Lecture 14:

Memory Consistency

Parallel Computer Architecture and Programming

CMU 15-418/15-618, Spring 2020

What is Correct Behavior for a Parallel Memory Hierarchy?

- Note: side-effects of writes are only observable when *reads* occur
  - so we will focus on the values returned by reads
- Intuitive answer:
  - reading a location should return the latest value written (by any thread)
- Hmm… what does "latest" mean exactly?
  - within a thread, it can be defined by program order
  - but what about across threads?
    - the most recent write in physical time?
      - hopefully not, because there is no way that the hardware can pull that off
        - » e.g., if it takes >10 cycles to communicate between processors, there is no way that processor 0 can know what processor 1 did 2 clock ticks ago
    - most recent based upon something else?
      - Hmm…

Refining Our Intuition

Thread 0

```
// write evens to X
for (i=0; i<N; i+=2) {
    X = i;
    …
}
```

Thread 1

```
// write odds to X
for (j=1; j<N; j+=2) {
    X = j;
    …
}
```

Thread 2

```
…
A = X;
…
B = X;
…
C = X;
…
```

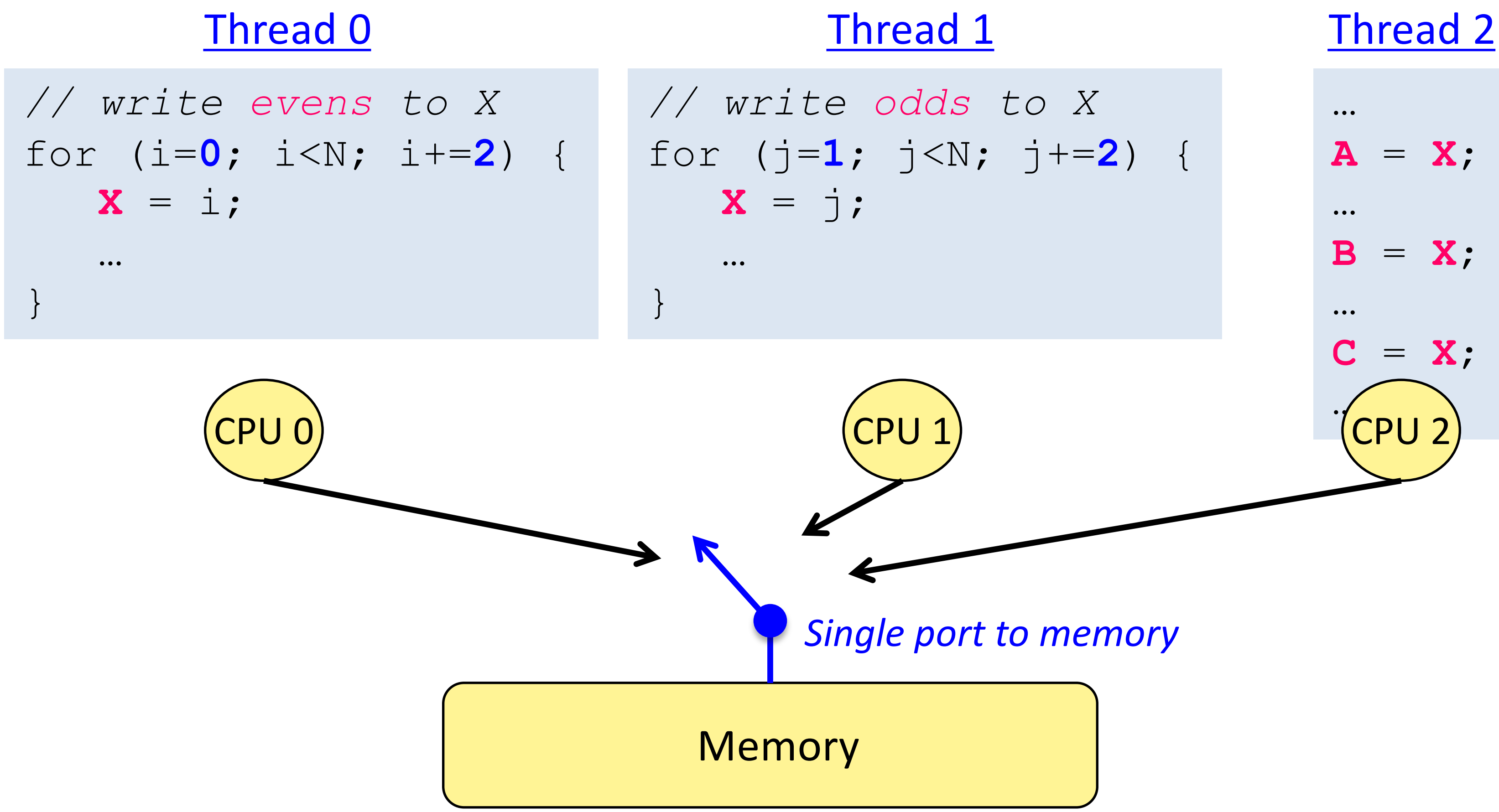
(Assume: X=0 initially, and these are the only writes to X.)

- What would be some clearly illegal combinations of (A,B,C)?
- How about:

  (4,8,1)?　　　(9,12,3)?　　　(7,19,31)?

- What can we generalize from this?
  - writes from any particular thread must be consistent with program order
    - in this example, observed even numbers must be increasing (ditto for odds)
  - across threads: writes must be consistent with *a valid interleaving of threads*
    - not physical time! (programmer cannot rely upon that)

Visualizing Our Intuition



- Each thread proceeds in program order
- Memory accesses interleaved (one at a time) to a single-ported memory
  - rate of progress of each thread is unpredictable

Correctness Revisited

Thread 0

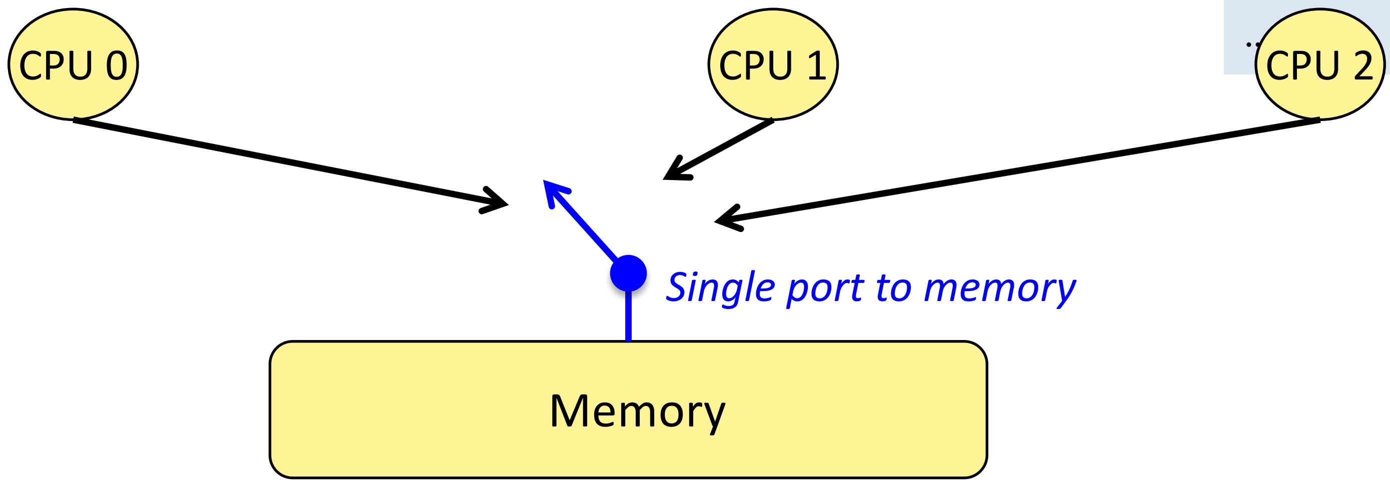
```
// write evens to X
for (i=0; i<N; i+=2) {
    X = i;
    …
}
```

