



# Locking

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Portions courtesy Emmett Witchel



# Too Much Milk: Lessons

- Software solution (Peterson's algorithm) works, but it is unsatisfactory
  - Solution is complicated; proving correctness is tricky even for the simple example
  - While thread is waiting, it is consuming CPU time
  - Asymmetric solution exists for 2 processes.
- How can we do better?
  - Use hardware features to eliminate busy waiting
  - Define higher-level programming abstractions to simplify concurrent programming



# Concurrency Quiz

If two threads execute this program concurrently, how many different final values of X are there?

**Initially, X == 0.**

Thread 1

```
void increment() {  
    int temp = X;  
    temp = temp + 1;  
    X = temp;  
}
```

Thread 2

```
void increment() {  
    int temp = X;  
    temp = temp + 1;  
    X = temp;  
}
```

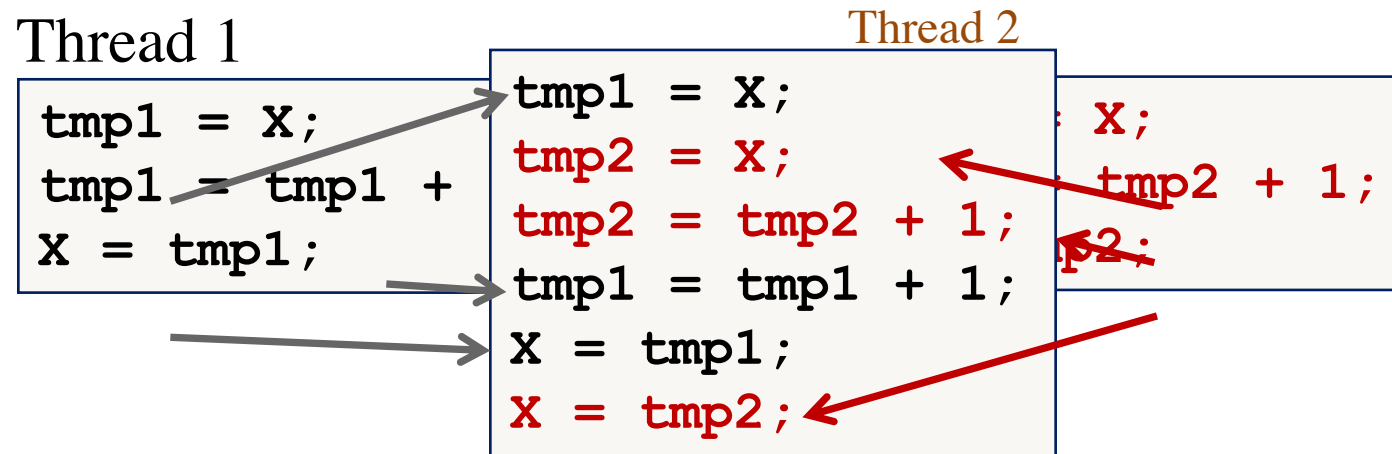
**Answer:**

- A. 0
- B. 1
- C. 2
- D. More than 2



# Schedules and Interleavings

- Model of concurrent execution
- Interleave statements from each thread into a single thread
- If **any** interleaving yields incorrect results, some synchronization is needed



If X==0 initially, X == 1 at the end. WRONG result!



# Locks fix this with Mutual Exclusion

```
void increment() {  
    lock.acquire();  
    int temp = X;  
    temp = temp + 1;  
    X = temp;  
    lock.release();  
}
```

- Mutual exclusion ensures only safe interleavings
  - *When is mutual exclusion too safe?*



# Introducing Locks

- **Locks** – implement mutual exclusion
  - Two methods
    - Lock::Acquire() – wait until lock is free, then grab it
    - Lock::Release() – release the lock, waking up a waiter, if any
- With locks, too much milk problem is very easy!
  - Check and update happen as one unit (exclusive access)

```
Lock.Acquire();  
if (noMilk) {  
    buy milk;  
}  
Lock.Release();
```

```
Lock.Acquire();  
x++;  
Lock.Release();
```

How can we implement locks?



