-cache transfers**
- good for:
  - multiple writes to same word or block by one processor
  - exploits **migratory sharing** from processor to processor (also called **processor locality**)

A Low-end MP


Processor 0
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One or more levels of cache
One or more levels of cache
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One or more levels of cache
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Cache Coherency Protocol Implementations

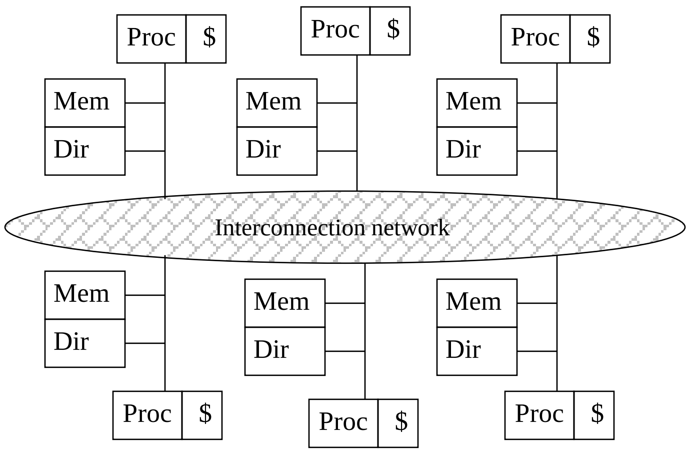
Snooping

- used with low-end MPs
  - few processors
  - centralized memory
  - bus-based (broadcast)
- distributed implementation: responsibility for maintaining coherence lies with each processor cache

Directory-based

- used with higher-end MPs
  - more processors
  - distributed memory
  - multi-path interconnect (point-to-point)
- distributed implementation: responsibility for maintaining coherence lies with the directory
  - directory structure is distributed with the memory
  - 1 directory entry for each cache-block-size chunk of memory

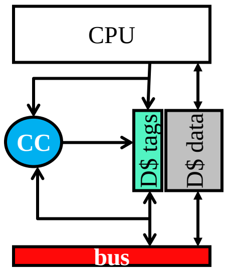
A High-end MP



Snooping Implementation

A distributed coherency protocol

- coherency state associated with each cache block
- each cache controller (the "snoop") maintains coherency for its own cache
  - compare address on the bus with address in cache
  - response depends on coherency state



Snooping Implementation

How the bus is used

- broadcast medium
- entire coherency operation is atomic wrt other processors
  - **keep-the-bus protocol**:
    - master holds the bus until the entire operation has completed
    - no processor can initiate another operation while any operation is in progress
  - **split-transaction protocol** :
    - request & response are different phases
    - state values that indicate that an operation is in progress
    - no processor can initiate another operation *for a cache block* that has an operation already in progress

Snooping Implementation

Snoop implementation:

- snoop on the highest level cache
  - another reason L2 is physically-accessed
  - property of **inclusion**:
    - all blocks in L1 must be in L2
    - therefore only have to snoop on L2
    - may need to update L1 state if change L2 state
- separate tags & state for snoop lookups
  - processor & snoop communicate for a state or tag change