Thread 1

```
// write odds to X
for (j=1; j<N; j+=2) {
    X = j;
    …
}
```

Thread 2

```
…
A = X;
…
B = X;
…
C = X;
…
```



Recall: "reading a location should return the latest value written (by any thread)"

→ "latest" means consistent with some interleaving that matches this model

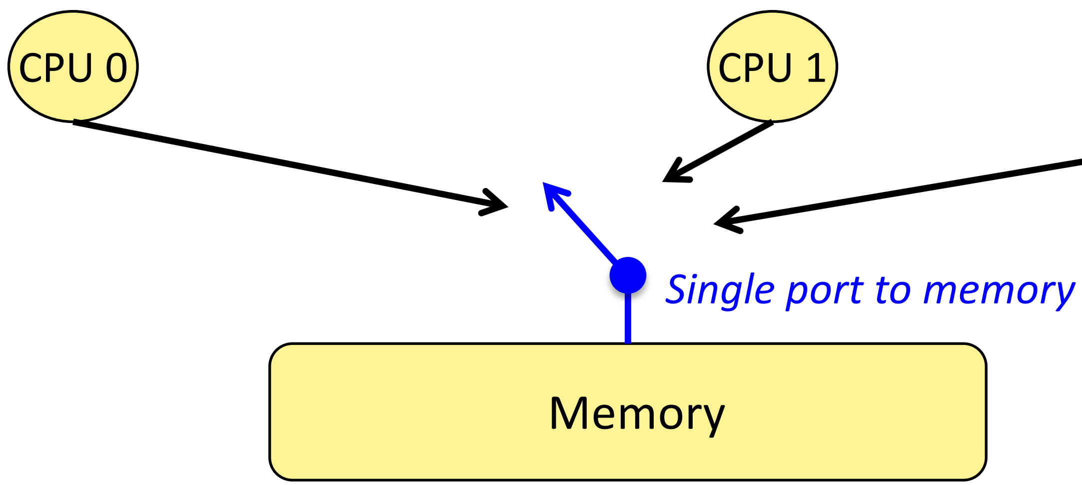
– this is a hypothetical interleaving; the machine didn't necessarily do this!

Part 2 of Memory Correctness: Memory Consistency Model

1. "Cache Coherence"
   - do all loads and stores to a given memory location behave correctly?

2. "Memory Consistency Model" (sometimes called "Memory Ordering")
   - do all loads and stores, even to separate memory locations, behave correctly?

Recall: our intuition

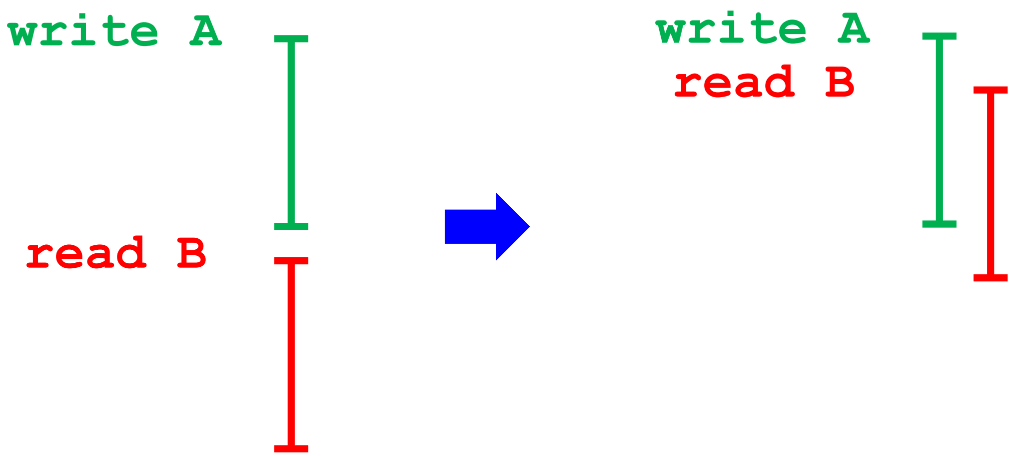


Why is this so complicated?

- Fundamental issue:
  - loads and stores are very expensive, even on a uniprocessor
    - can easily take 10's to 100's of cycles
- What programmers intuitively expect:
  - processor atomically performs one instruction at a time, in program order
- In reality:
  - if the processor actually operated this way, it would be painfully slow
  - instead, the processor *aggressively reorders instructions* to hide memory latency
- Upshot:
  - *within a given thread*, the processor preserves the program order illusion
  - but this illusion has nothing to do with what happens in physical time!
  - from the perspective of *other threads*, all bets are off!

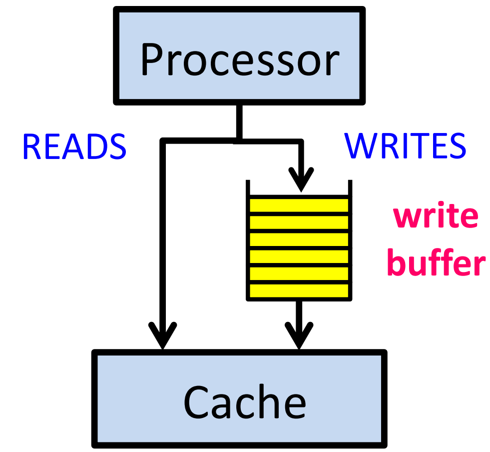
Hiding Memory Latency is Important for Performance

- Idea: *overlap* memory accesses with other accesses and computation



- Hiding write latency is simple in uniprocessors:
  - add a write buffer
  - (more on this later)

- (But this affects correctness in multiprocessors)



How Can We Hide the Latency of Memory Reads?

"Out of order" pipelining:

– when an instruction is stuck, perhaps there are subsequent instructions that can be executed

```
x = *p;        ← suffers expensive cache miss
y = x + 1;     ← stuck waiting on true dependence
z = *q;        } ← these do not need to wait
*r = c;        }
```

- Implication: memory accesses may be performed out-of-order!!!

What About Conditional Branches?

- Do we need to wait for a conditional branch to be resolved before proceeding?
  - No! Just predict the branch outcome and continue executing speculatively.
    - if prediction is wrong, squash any side-effects and restart down correct path

```
x = *p;
y = x + 1;
z = *q;
*r = c;
if (x != z)
  d = e - 7;
else d = e + 5;
…
```

