

# CS5460/6460: Operating Systems

## Lecture 13: Memory barriers

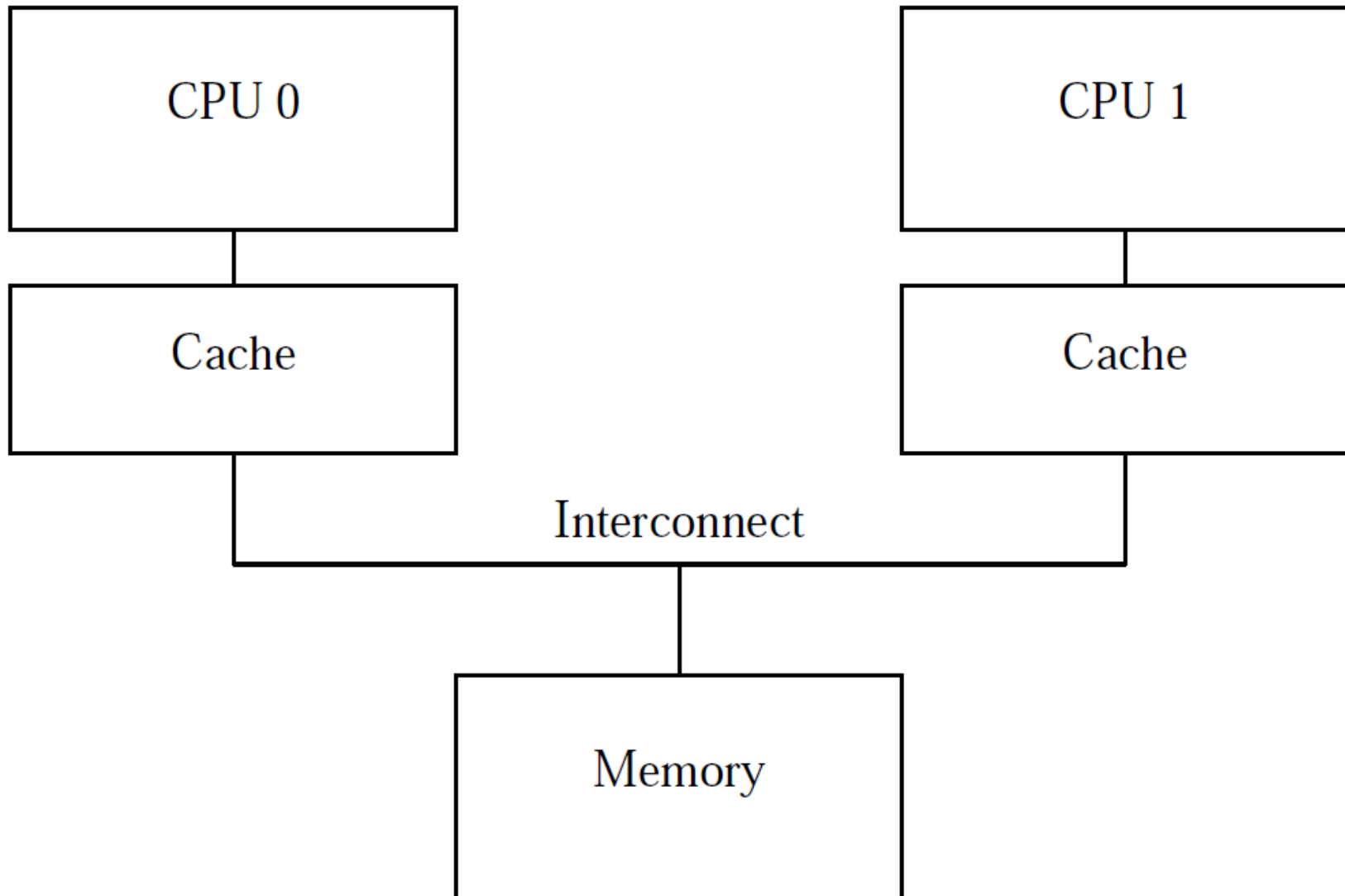
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# Recap from last time

- Two synchronization paradigm
  - Critical sections
    - Implemented as spinlocks
    - Doesn't scale (atomic operations don't scale)
  - Read Copy Update
    - Lock-free
    - Scales well for a large number of readers
    - Updates must be infrequent

# Cache coherence

# CPU cache



# CPU cache

- Effectively a hash
  - Contains sequential blocks of memory
    - Called “cache lines”, 16 – 256 bytes each
  - Simple hashing function
    - E.g. 16-set cache means, 16 buckets
  - Limited chain length to resolve conflicts
    - E.g. 2-way cache means chain of length 2