# How do locks work?

- Two key ingredients:
  - A hardware-provided atomic instruction
    - Determines who wins under contention
  - A waiting strategy for the loser(s)



# Atomic instructions

- A “normal” line of code (or CISC instruction) can span multiple memory operations
  - Example: ‘ $a = b + c$ ’ requires 2 loads and a store
  - These loads and stores can interleave with other CPUs’ memory accesses
- An atomic instruction guarantees that the entire operation is not interleaved with any other CPU
  - x86: Certain instructions can have a ‘lock’ prefix
  - Intuition: This CPU ‘locks’ all of memory
  - Expensive! Not ever used automatically by a compiler; must be explicitly used by the programmer





# Atomic instruction examples

- Atomic increment/decrement (  $x++$  or  $x--$  )
  - Used for reference counting
  - Some variants also return the value  $x$  was set to by this instruction (useful if another CPU immediately changes the value)
- Compare and swap
  - if ( $x == y$ )  $x = z$ ;
  - Used for many lock-free data structures



# Atomic instructions + locks

- Most lock implementations have some sort of counter
- Say initialized to 1
- To acquire the lock, use an atomic decrement
  - If you set the value to 0, you win! Go ahead
  - If you get  $< 0$ , you lose. Wait ☹️
  - Atomic decrement ensures that only one CPU will decrement the value to zero
- To release, set the value back to 1

# Waiting strategies

- Spinning: Just poll the atomic counter in a busy loop; when it becomes 1, try the atomic decrement again
- Blocking: Create a kernel wait queue and go to sleep, yielding the CPU to more useful work
  - Winner is responsible to wake up losers (in addition to setting lock variable to 1)
  - Create a kernel wait queue – the same thing used to wait on I/O
    - Reminder: Moving to a wait queue takes you out of the scheduler's run queue



# Which strategy to use?

- Main consideration: Expected time waiting for the lock vs. time to do 2 context switches
  - If the lock will be held a long time (like while waiting for disk I/O), blocking makes sense
  - If the lock is only held momentarily, spinning makes sense
- Other, subtle considerations we will discuss later



# Reminder: Correctness Conditions

- Safety
  - Only one thread in the critical region
- Liveness
  - Some thread that enters the entry section eventually enters the critical region
  - Even if other thread takes forever in non-critical region
- Bounded waiting
  - A thread that enters the entry section enters the critical section within some bounded number of operations.
- Failure atomicity
  - It is OK for a thread to die in the critical region
  - Many techniques do not provide failure atomicity



# Example: Linux spinlock (simplified)

```
1: lock; decb slp->slock    // Locked decrement of lock var
    jns 3f                  // Jump if not set (result is zero) to 3

2: pause                    // Low power instruction, wakes on
                           // coherence event

    cmpb $0,slp->slock      // Read the lock value, compare to zero
    jle 2b                  // If less than or equal (to zero), goto 2
    jmp 1b                  // Else jump to 1 and try again

3:                           // We win the lock
```



## Rough C equivalent

```
while (0 != atomic_dec(&lock->counter)) {  
    do {  
        // Pause the CPU until some coherence  
        // traffic (a prerequisite for the counter  
        // changing) saving power  
  
    } while (lock->counter <= 0);  
}
```