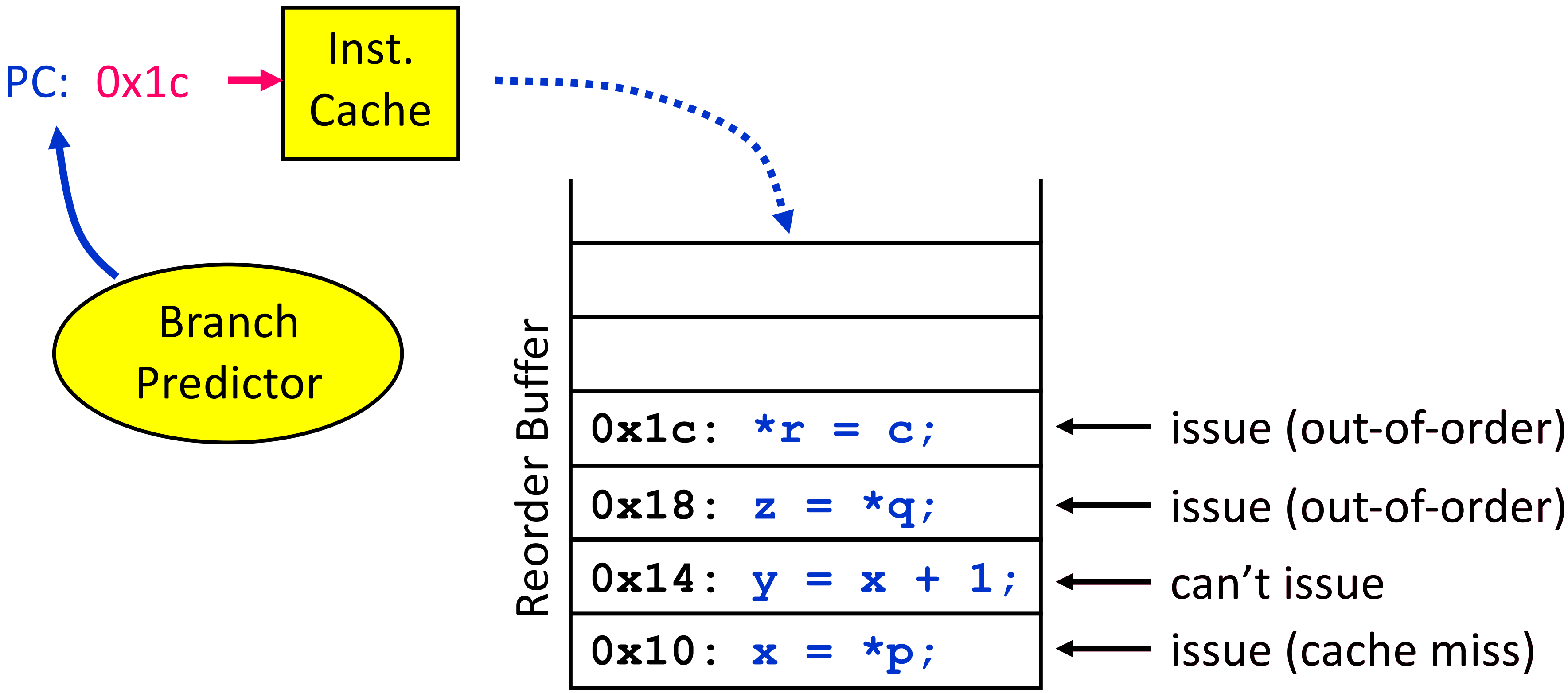
if hardware guesses that this is true (pointing to `if (x != z)`)

then execute "then" part (speculatively) (pointing to `d = e - 7;`)

(without waiting for **x** or **z**)

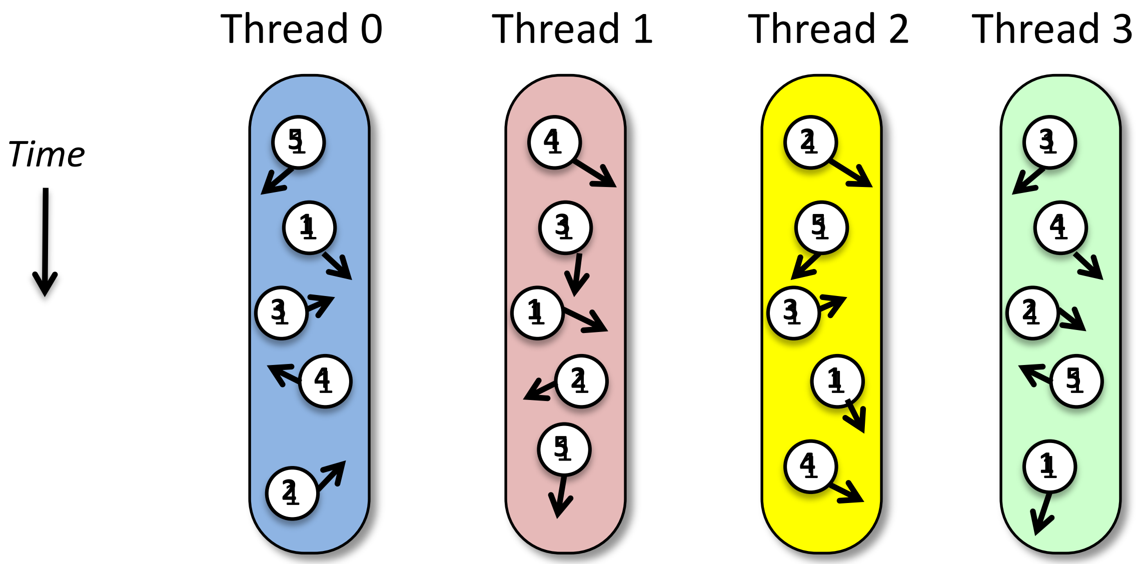
How Out-of-Order Pipelining Works in Modern Processors

- Fetch and graduate instructions in-order, but issue out-of-order



- Intra-thread dependences are preserved, but memory accesses get reordered!

Analogy: Gas Particles in Balloons



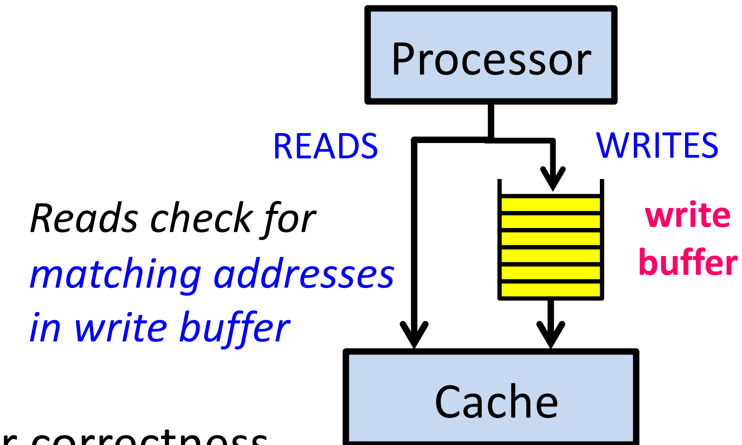
(wikiHow)

- Imagine that each instruction within a thread is a gas particle inside a twisty balloon
- They were numbered originally, but then they start to move and bounce around
- When a given thread observes memory accesses from a *different* thread:
  - those memory accesses can be (almost) arbitrarily jumbled around
    - like trying to locate the position of a particular gas particle in a balloon
- As we'll see later, the only thing that we can do is to put *twists* in the balloon

Uniprocessor Memory Model

- Memory model specifies ordering constraints among accesses
- Uniprocessor model: memory accesses atomic and in program order

```
write A
write B
read A
read B
```



- Not necessary to maintain sequential order for correctness
  - hardware: buffering, pipelining
  - compiler: register allocation, code motion
- Simple for programmers
- Allows for high performance

In Parallel Machines (with a Shared Address Space)

- Order between accesses to different locations becomes important

(Initially A and Ready = 0)