# Cache hierarchy

- Hierarchy of caches: L1, L2, L3
- Grow in size but get slower
- Ivy Bridge-EP
  - L1 cache 32 KB per core
  - L2 cache 256 KB per core
  - L3 cache 10 MB to 30 MB shared

# Some latency numbers

- L1 cache reference 0.5 ns
  - On a 2GHz CPU, 1 ns == 2 cycles
- L2 cache reference 7 ns
- L3 cache reference 15 ns
- Main memory reference 100 ns
- Send 1K bytes over 1 Gbps network 10,000 ns
- Read 4K randomly from SSD\* 150,000 ns
- Round trip within same datacenter 500,000 ns
- Disk seek 10,000,000 ns

# Example: 16 set, 2-way, 256 byte line

	Way 0	Way 1
0x0	0x12345000	
0x1	0x12345100	
0x2	0x12345200	
0x3	0x12345300	
0x4	0x12345400	
0x5	0x12345500	
0x6	0x12345600	
0x7	0x12345700	
0x8	0x12345800	
0x9	0x12345900	
0xA	0x12345A00	
0xB	0x12345B00	
0xC	0x12345C00	
0xD	0x12345D00	
0xE	0x12345E00	0x43210E00
0xF		



# Example: 16 set, 2-way, 256 byte line

	Way 0	Way 1
0x0	0x12345000	
0x1	0x12345100	
0x2	0x12345200	
0x3	0x12345300	
0x4	0x12345400	
0x5	0x12345500	
0x6	0x12345600	
0x7	0x12345700	
0x8	0x12345800	
0x9	0x12345900	
0xA	0x12345A00	
0xB	0x12345B00	
0xC	0x12345C00	
0xD	0x12345D00	
0xE	0x12345E00	0x43210E00
0xF		

# Cache coherency protocol

- MESI: 4 states:
  - Modified
  - Exclusive
  - Shared
  - Invalid

# Protocol messages

- Read
  - The physical address of the cache line to be read
- Read response
  - The data requested by an earlier “read”
  - Might be supplied either by memory or by one of the caches
    - If one of the caches has the desired data in “modified” state, that cache must supply the “read response” message.

# Protocol messages (2)

- Invalidate
  - The physical address of the cache line to be invalidated
- Invalidate acknowledge
  - A CPU receiving an “invalidate” message must respond with an “invalidate acknowledge” message after removing the specified data from its cache.

# Protocol messages (3)

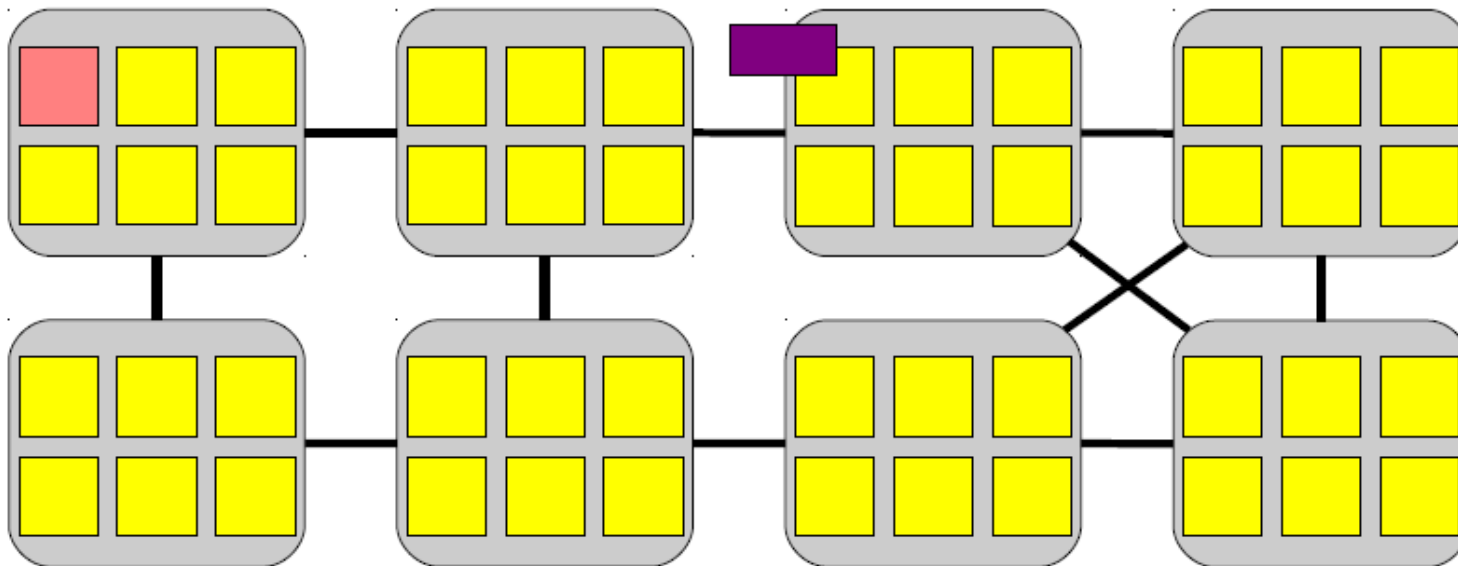
- Read Invalidate
  - The physical address of the cache line to be read, while at the same time directing other caches to remove the data
  - A combination of a “read” and an “invalidate”
  - Requires
    - “read response” and
    - a set of “invalidate acknowledge”
- Writeback
  - The address and the data to be written back to memory
  - And possibly other caches
  - The way to eject lines in the “modified” state as needed to make room for other data