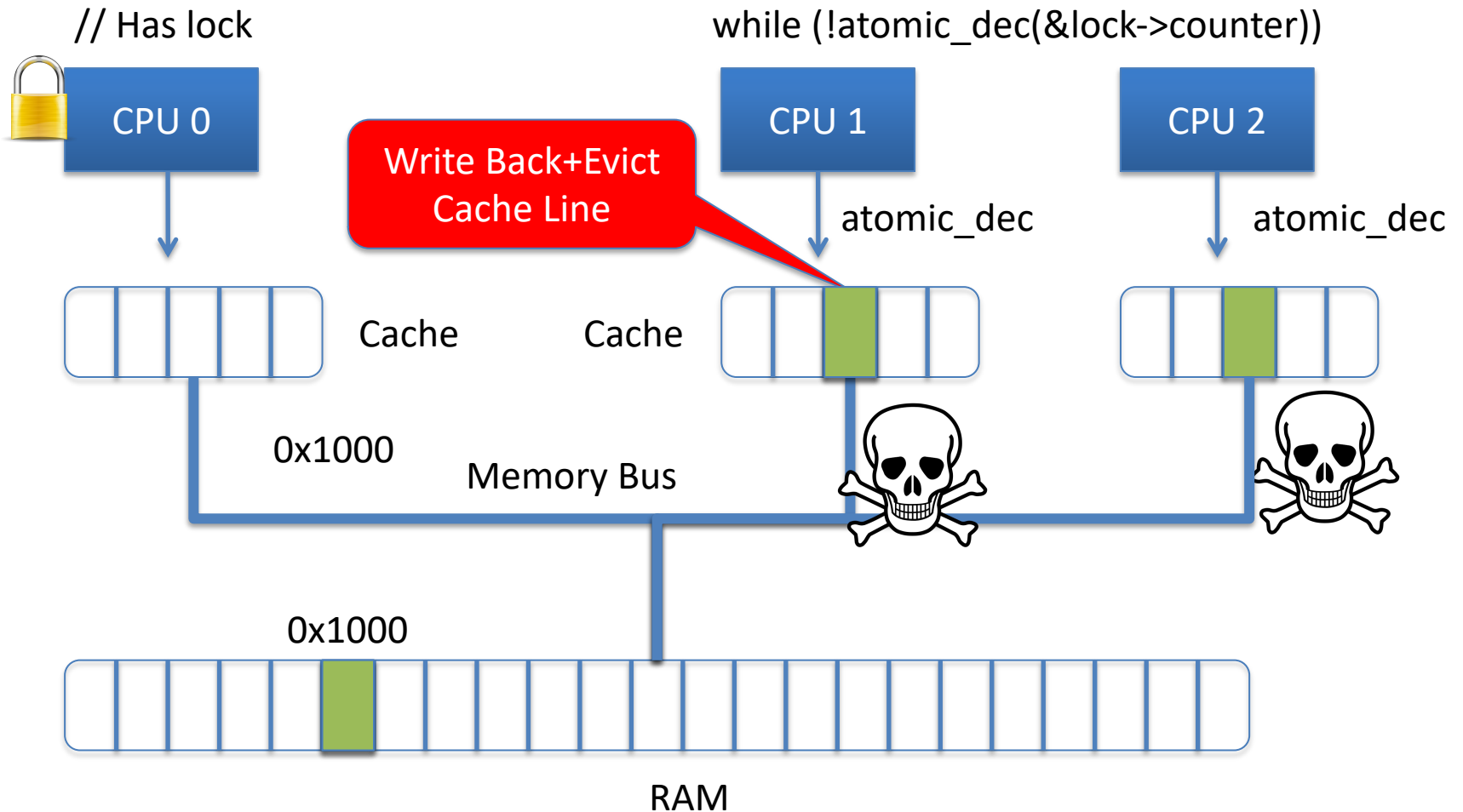


## Why 2 loops?

- Functionally, the outer loop is sufficient
- Problem: Attempts to write this variable invalidate it in all other caches
  - If many CPUs are waiting on this lock, the cache line will bounce between CPUs that are polling its value
    - This is VERY expensive and slows down EVERYTHING on the system
  - The inner loop read-shares this cache line, allowing all polling in parallel
- This pattern called a Test&Test&Set lock (vs. Test&Set)