An Example Snooping Protocol

Each cache block is in one of three states

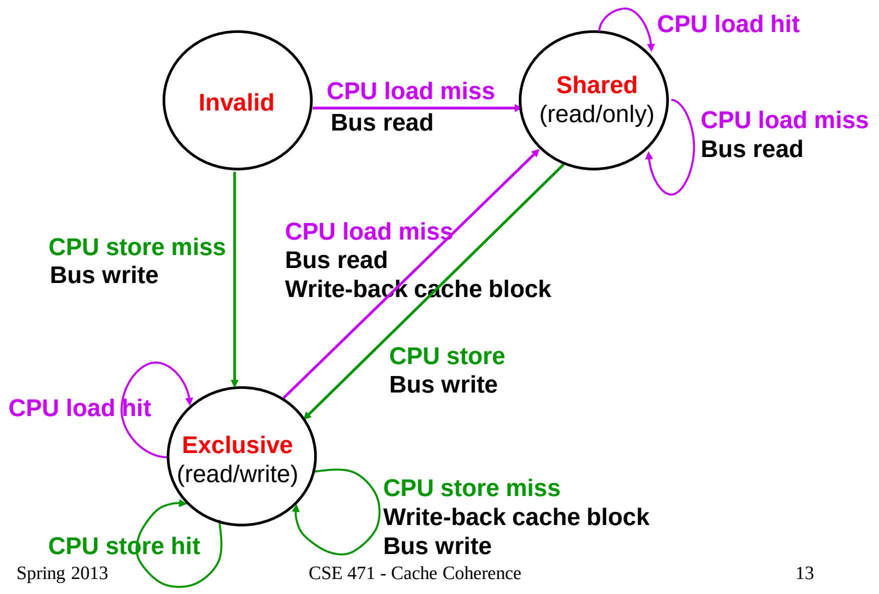
- **shared**:
  - clean in all caches & up-to-date in memory
  - block can be repeatedly read by any processor
- **exclusive**:
  - dirty in exactly one cache, the owner of the block
  - only that processor can read/write to it
- **invalid**:
  - block contains no valid data

State Transitions for a Given Cache Block

State transitions caused by:

- events caused by the **requesting processor**, e.g.,
  - read/load miss (go from invalid to shared)
  - write/store miss (go from invalid to exclusive)
  - write/store to a shared block (go from shared to exclusive)
- events caused by **snoops of other caches**, e.g.,
  - read/load miss by P1 makes P2’s owned block change from exclusive to shared
  - write/store miss by P1 makes P2’s owned block change from exclusive to invalid

State Machine (CPU side)



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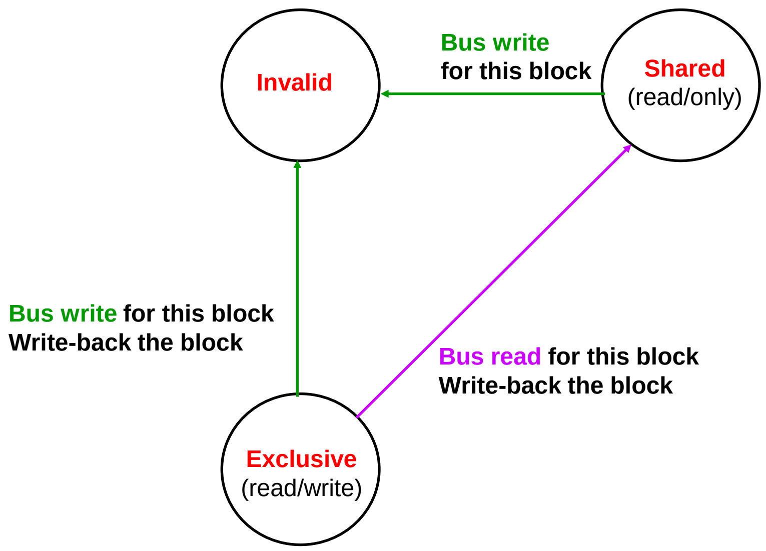
State Machine (Bus side: the snoop)



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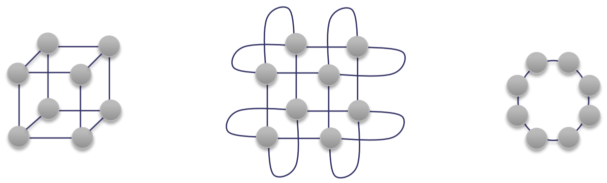
Scalable Cache Coherence

Simple, but is it scalable?