# Atomic increment next ticket

```
void spin_lock(spinlock_t *lock)
{
  t = atomic_inc(lock->next_ticket);
  while (t != lock->current_ticket)
    ; /* Spin */
}
```

```
void spin_unlock(spinlock_t *lock)
{
  lock->current_ticket++;
}
```

```
struct spinlock_t {
  int current_ticket;
  int next_ticket;
}
```



# Example

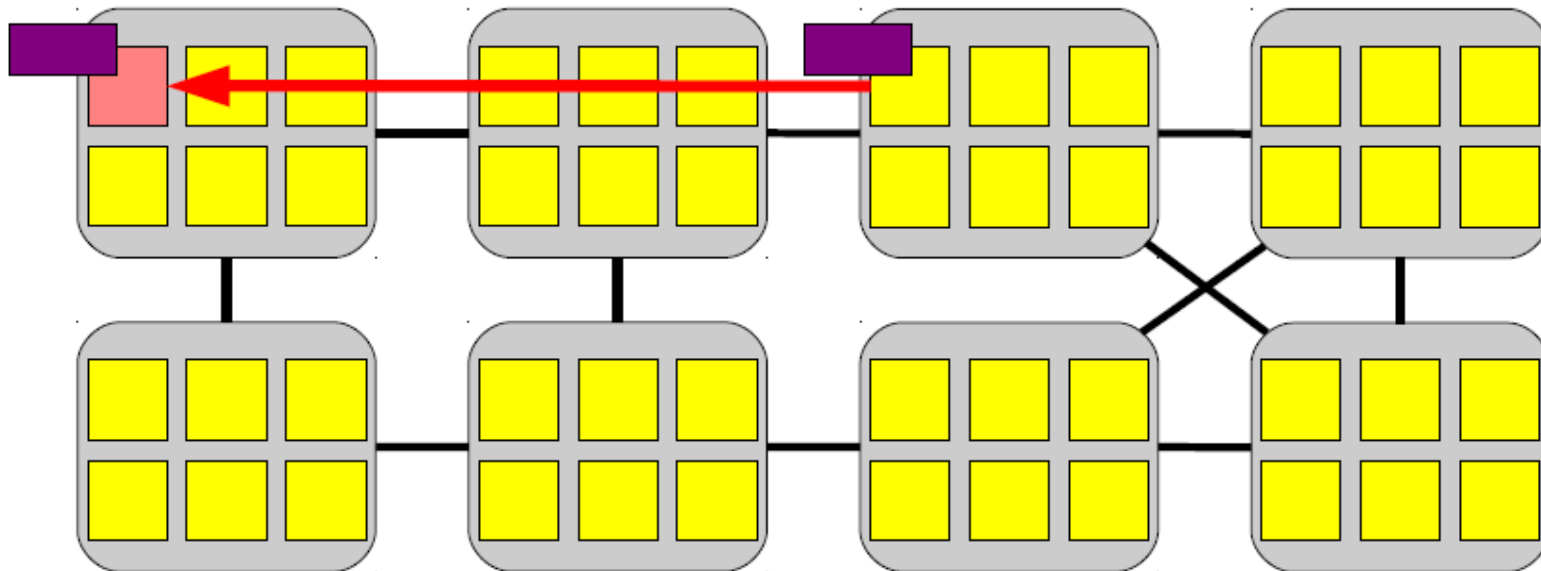
- Invalid → modify
  - An atomic read-modify-write operation on a data item that was not present in its cache
  - Transmits a “read invalidate”, receiving the data via a “read response”
  - The CPU can complete the transition once it has also received a full set of “invalidate acknowledge” responses

# Read current ticket

```
void spin_lock(spinlock_t *lock)
{
    t = atomic_inc(lock->next_ticket);
    while (t != lock->current_ticket)
        ; /* Spin */
}
```

```
void spin_unlock(spinlock_t *lock)
{
    lock->current_ticket++;
}
```

```
struct spinlock_t {
    int current_ticket;
    int next_ticket;
}
```