P1

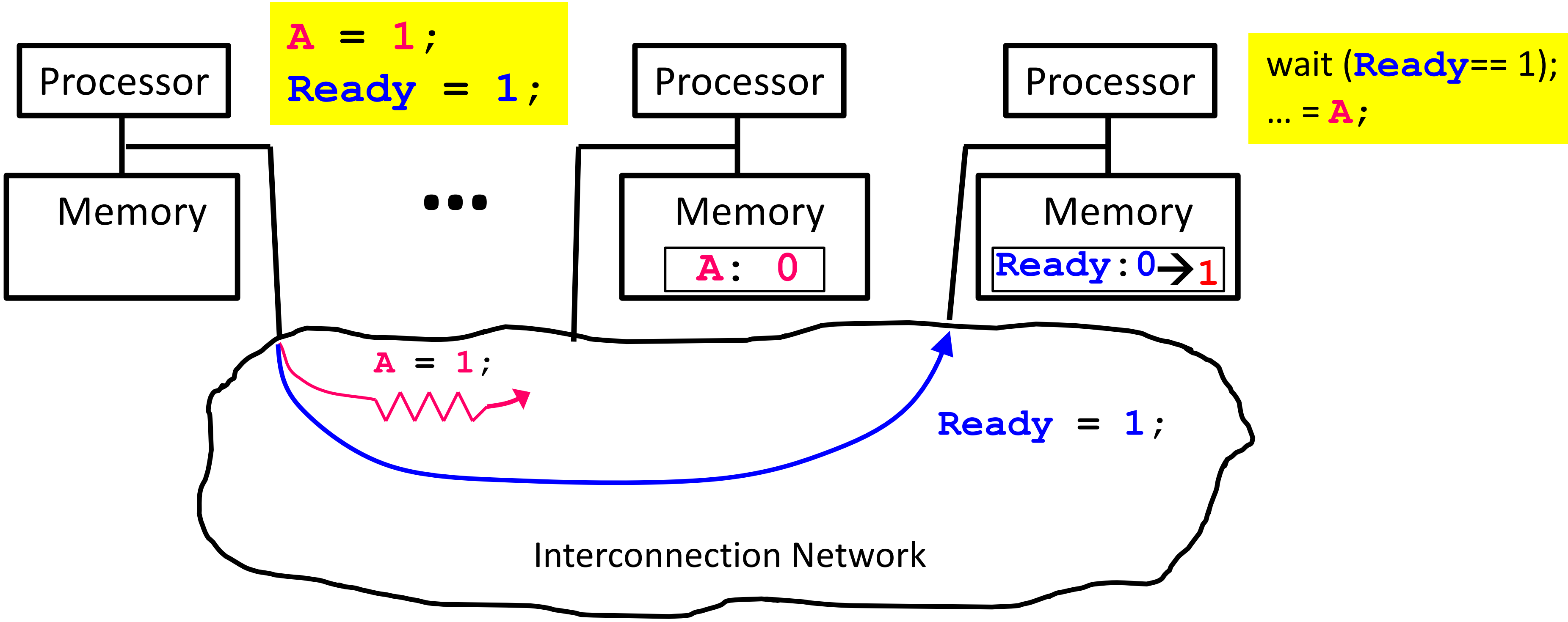
```
A = 1;
Ready = 1;
```

P2

```
while (Ready != 1);
… = A;  // Should be 1
```

Carnegie Mellon

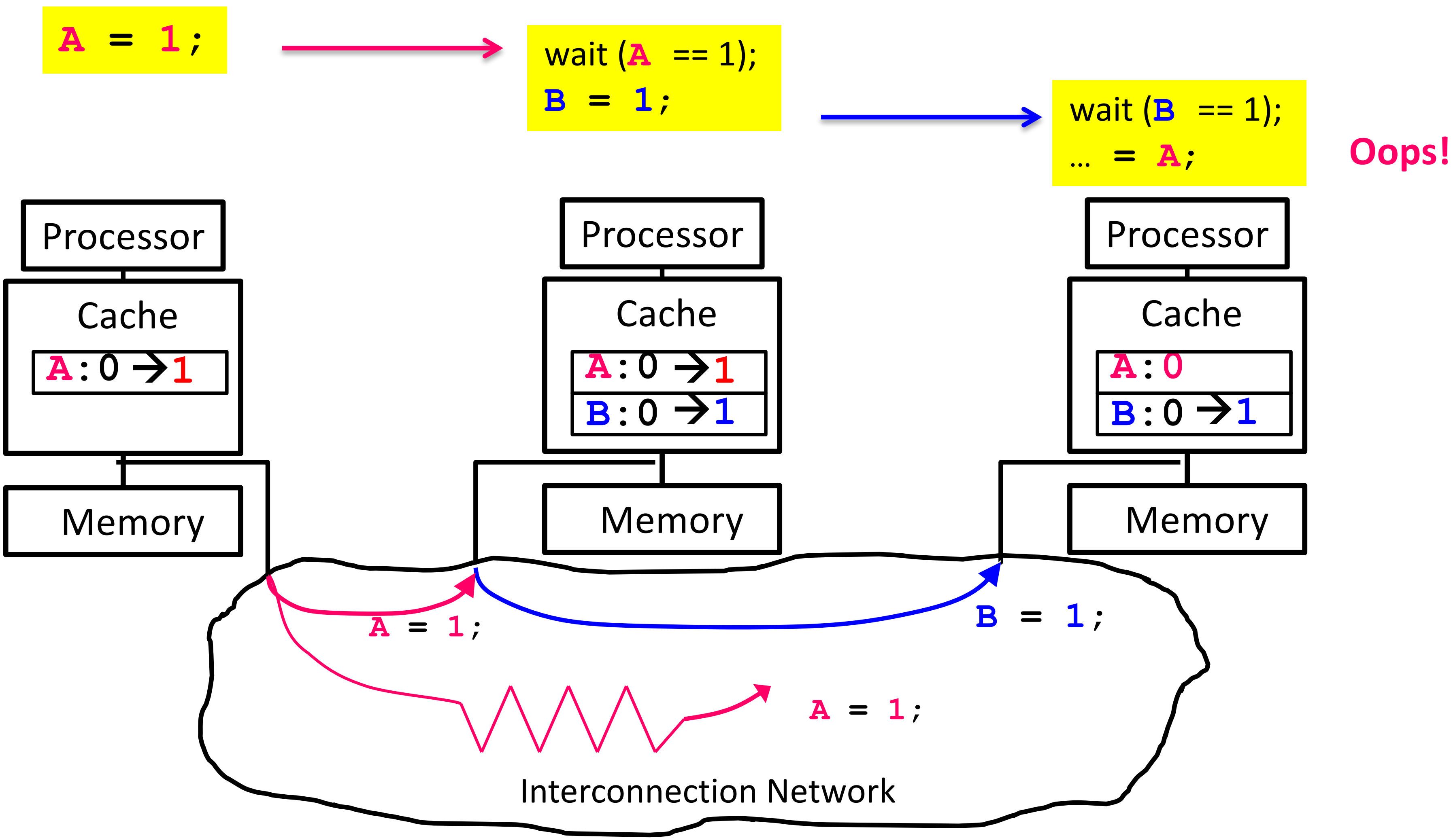
How Unsafe Reordering Can Happen



- Distribution of memory resources
  - accesses issued in order may be observed out of order

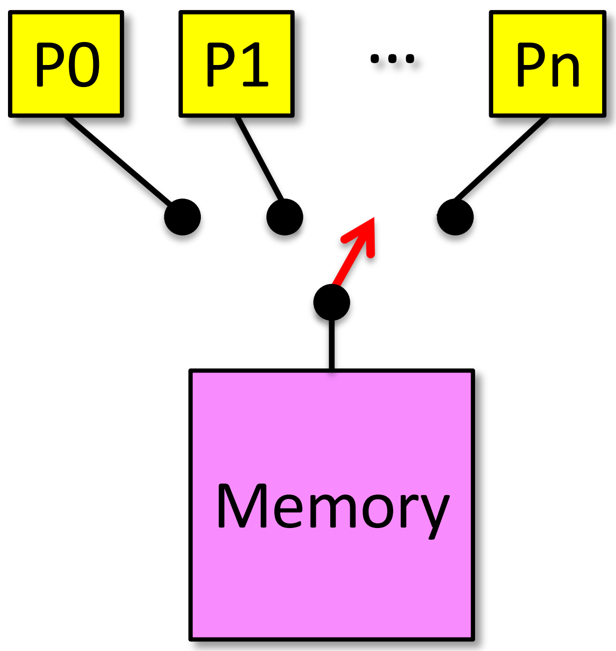
Caches Complicate Things More

- Multiple copies of the same location



Our Intuitive Model: "Sequential Consistency" (SC)

- Formalized by Lamport (1979)
  - accesses of each processor in program order
  - all accesses appear in sequential order



- Any order implicitly assumed by programmer is maintained

Example with Sequential Consistency

Simple Synchronization:

P0		P1	
`A = 1`	(a)		
`Ready = 1`	(b)	`x = Ready`	(c)
		`y = A`	(d)