- one operation at a time
- snooping requires broadcasting all operations
- fine for 2 or 4 processors

Alternatives:

- multiple operations at a time
- point-to-point communication (most snoops result in no action)
- hundreds of processors

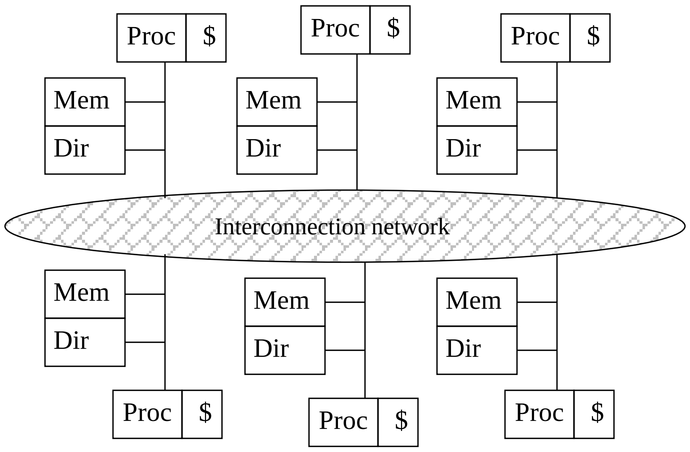


Directory Implementation

Distributed memory machine

- processor-memory pairs are connected via a multi-path interconnection network
  - **point-to-point communication**
  - snooping with broadcasting is wasteful of the parallel communication capability
- each processor (or cluster of processors) has its own portion of physical memory
- a processor has fast access to its local memory & slower access to “remote” memory located at other processors
  - **NUMA** (non-uniform memory access) machines

A High-end MP



Directory Implementation

Coherency state is associated with units of memory that are the size of cache blocks: directory state

- each directory tracks the coherence state of the units in its memory & updates it
  - **uncached** (invalid in snooping):
    - no processor has the data cached & memory is up-to-date
  - **shared**:
    - at least 1 processor has the data cached & memory is up-to-date
    - block can be read by any processor
  - **exclusive** (also called modified):
    - only 1 processor (the owner) has the data cached & memory is stale
    - only that processor can write to it
- directory tracks which processors share its memory blocks
  - vector of presence bits (1/processor) to indicate which processor(s) has cached the data
  - dirty bit to indicate if exclusive

Directory Implementation

Different nodes have different uses when maintaining coherency

- **home** node: where the memory location of an address resides (and cached data may be there too)
- **local** node: where the memory request initiated
- **remote** node: an alternate location for the data, if the processor has previously requested & cached it

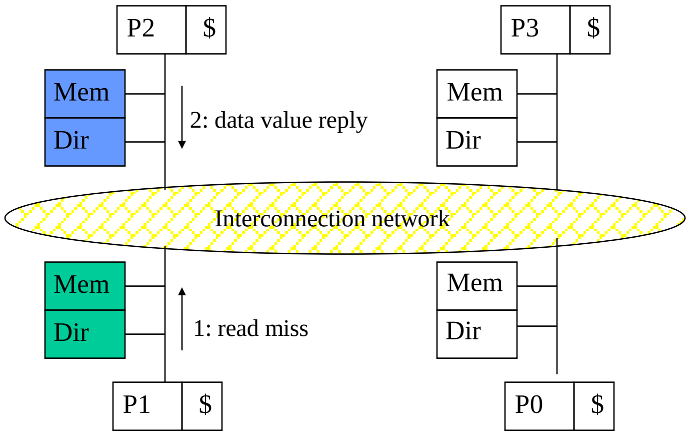
In satisfying a memory request:

- home node identified by the data memory address; local node is the initiator; directory knows who remote node is
- messages sent between the different nodes in point-to-point communication
- messages get explicit replies