# Example

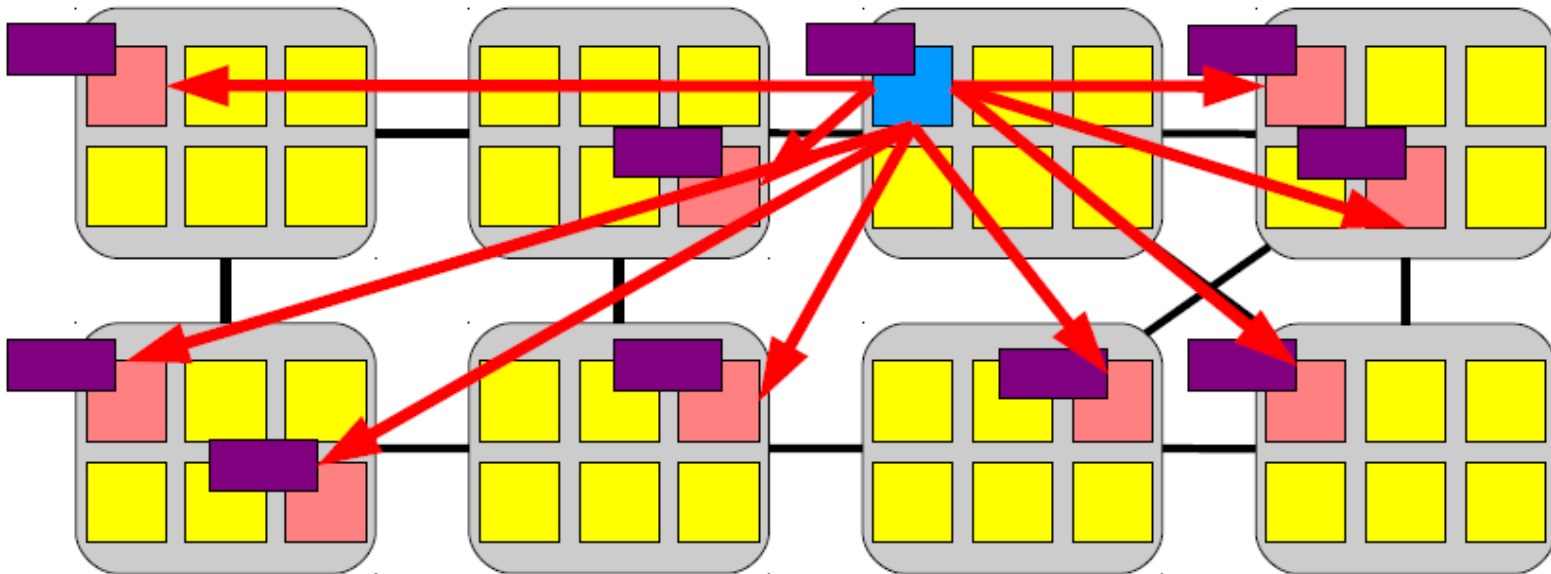
- Invalid → shared
  - Load data that is not in the cache
  - “Read” message, wait for “read response”

# Update current ticket

```
void spin_lock(spinlock_t *lock)
{
    t = atomic_inc(lock->next_ticket);
    while (t != lock->current_ticket)
        ; /* Spin */
}
```

```
void spin_unlock(spinlock_t *lock)
{
    lock->current_ticket++;
}
```

```
struct spinlock_t {
    int current_ticket;
    int next_ticket;
}
```



