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;
}
```

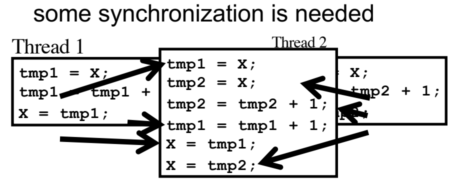
Thread 2

```
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?

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How do locks work?

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

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Atomic instructions

- A "normal" instruction can span many CPU cycles
  - 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

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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

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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

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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

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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

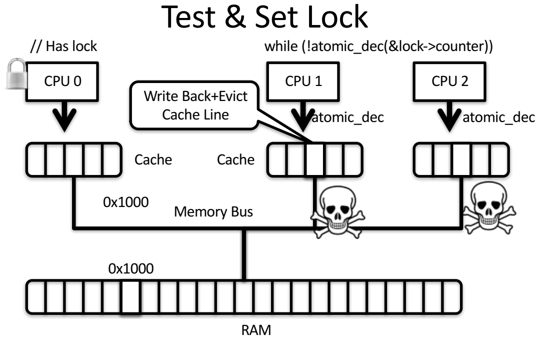
```
while (0 != atomic_dec(&lock->counter)) {
        do {
                // Pause the CPU until some coherence
                // traffic (a prerequisite for the counter
                //  changing) saving power

        } while (lock->counter <= 0);
}
```


Why 2 loops?

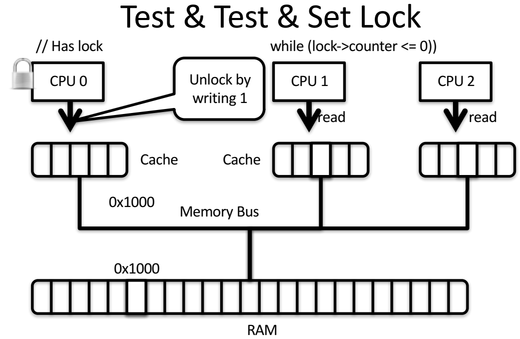
- Functionally, the outer loop is sufficient
- Problem: Attempts to write this variable invalidate it in all other caches
  - If many CPUs are waiting on this lock, the cache line will bounce between CPUs that are polling its value
    - This is VERY expensive and slows down EVERYTHING on the system
  - 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

With busy-waiting

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

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

Without busy-waiting, use a queue

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

```
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 awaked? Is this code fair?

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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

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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.

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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

```
move(a, b, key1);
```

Thread 1

```
move(b, a, key2);
```

DEADLOCK!