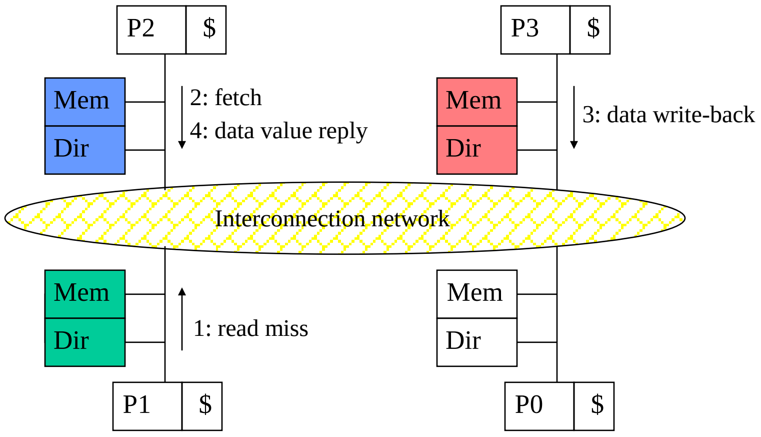
Some simplifying assumptions for using the protocol

- processor blocks until the access is complete
- messages processed in the order received

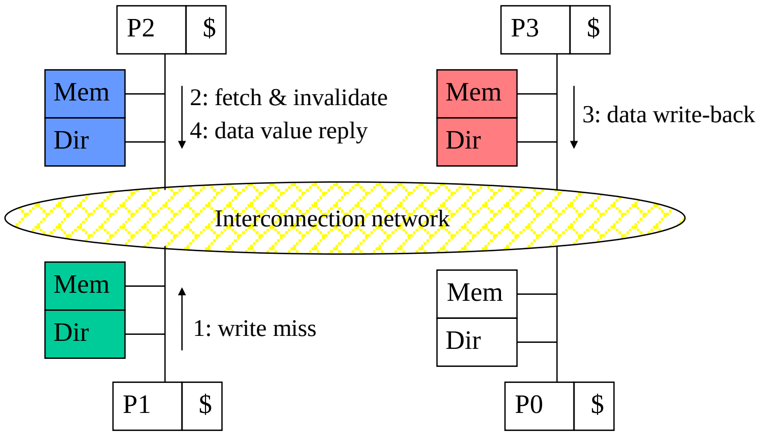
Read Miss for an Uncached Block



Read Miss for an Exclusive, Remote Block



Write Miss for an Exclusive, Remote Block



Directory Protocol Messages

Message type	*Source*	*Destination*	*Message Content*
Read miss	Local cache	Home directory	P, A
– *Processor P reads data at address A; make P a read sharer and arrange to send data back*			
Write miss	Local cache	Home directory	P, A
– *Processor P writes data at address A; make P the exclusive owner and arrange to send data back*			
Invalidate	Home directory	Remote caches	A
– *Invalidate a shared copy at address A.*			
Fetch	Home directory	Remote cache	A
– *Fetch the block at address A and send it to its home directory*			
Fetch/Invalidate	Home directory	Remote cache	A
– *Fetch the block at address A and send it to its home directory; invalidate the block in the cache*			
Data value reply	Home directory	Local cache	Data
– *Return a data value from the home memory (read or write miss response)*			
Data write-back	Remote cache	Home directory	A, Data
– *Write-back a data value for address A (invalidate response)*			

Evaluating the Performance of Directory Schemes

Greater bandwidth capability

- multiple paths
- not contacting processors not involved in the memory operation