# Example

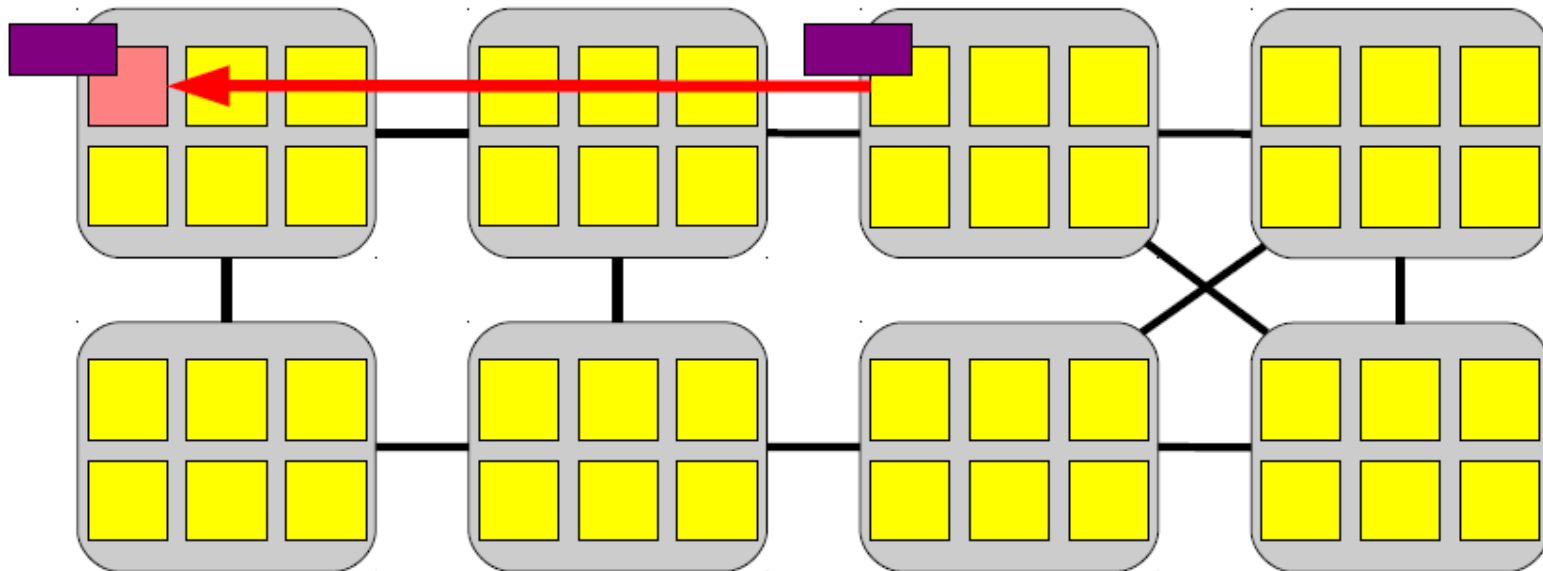
- Shared → exclusive
  - This CPU realizes that it will soon need to write to some data item in this cache line, and thus transmits an “invalidate” message.
  - The CPU cannot complete the transition until it receives a full set of “invalidate acknowledge” responses
- Exclusive → modified
  - The CPU writes to the cache line that it already had exclusive access to.
  - This transition does not require any messages to be sent or received.

# Re-read current-ticket

```
void spin_lock(spinlock_t *lock)
{
    t = atomic_inc(lock->next_ticket);
    while (t != lock->current_ticket)
        ; /* Spin */
}
```

```
void spin_unlock(spinlock_t *lock)
{
    lock->current_ticket++;
}
```

```
struct spinlock_t {
    int current_ticket;
    int next_ticket;
}
```

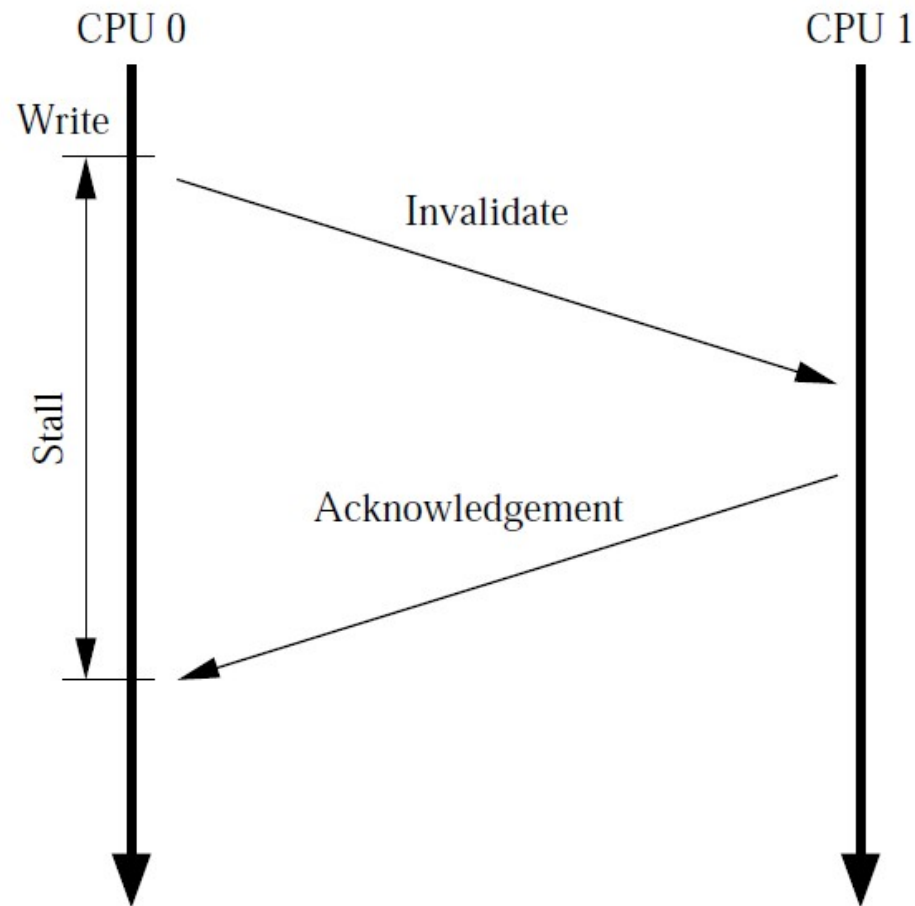


# Example

- Modified → shared
  - Some other CPU reads the cache line, and it is supplied from this CPU's cache, which retains a read-only copy, possibly also writing it back to memory.
  - This transition is initiated by the reception of a “read” message, and this CPU responds with a “read response” message containing the requested data.