- all locations are initialized to 0
- possible outcomes for (x,y):
  - (0,0), (0,1), (1,1)
- (x,y) = (1,0) is not a possible outcome (i.e. `Ready` = 1, `A` = 0):
  - we know a->b and c->d by program order
  - b->c implies that a->d
  - y==0 implies d->a which leads to a contradiction
  - *but real hardware will do this!*

Another Example with Sequential Consistency

Stripped-down version of a 2-process mutex (minus the turn-taking):

P0		P1	
`want[0] = 1`	(a)	`want[1] = 1`	(c)
`x = want[1]`	(b)	`y = want[0]`	(d)

- all locations are initialized to 0
- possible outcomes for (x,y):
  - (0,1), (1,0), (1,1)
- (x,y) = (0,0) is not a possible outcome (i.e. **`want[0]`**= **0**, **`want[1]`**= **0**):
  - a->b and c->d implied by program order
  - x = 0 implies b->c which implies a->d
  - a->d says y = 1 which leads to a contradiction
  - similarly, y = 0 implies x = 1 which is also a contradiction
  - *but real hardware will do this!*

One Approach to Implementing Sequential Consistency

1. Implement cache coherence

   → writes to the same location are observed in same order by all processors

2. For each processor, delay start of memory access until previous one completes

   → each processor has only one outstanding memory access at a time

- What does it mean for a memory access to complete?

When Do Memory Accesses Complete?

- Memory Reads:
  - a read completes when its return value is bound

```
load r1 ← X
```

X = ???

(Find **X** in memory system)

X = 17

r1 = 17

When Do Memory Accesses Complete?

- Memory Reads:
  - a read completes when its return value is bound
- Memory Writes:
  - a write completes when the new value is "visible" to other processors

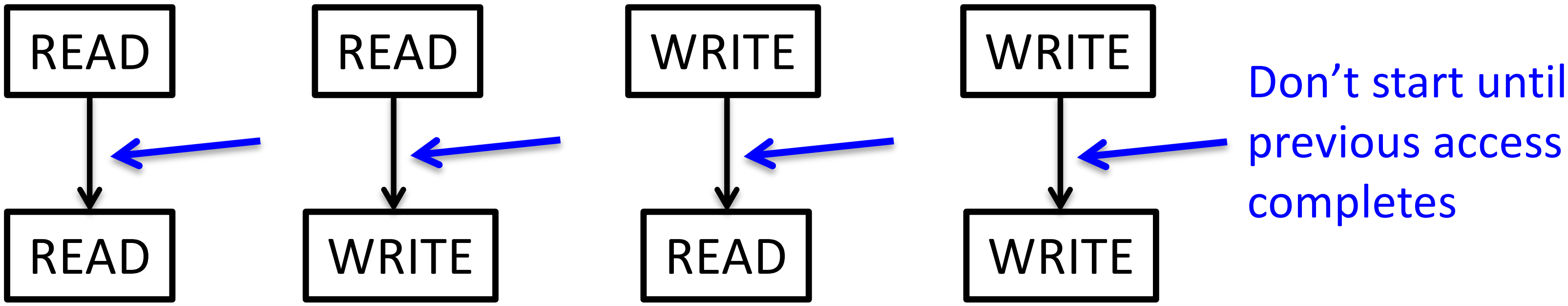
```
store 23 → X
```

X = 23 → *(Commit to memory order)* *(aka "serialize")*

- What does "visible" mean?
  - it does NOT mean that other processors have necessarily seen the value yet
  - it means the new value is committed to the hypothetical serializable order (HSO)
    - a later read of **X** in the HSO will see either this value or a later one
  - (for simplicity, assume that writes occur atomically)

Summary for Sequential Consistency

- Maintain order between shared accesses in each processor

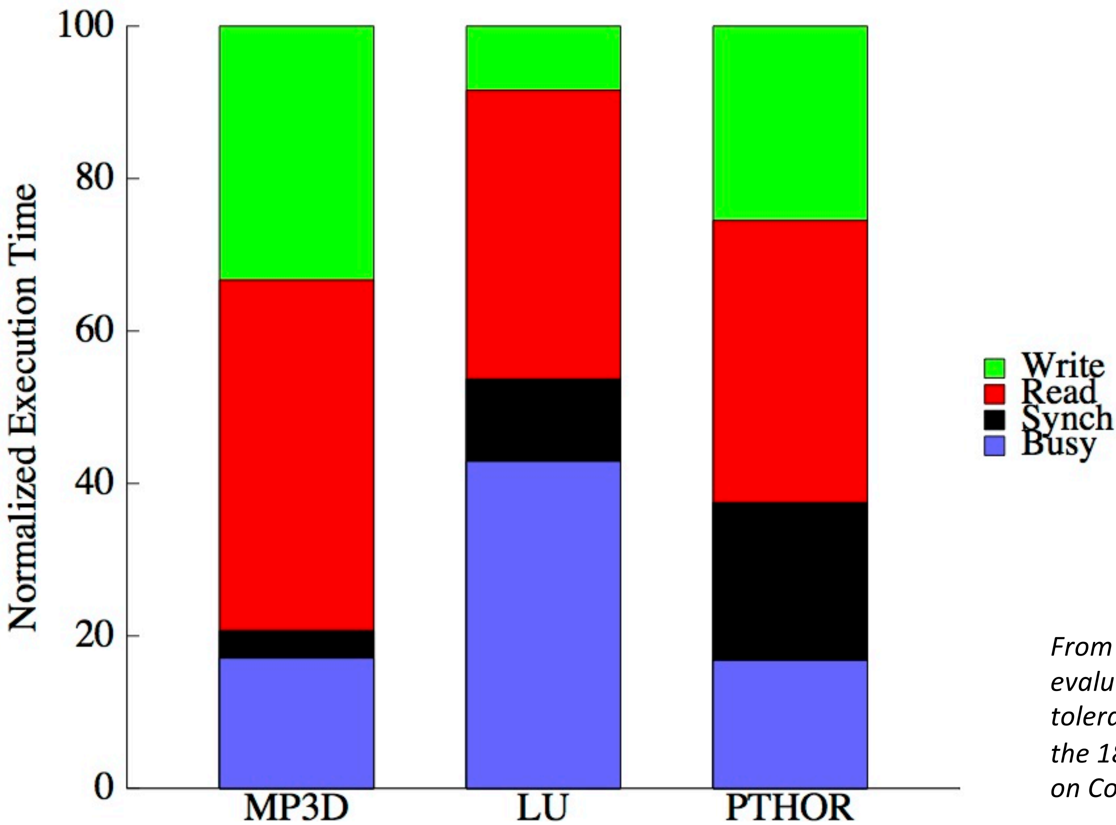


- Balloon analogy:
  - like putting a twist between each individual (ordered) gas particle

- Severely restricts common hardware and compiler optimizations

Performance of Sequential Consistency

- Processor issues accesses one-at-a-time and stalls for completion

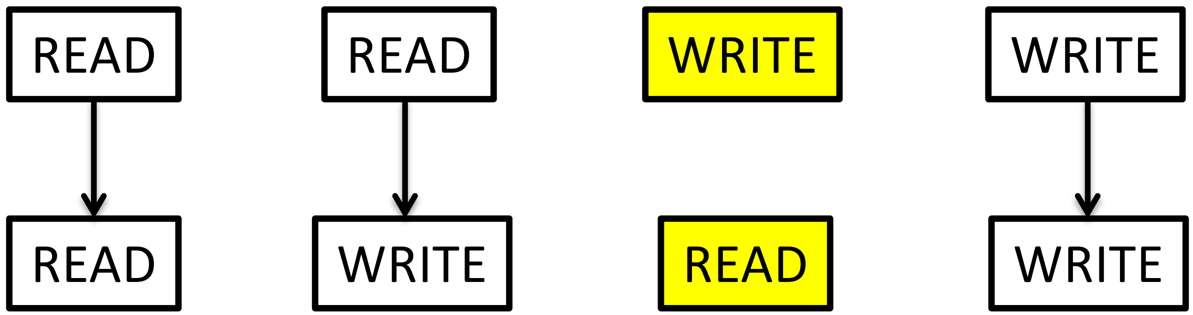


From Gupta et al, "Comparative evaluation of latency reducing and tolerating techniques." In Proceedings of the 18th annual International Symposium on Computer Architecture (ISCA '91)