Longer operation latency

- extra hops
- acking

Directory FSM for a Memory Block

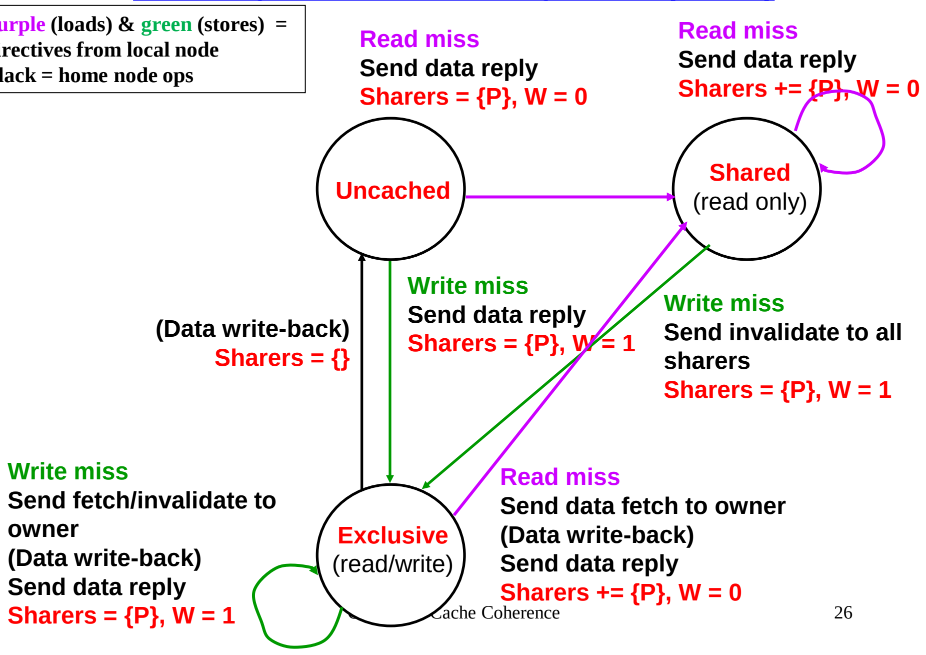
Tracks all copies of a memory block

Makes two state changes:

- update coherency state (same as for snooping protocol)
- alter the number of sharers in the sharing set

Directory FSM for a Memory Block (Home)

Purple (loads) & green (stores) = directives from local node
Black = home node ops



CPU FSM for a Cache Block

Same coherency states as for the directory FSM

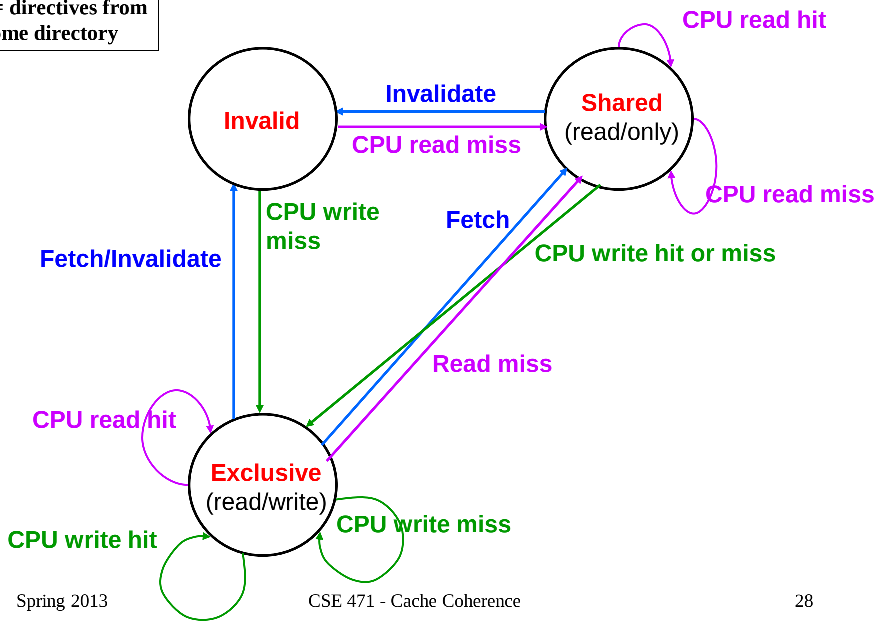
Transactions very similar to snooping implementations

- read & write misses sent to home directory
- invalidate & data fetch requests to the node with the data replace broadcasted read/write misses