# Memory ordering

# Writes become slow

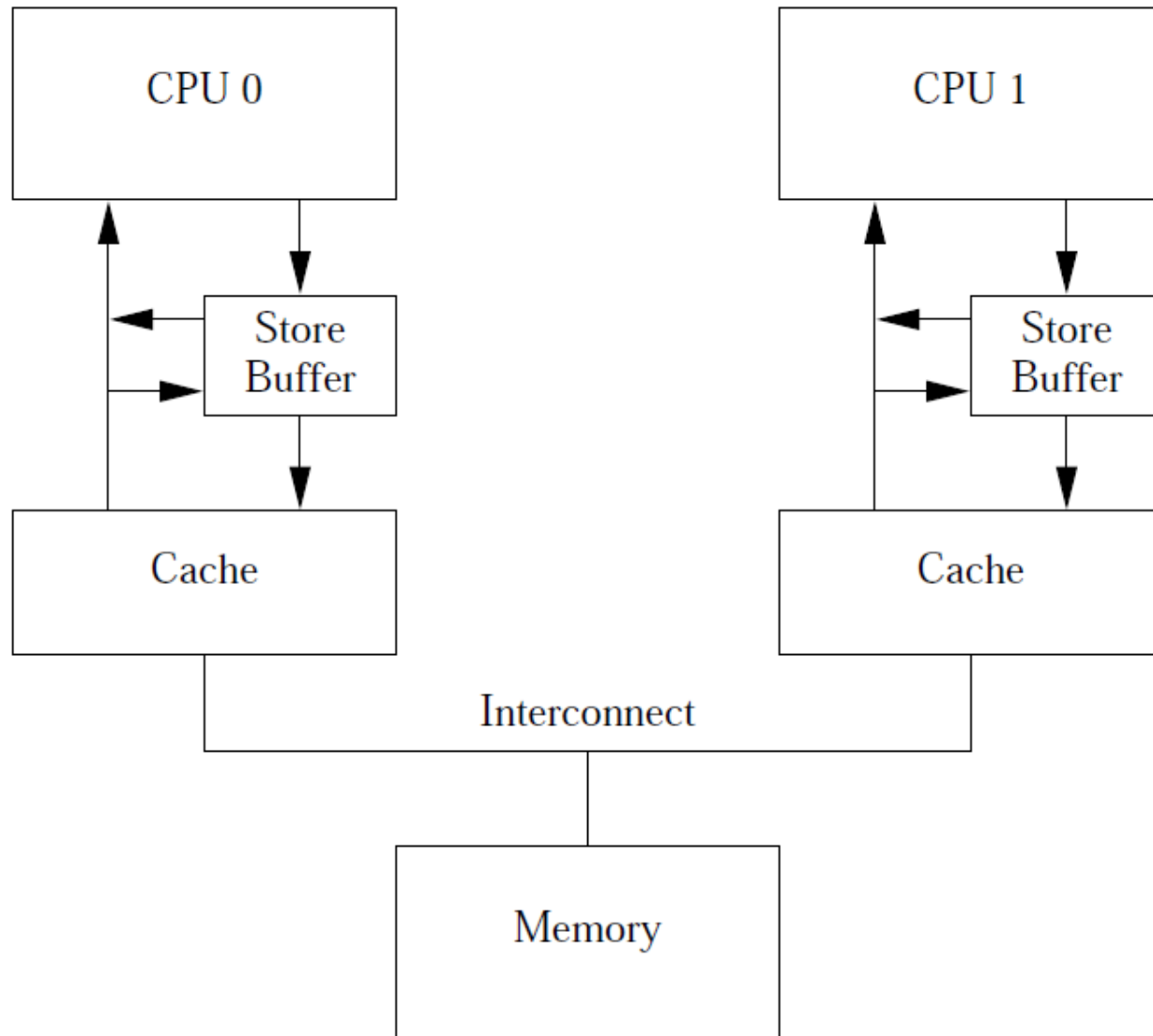


# Store buffers

- Idea:
  - Record a store in a CPU buffer
  - CPU can proceed immediately
- Complete store when invalidate message is received
  - Move a cache line from the store buffer to the cache