- Low processor utilization (17% - 42%) even with caching

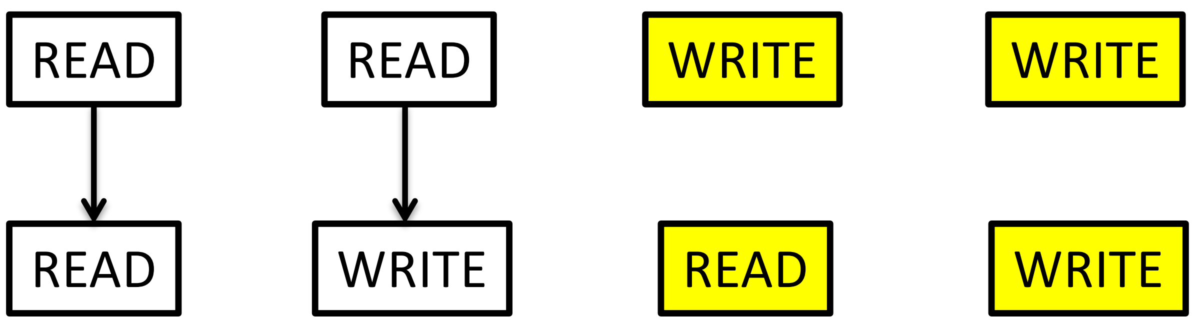
Alternatives to Sequential Consistency

- Relax constraints on memory order



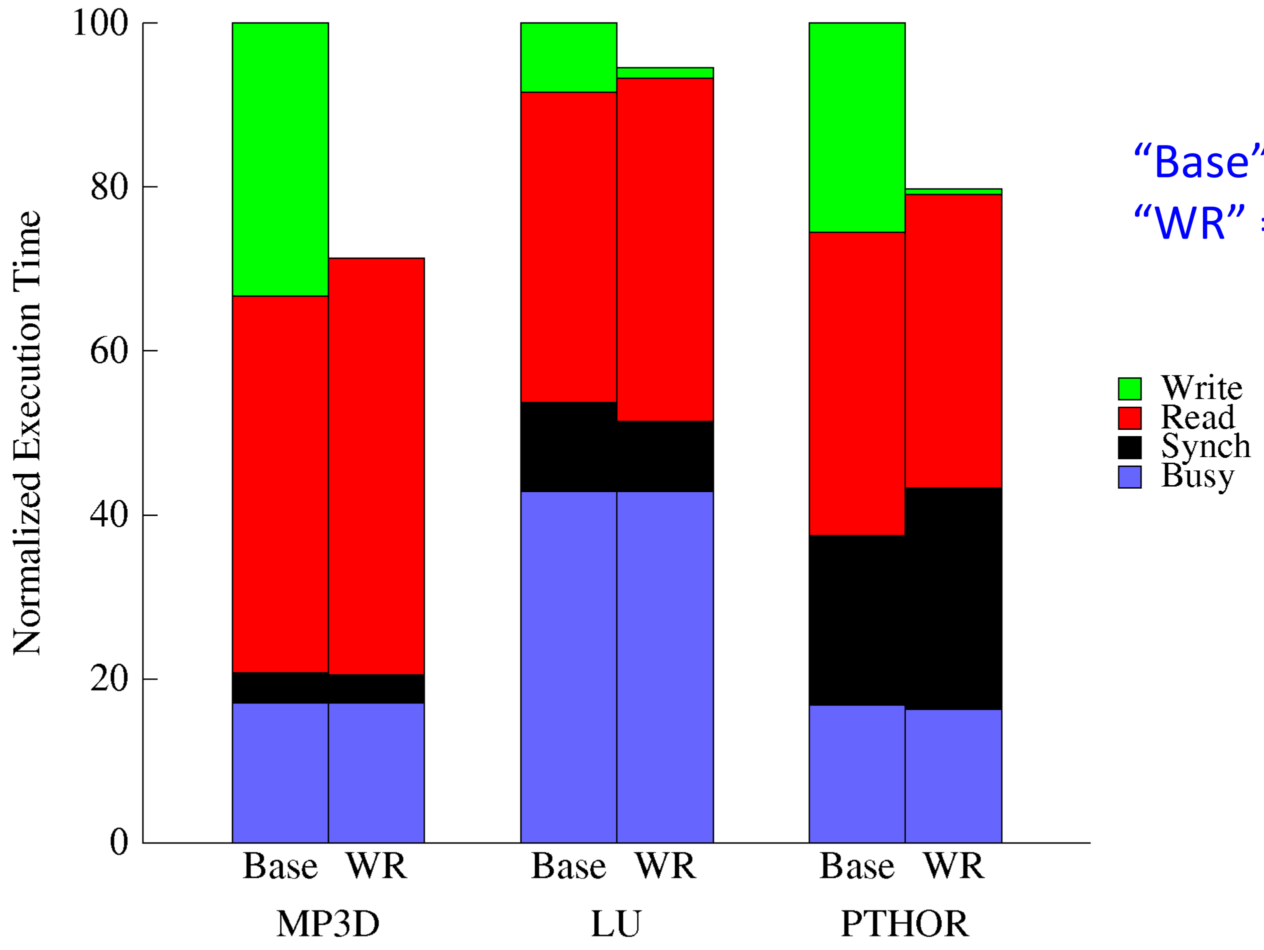
Total Store Ordering (TSO) (Similar to Intel)

See Section 8.2 of "Intel® 64 and IA-32 Architectures Software Developer's Manual, Volume 3A: System Programming Guide, Part 1", http://www.intel.com/content/dam/www/public/us/en/documents/manuals/64-ia-32-architectures-software-developer-vol-3a-part-1-manual.pdf

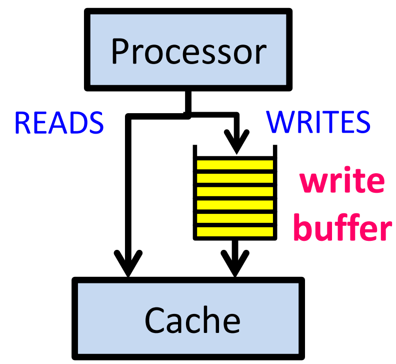


Partial Store Ordering (PSO)

Performance Impact of TSO vs. SC



"Base" = SC
"WR" = TSO



- Can use a write buffer
- Write latency is effectively hidden

But Can Programs Live with Weaker Memory Orders?

- "Correctness": same results as sequential consistency
- Most programs don't require strict ordering (all of the time) for "correctness"

Program Order

```
A = 1;
B = 1;
unlock L;        lock L;
                 … = A;
                 … = B;
```

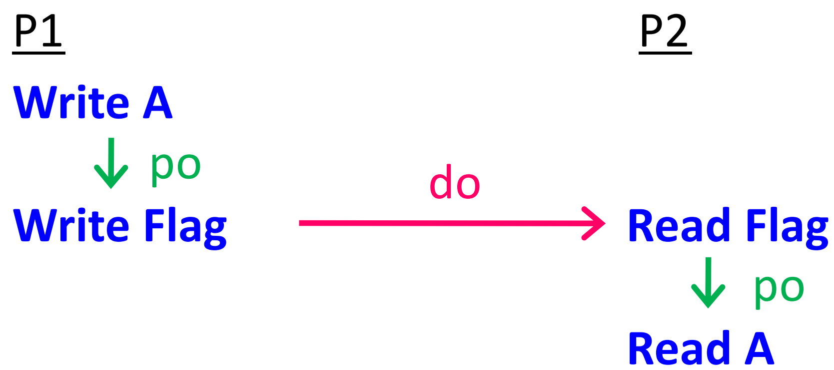
Sufficient Order

```
A = 1;
B = 1;
unlock L;        lock L;
                 … = A;
                 … = B;
```

- But how do we know when a program will behave correctly?