Purple & green = directives from the local node

Blue = directives from the home directory

CPU FSM for a Cache Block

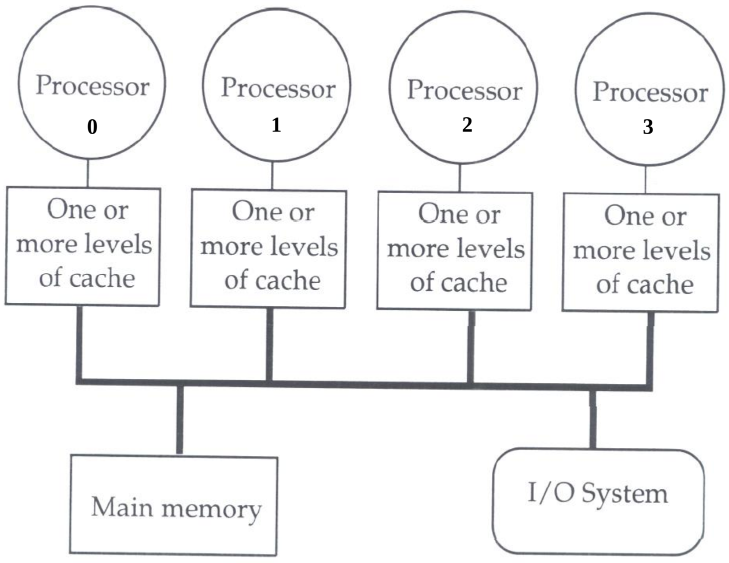


False Sharing

Processors read & write to ***different*** words in a shared cache block

- cache coherency is maintained on a cache block basis
  - processes share cache blocks, not data
  - block ownership bounces between processor caches

A Low-end MP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One or more levels of cache
One or more levels of cache
One or more levels of cache
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I/O System

False Sharing

Impact aggravated by:

- larger block size: why?
- larger cache size: why?
- large miss penalties: why?

Reduced by:

- coherency protocols (coherency state per subblock)
  - let cache blocks become incoherent as long as there is only false sharing
  - make them coherent if any processor true shares
- compiler optimizations (group & transpose, cache block padding)
- cache-conscious programming wrt initial data structure layout

Important Issues

Cache coherency:

- its definition
- the hardware support
- write-invalidate protocols
  - how bus-based protocols work
  - how directories work
- how coherency protocols match or take advantage of the MP design

Adding to our knowledge:

- a 4th type of miss (coherency misses)
- a 3rd locality (processor)
- a 2nd application of snooping (bus-based coherency protocol)
- a 2nd use of sub-block placement
- a 3rd latency vs. throughput trade-off

Important Issues

Anything in red or green:

- 2 bus protocols
- inclusion property
- UMA vs. NUMA
- role of local, home, remote nodes
- bus vs. multipath
- snooping vs. directory
- snooping in a coherency protocol vs. snooping in Tomasulo's algorithm
- false sharing: why it occurs, what makes it worse, how to fix it

Apply What You Know

A different 4th state:

- what triggers state transitions
- what are the state changes, given a sequence of memory operations

A protocol that isn't based on invalidations:

- what triggers state transitions
- what are the state changes, given a sequence of memory operations

Apply What You Know

Example:

Assume you have a 4-state, write-invalidate protocol, in which three of the states are those used in the baseline 3-state protocol we studied in class and the fourth state is a new one, called *private clean*. A private clean state means that there is only one cached copy of the data, and that it is a read-only copy (i.e., it has the same value as its backup in memory). Using this new 4-state coherency protocol, fill in the state values for a single cache block in each of the processors (P0, P1, P2), for each of the memory operations listed in the first column. Assume the multiprocessor is bus-based.

Operations	P0	P1	P2
Initially	invalid	invalid	invalid
P1: loads B			
P2: loads B			
P0: stores B			
P1: loads B			
P1: stores B			