# Store buffers



# Consistency problem

```
1 void foo(void)
2 {
3     a = 1;
4     b = 1;
5 }
6
7 void bar(void)
8 {
9     while (b == 0) continue;
10    assert(a == 1);
11 }
```

- CPU0: foo()
- CPU1: bar()
- Can assert fail?

```
a = [invalid], b = 0 [owned]
a = 1;
// save a in store buffer
// send invalidate(a) message to
// finish write

b = 1;
// b = [owned], update it in cache
// receive read(b), b → [shared]
// send read_reply(b, 1)
```

```
a = 0 [shared], b = [invalid]

while (b == 0)
// read(b)

// receive read_reply (b, 1)
assert (a == 1) // fails
// receive invalidate(a)
```

```
a = [invalid], b = 0 [owned]
a = 1;
// save a in store buffer
// send invalidate(a) message to
// finish write

b = 1;
// b = [owned], update it in cache
// DO NOT UPDATE CACHE UNTILL STORE
// BUFFER IS DRAINED
// receive read(b), b → [shared]
// send read_reply(b, 1)
```

```
a = 0 [shared], b = [invalid]

while (b == 0)
// read(b)

// receive read_reply (b, 1)
assert (a == 1) // fails
// receive invalidate(a)
```

# Write memory barrier

- Memory barrier `smp_wmb()`
  - *Cause the CPU to flush its store buffer before applying subsequent stores to their cache lines*
  - The CPU could either simply stall until the store buffer was empty before proceeding,
  - Or it could use the store buffer to hold subsequent stores until all of the prior entries in the store buffer had been applied

# Consistency fixed

```
1 void foo(void)
2 {
3     a = 1;
4     smp_wmb();
5     b = 1;
6 }
7 void bar(void)
8 {
9     while (b == 0) continue;
10    assert(a == 1);
11 }
```

```
a = [invalid], b = 0 [owned]
a = 1;
// save a in store buffer
// send invalidate(a) message
smp_wmb()
// mark store buffer

b = 1;
// b = [owned], but there are marked
// entries in the store buffer
// put b = 1 on the store buffer, but
// do not update cache

// receive read(b), b → [shared]
// send read_reply(b, 0)

// receive invalidate(a)
// flush the store buffer
```

```
a = 0 [shared], b = [invalid]

while (b == 0)
// read(b)

// receive read_reply (b, 0)
// loop

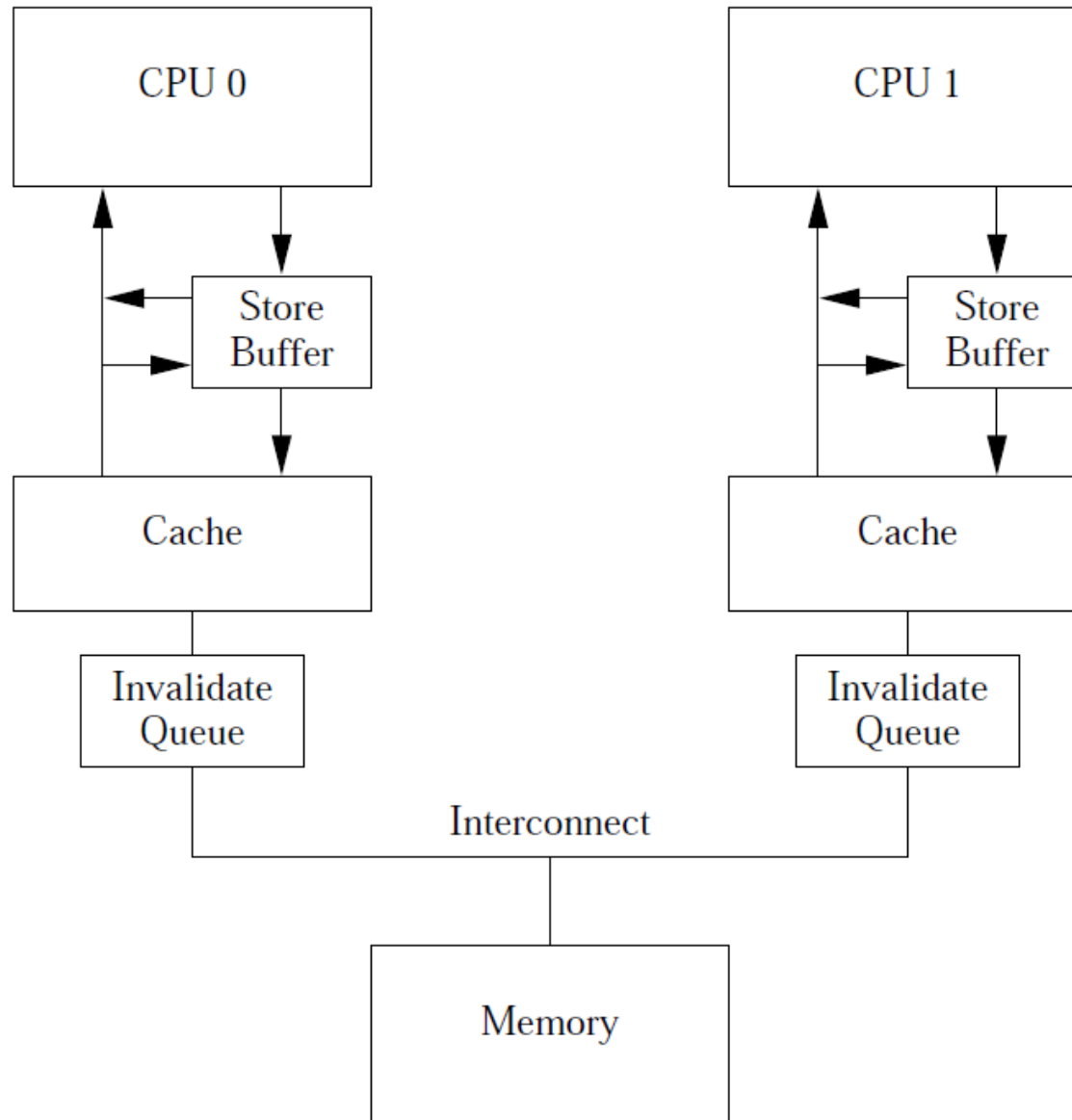
while (b == 0)
// b is [invalid], read(b) again
assert (a == 1) // succeed
// receive invalidate(a)
```