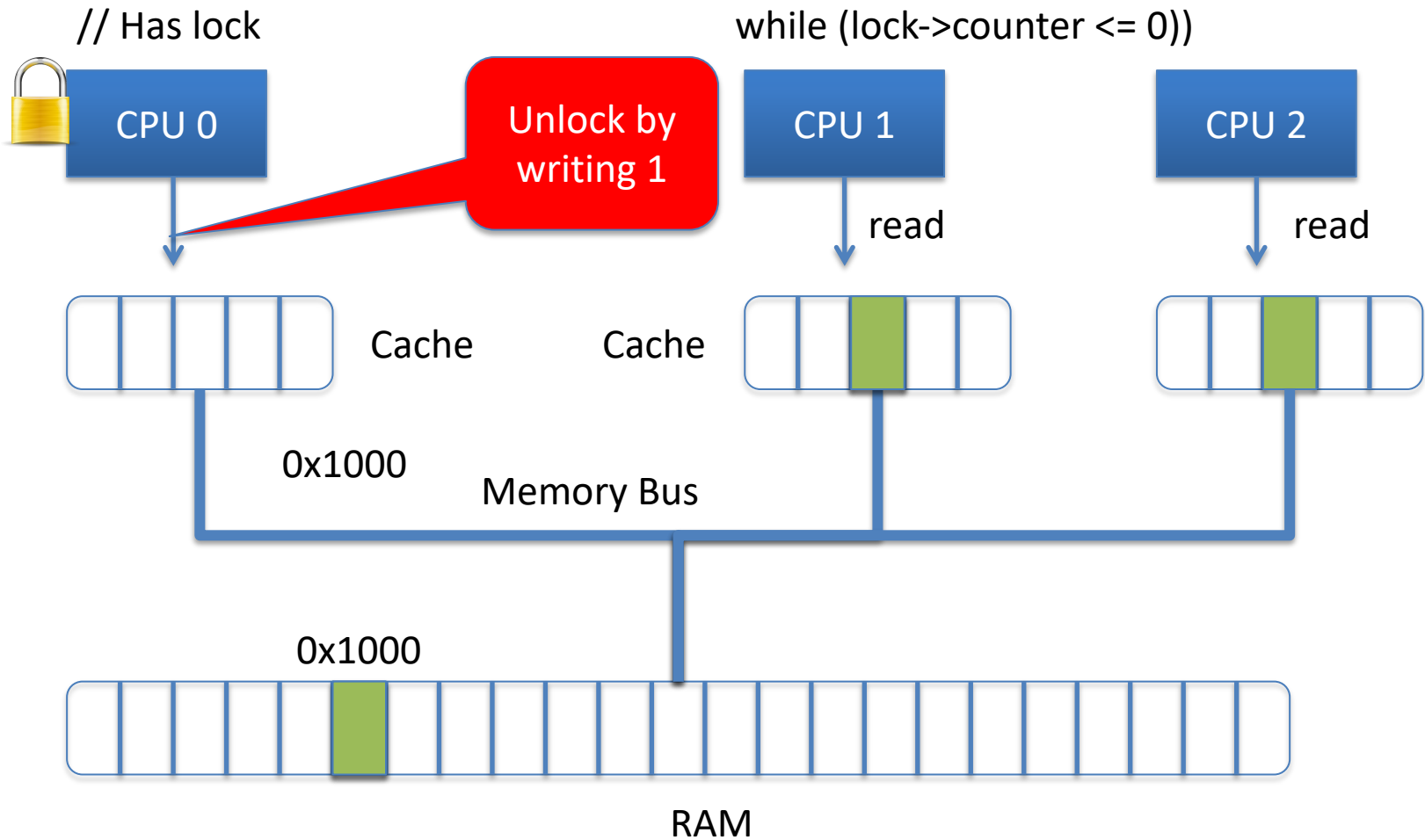
# Test & Set Lock



Cache Line “ping-pongs” back and forth



# Test & Test & Set Lock



Line shared in read mode until unlocked



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# Implementing Blocking Locks

```
Lock::Acquire() {  
    while (test&set(lock) == 1)  
        ; // spin  
}
```

With busy-waiting

```
Lock::Release() {  
    *lock := 0;  
}
```

```
Lock::Acquire() {  
    while (test&set(q_lock) == 1) {  
        Put TCB on wait queue for lock;  
        Lock::Switch(); // dispatch thread  
    }
```

Without busy-waiting, use a queue

```
Lock::Release() {  
    *q_lock = 0;  
    if (wait queue is not empty) {  
        Move 1 (or all?) waiting threads to ready  
        queue;  
    }
```

Must only one thread be awakened? Is this code fair?



# Best Practices for Lock Programming

- When you enter a critical region, check what may have changed while you were spinning
  - Did Jill get milk while I was waiting on the lock?
- Always unlock any locks you acquire



# Implementing Locks: Summary

- Locks are higher-level programming abstraction
  - Mutual exclusion can be implemented using locks
- Lock implementations have 2 key ingredients:
  - Hardware instruction: atomic read-modify-write
  - Blocking mechanism
    - Busy waiting, or
      - Cheap Busy waiting important
    - Block on a scheduler queue in the OS
- Locks are good for mutual exclusion but weak for coordination, e.g., producer/consumer patterns.



# Why locking is also hard (Preview)

- Coarse-grain locks
  - Simple to develop
  - Easy to avoid deadlock
  - Few data races
  - Limited concurrency
- Fine-grain locks
  - Greater concurrency
  - Greater code complexity
  - Potential deadlocks
    - Not composable
  - Potential data races
    - Which lock to lock?

```
// WITH FINE-GRAIN LOCKS
void move(T s, T d, Obj key){
    LOCK(s);
    LOCK(d);
    tmp = s.remove(key);
    d.insert(key, tmp);
    UNLOCK(d);
    UNLOCK(s);
}
```

Thread 0	Thread 1
move(a, b, key1);	
	move(b, a, key2);

DEADLOCK!