Mutual Exclusion: Primitives and Implementation Considerations

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
 - $\,\succ\,$ 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

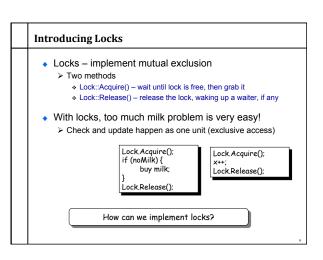
Concurrency Quiz If two threads execute this program concurrently, how many different final values of X are there? Initially, X == 0. Thread 1 Thread 2 void increment() { void increment() { int temp = X; int temp = X; temp = temp + 1;temp = temp + 1;X = temp;X = temp;Answer: A. 0 B. 1 C. 2 D. More than 2

Schedules/Interleavings Model of concurrent execution Interleave statements from each thread into a single If any interleaving yields incorrect results, some synchronization is needed Thread 1 tmp1 = X;tmp1 = X; tmp1 = tmp1 + х; tmp2 = X;tmp2 + 1: tmp2 = tmp2 + 1;X = tmp1;tmp1 = tmp1 + 1; \rightarrow X = tmp1; X = tmp2;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?
```



How to think about synchronization code

- Every thread has the same pattern
 - > Entry section: code to attempt entry to critical section
 - > Critical section: code that requires isolation (e.g., with mutual
 - > Exit section: cleanup code after execution of critical region
- > Non-critical section: everything else
- There can be multiple critical regions in a program
 - Only critical regions that access the same resource (e.g., data structure) need to synchronize with each other

```
while(1) {
  Entry section
   Critical section
  Exit section
  Non-critical section
```

The correctness conditions

- Safety
 - > Only one thread in the critical region
- Liveness
 - > Some thread that enters the entry section eventually enters the
- > 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

```
while(1)
  Entry section
  Critical section
  Exit section
  Non-critical section
```

Read-Modify-Write (RMW)

- Implement locks using read-modify-write instructions
 - > As an atomic and isolated action
 - read a memory location into a register, AND
 - write a new value to the location
 - Implementing RMW is tricky in multi-processors
 - . Requires cache coherence hardware. Caches snoop the memory bus.
- Examples:
 - Test&set instructions (most architectures)
 Reads a value from memory
 Write "1" back to memory location

 - Compare & swap (a.k.a. cmpxchg on x86)
 - Test the value against some constant
 If the test returns true, set value in memory to different value
 - Report the result of the test in a flag
 - if [addr] == r1 then [addr] = r2;
 - > Double Compare & Swap (68000)
 - Variant: if [addr1] == r1 then [addr2] = r2 Exchange, locked increment, locked decrement (x86)
 - Load linked/store conditional (PowerPC,Alpha, MIPS)

Implementing Locks with Test&set int lock_value = 0; int* lock = &lock value If lock is free (lock_value == 0), then test&set reads 0 and sets value to 1 → lock is set to busy and Acquire Lock::Acquire() { completes while (test&set(lock) == 1) ; //spin If lock is busy, the test&set reads 1 and sets value to 1 → no change in lock's status and Acquire loops Does this lock have bounded Lock::Release() { *lock = 0; waiting?

Locks and Busy Waiting

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

- Busy-waiting:
- Threads consume CPU cycles while waiting
 - > Low latency to acquire
- Limitations
 - > Occupies a CPU core
 - > What happens if threads have different priorities?
 - . Busy-waiting thread remains runnable
 - If the thread waiting for a lock has higher priority than the thread occupying the lock, then?

 Ugh, I just wanted to lock a data structure, but now I' m
 - involved with the scheduler!
 - > What if programmer forgets to unlock?

Remember to always release locks

Java provides a convenient mechanism.

```
import
  java.util.concurrent.locks.ReentrantLock;
public static final aLock = new
 ReentrantLock():
aLock.lock();
```

```
try {
} finally {
   aLock.unlock();
return 0;
```

```
Remember to always release locks

Java also has implicit locks:

synchronized void method(void) {

XXX

}

is short for

void method(void) {

synchronized(this) {

XXX }}

is short for

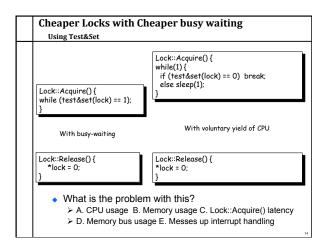
void method(void) {

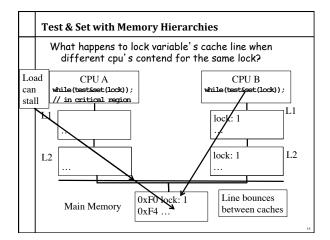
this.l.lock();

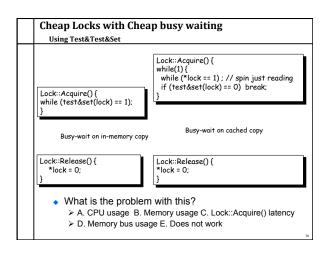
try {

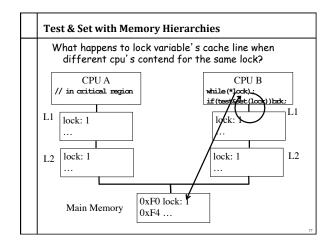
XXX } finally {

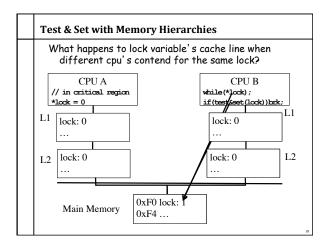
this.l.unlock();}
```











Implementing Locks: Summary

- Locks are higher-level programming abstraction
 Mutual exclusion can be implemented using locks
- Lock implementation generally requires some level of hardware support
 - > Details of hardware support affects efficiency of locking
- Locks can busy-wait, and busy-waiting cheaply is important
 - > Soon come primitives that block rather than busy-wait

Best Practices for Lock Programming (So Far...)

- 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 without Busy Waiting (blocking)
Using Test&Set

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

With busy-waiting

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

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

Lock::Switch() {
    q_lock = 0;
    pid = schedule();
    if(waited_on_lock(pid))
    while(test&set(q_lock)==1):
    dispatch pid

Must only 1 thread be awakened?
```

Implementing Locks: Summary

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

```
Why Locks are Hard (Preview)

    Coarse-grain locks

                                • Fine-grain locks
     > Simple to develop
                                   > Greater concurrency
     Easy to avoid deadlock
                                    > Greater code complexity
     > Few data races
                                   > Potential deadlocks
     > Limited concurrency
                                       * Not composable
                                    > Potential data races
                                       . Which lock to lock?
// WITH FINE-GRAIN LOCKS
void move(T s, T d, Obj key){
 LOCK(s);
                                    Thread 0
                                                      Thread 1
                                move(a, b, key1);
 LOCK(d);
 tmp = s.remove(key);
                                           move(b, a, key2);
 d.insert(key, tmp);
                                      DEADLOCK!
 UNLOCK(s);
```