# Invalidate queues

- Invalidate messages can be slow
  - Caches can be overloaded
- While waiting for invalidate acknowledgements
  - Run out of space in the store buffer
- Idea: Why wait for cache?
  - Store invalidate request in a queue
  - Acknowledge it right away
  - Apply later



# Invalidate queues



```
a = [invalid], b = 0 [owned]
a = 1;
// save a in store buffer
// send invalidate(a) message
smp_wmb()
// mark store buffer

// receive invalidate(a)
// flush the store buffer

b = 1;
// b = [owned], update cache

// receive read(b), b → [shared]
// send read_reply(b, 1)
```

```
a = 0 [shared], b = [invalid]

while (b == 0)
// read(b)
// receive invalidate(a), queue it and
// reply right away

// receive read_reply (b, 1)
assert (a == 1) // fail
// receive invalidate(a)
```

```
a = [invalid], b = 0 [owned]
a = 1;
// save a in store buffer
// send invalidate(a) message
smp_wmb()
// mark store buffer
```

```
// receive invalidate(a)
// flush the store buffer
```

```
b = 1;
// b = [owned], update cache
```

```
// receive read(b), b → [shared]
// send read_reply(b, 1)
```

```
a = 0 [shared], b = [invalid]

while (b == 0)
// read(b)
// receive invalidate(a), queue it and
// reply right away
```

```
// receive read_reply (b, 1)
// MAKE SURE INVALIDATE QUEUE IS DRAINED
assert (a == 1) // fail
// receive invalidate(a)
```

# Read memory barrier

- Read barrier `smp_rmb()`
  - *Marks all the entries currently in its invalidate queue, and forces any subsequent load to wait until all marked entries have been applied to the CPU's cache.*

# Consistency fixed

```
1 void foo(void)
2 {
3     a = 1;
4     smp_wmb();
5     b = 1;
6
7 void bar(void)
8 {
9     while (b == 0) continue;
10    smp_rmb();
11    assert(a == 1);
12 }
```

## Trying to execute

```
while (b == 0)
```

- CPU 1 sends read (b) message, receives the cache line containing “b” and installs it in its cache
- CPU 1 can now finish executing while(b==0) continue, and since it finds that the value of “b” is 1, it proceeds to the next statement, which is now a memory barrier
- CPU 1 must now stall until it processes all preexisting messages in its invalidation queue
- CPU 1 now processes the queued “invalidate” message, and invalidates the cache line containing “a” from its own cache
- CPU 1 executes the assert(a==1), and, since the cache line containing “a” is no longer in CPU 1’s cache, it transmits a “read” message
- CPU 0 responds to this “read” message with the cache line containing the new value of “a”
- CPU 1 receives this cache line, which contains a value of 1 for “a”, so that the assertion does not trigger

# Conclusion

- Memory barriers are required to ensure correct order of cross-CPU memory updates
  - E.g. update two memory locations a, and b
- Two memory barriers are common
  - Write
  - Read

Thank you!