Identifying Data Races and Synchronization

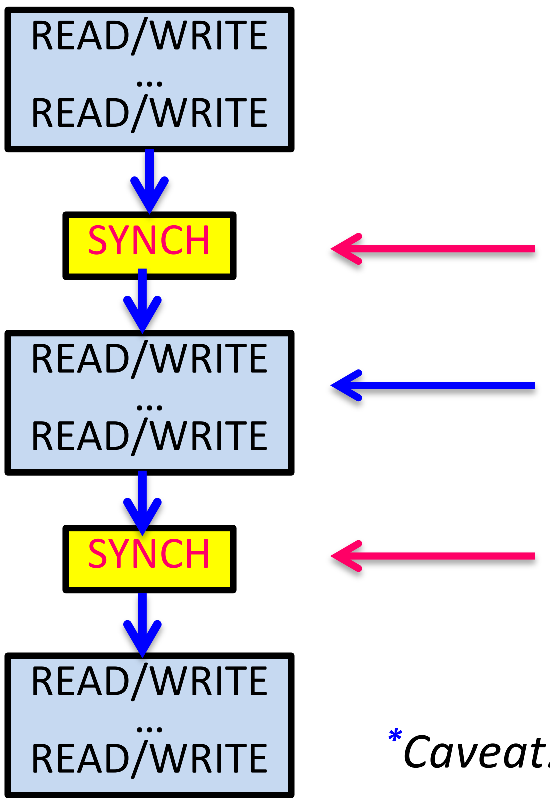
- Two accesses *conflict* if:
  - (i) access same location, and (ii) at least one is a write
- Order accesses by:
  - program order (po)
  - dependence order (do): op1 --> op2 if op2 reads op1



- Data Race:
  - two conflicting accesses on different processors
  - not ordered by intervening accesses
- Properly Synchronized Programs:
  - all synchronizations are explicitly identified
  - all data accesses are ordered through synchronization

Optimizations for Synchronized Programs

- Intuition: many parallel programs have mixtures of "private" and "public" parts*
  - the "private" parts must be protected by synchronization (e.g., locks)
  - can we take advantage of synchronization to improve performance?



Example:

Grab a lock

Insert node into data structure

- Essentially a "private" activity; reordering is ok

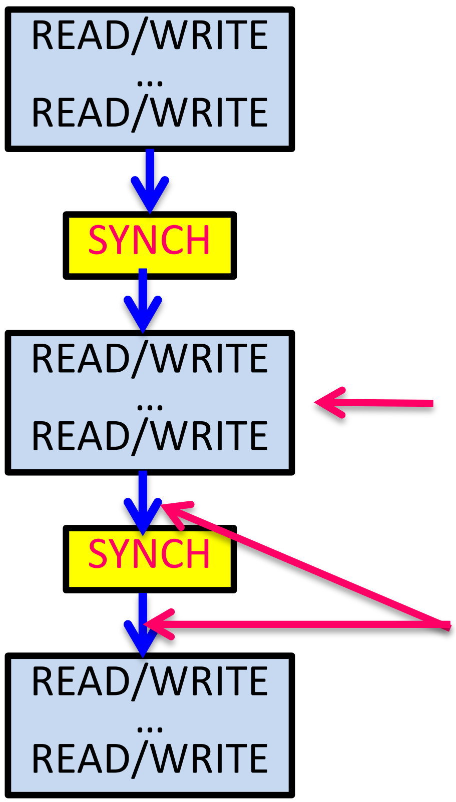
Release the lock

- Now we make it "public" to the other nodes

**Caveat: shared data is in fact always visible to other threads.*

Optimizations for Synchronized Programs

- Exploit information about synchronization



"Weak Ordering" (WO)

Between synchronization operations:

- we can allow reordering of memory operations
- *(as long as intra-thread dependences are preserved)*

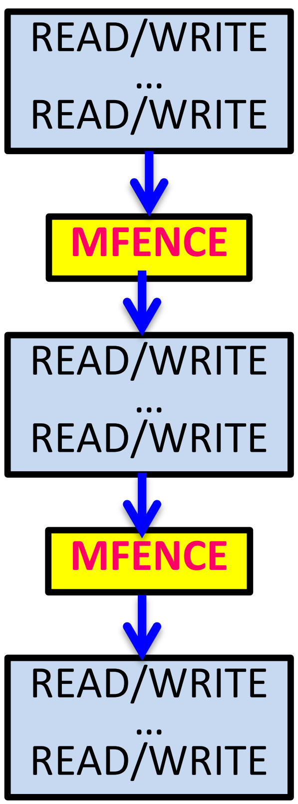
Just before and just after synchronization operations:

- thread must wait for all prior operations to complete

- properly synchronized programs should yield the same result as on an SC machine

Intel's MFENCE (Memory Fence) Operation

- An **MFENCE** operation enforces the ordering seen on the previous slide:
  - does not begin until all prior reads & writes from that thread have completed
  - no subsequent read or write from that thread can start until after it finishes



Balloon analogy: it is a twist in the balloon

- no gas particles can pass through it

(wikiHow)

Implementing Lock with Xchg

```
xchg(mem, reg)  =  temp = *mem;
                   *mem = reg;
                   reg = temp;
```

} Done atomically

```
acquire():

  while (1) {
    reg = 1;
    xchg(&lock, reg);
    if (reg == 0)
      break;
  }
```

```
release():
  reg = 0;
  xchg(&lock, reg);
```

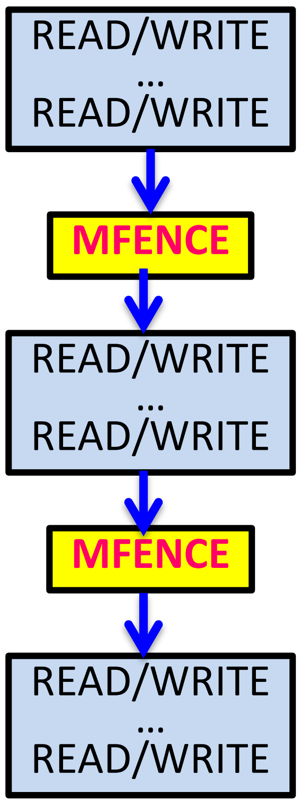
Good news: **xchg** also performs MFENCE

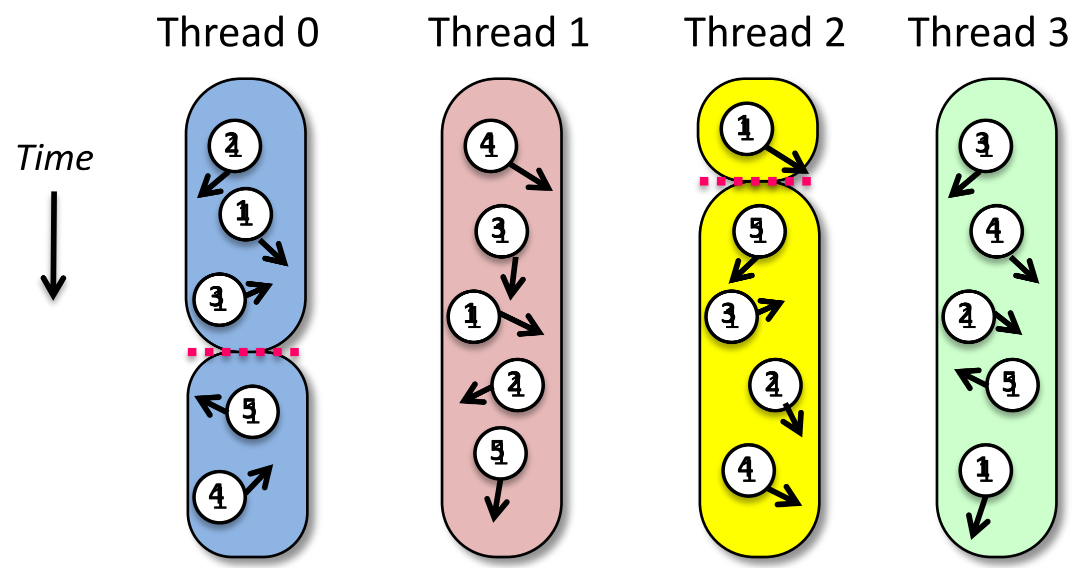
ARM Processors

- ARM processors have a very relaxed consistency model
- ARM has some great examples in their programmer's reference:
  - http://infocenter.arm.com/help/topic/com.arm.doc.genc007826/Barrier_Litmus_Tests_and_Cookbook_A08.pdf
- A great list regarding relaxed memory consistency in general:
  - http://www.cl.cam.ac.uk/~pes20/weakmemory/

Common Misconception about MFENCE

- MFENCE operation does NOT push values out to other threads
  - it is not a magic “make every thread up-to-date” operation
- It simply stalls the thread that performs the MFENCE until write buffer empty





MFENCE operations create *partial orderings*

- that are observable across threads

Earlier (Broken) Example Revisited

Where exactly should we insert MFENCE operations to fix this?

(Assume machine does not provide consistency guarantees.)

P0	P1
[1: Here?]	
`A = 1`	
[2: Here?]	*[4: Here?]*
`Ready = 1`	`x = Ready`
[3: Here?]	*[5: Here?]*
	`y = A`
	[6: Here?]

Earlier (Broken) Example Revisited

Where exactly should we insert MFENCE operations to fix this?

P0

[1: Here?]

```
A = 1
```

MFENCE

```
Ready = 1
```

[3: Here?]

P1

[4: Here?]

```
x = Ready
```

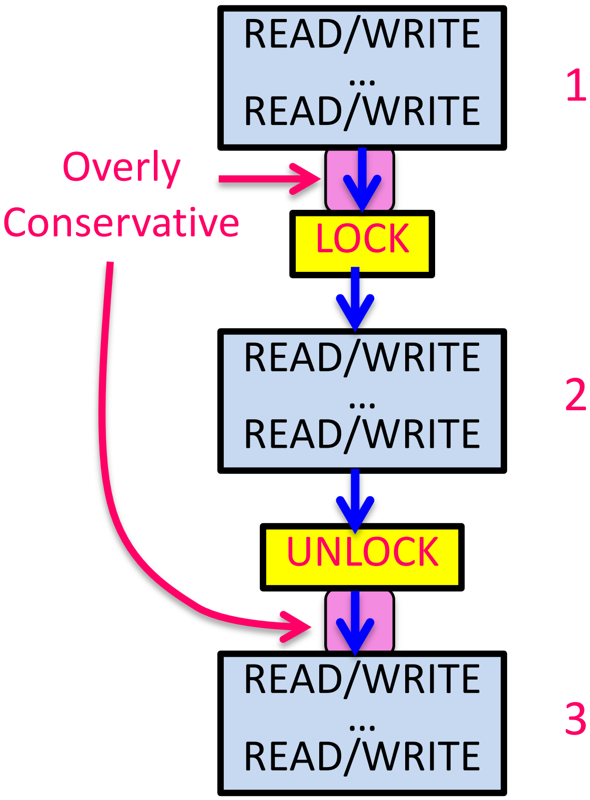
MFENCE

```
y = A
```

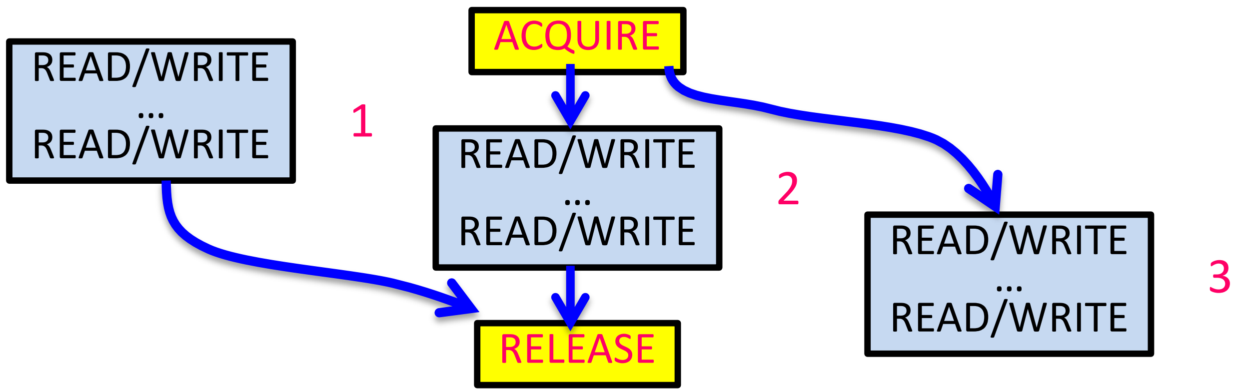
[6: Here?]

Exploiting Asymmetry in Synchronization: "Release Consistency"

- Lock operation: only gains ("acquires") permission to access data
- Unlock operation: only gives away ("releases") permission to access data



Weak Ordering (WO)



Release Consistency (RC)
Make sure writes completed before exit critical section
Make sure don't read/write shared state until lock acquired

Allowed overlaps

- Read/write private state in 1 with critical section (2)
- Read/write private state in 3 with critical section (2)

Intel's Full Set of Fence Operations

- In addition to **MFENCE**, Intel also supports two other fence operations:
  - **LFENCE**: serializes only with respect to load operations (not stores!)
  - **SFENCE**: serializes only with respect to store operations (not loads!)
    - Note: It does slightly more than this; see the spec for details:
      - *Section 8.2.5 of "Intel® 64 and IA-32 Architectures Software Developer's Manual, Volume 3A: System Programming Guide, Part 1*

- In practice, you are most likely to use:
  - **MFENCE**
  - **xchg**

Earlier (Broken) Example Revisited

Where exactly should we insert FENCE operations to fix this?

P0	P1
[1: Here?]	
`A = 1`	
SFENCE	*[4: Here?]*
`Ready = 1`	`x = Ready`
[3: Here?]	*LFENCE*
	`y = A`
	[6: Here?]

Take-Away Messages on Memory Consistency Models

- **DON'T** use only normal memory operations for synchronization
  - e.g., Peterson's solution for mutual exclusion

```
boolean want[2] = {false, false};
int turn = 0;

want[i] = true;
turn = 1-i;
while (want[1-i] && turn == 1-i)
    continue;
… critical section …
want[i] = false;
```

Exercise for the reader: Where should we add fences (and which type) to fix this?

- **DO** use either explicit synchronization operations (e.g., **xchg**) or fences

```
while (!xchg(&lock_available, 0)
  continue;
… critical section …
xchg(&lock_available, 1);
```

Summary: Relaxed Consistency

- Motivation:
  - obtain higher performance by allowing reordering of memory operations
    - (reordering is not allowed by sequential consistency)

- One cost is software complexity:
  - the programmer or compiler must insert synchronization
    - to ensure certain specific orderings when needed

- In practice:
  - complexities often encapsulated in libraries that provide intuitive primitives
    - e.g., lock/unlock, barriers (or lower-level primitives like fence)
  - It's risky to implement your own synchronization primitives
    - Hard to make portable

- Relaxed models differ in which memory ordering constraints they ignore