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
  - 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;
}
```

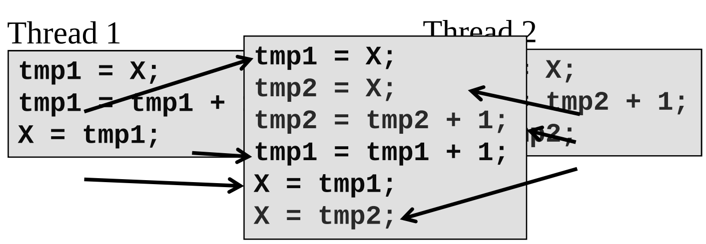
Thread 2

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

Answer:
A. 0
B. 1
C. 2
D. More than 2

Schedules/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 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 exclusion)
  - 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 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

```
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
    1. read a memory location into a register, **AND**
    2. 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 (68000)
    - 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;
  - 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;
```

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

- If lock is free (lock_value == 0), then test&set reads 0 and sets value to 1 ➔ lock is set to busy and Acquire completes
- If lock is busy, the test&set reads 1 and sets value to 1 ➔ no change in lock's status and Acquire loops

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

- Does this lock have bounded 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 convenient mechanism.

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

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

Cheaper Locks with Cheaper busy waiting

Using Test&Set

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

With busy-waiting

```
Lock::Acquire() {
while(1) {
  if (test&set(lock) == 0)  break;
  else sleep(1);
}
```

With voluntary yield of CPU

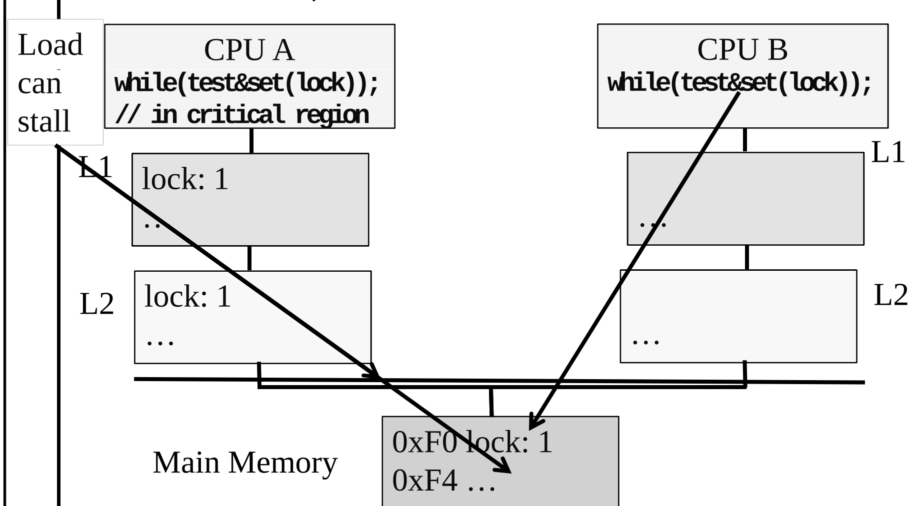
```
Lock::Release() {
    *lock = 0;
}
```

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

- What is the problem with this?
  - A. CPU usage B. Memory usage C. Lock::Acquire() latency
  - D. Memory bus usage E. Messes up interrupt handling

Test & Set with Memory Hierarchies

What happens to lock variable's cache line when different cpu's contend for the same lock?



Cheap Locks with Cheap busy waiting

Using Test&Test&Set

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

Busy-wait on in-memory copy

```
Lock::Acquire() {
while(1) {
  while (*lock == 1) ; // spin just reading
  if (test&set(lock) == 0)  break;
}
```

Busy-wait on cached copy

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

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

- What is the problem with this?
  - A. CPU usage B. Memory usage C. Lock::Acquire() latency
  - D. Memory bus usage E. Does not work

Test & Set with Memory Hierarchies

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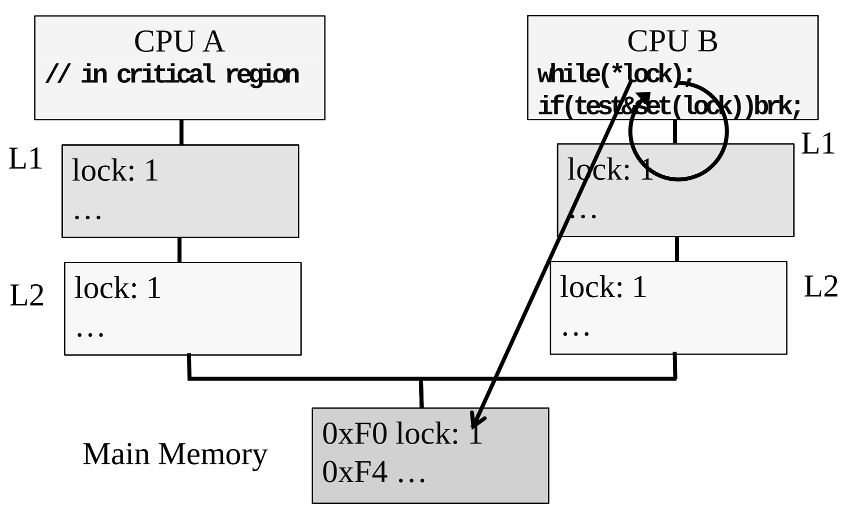
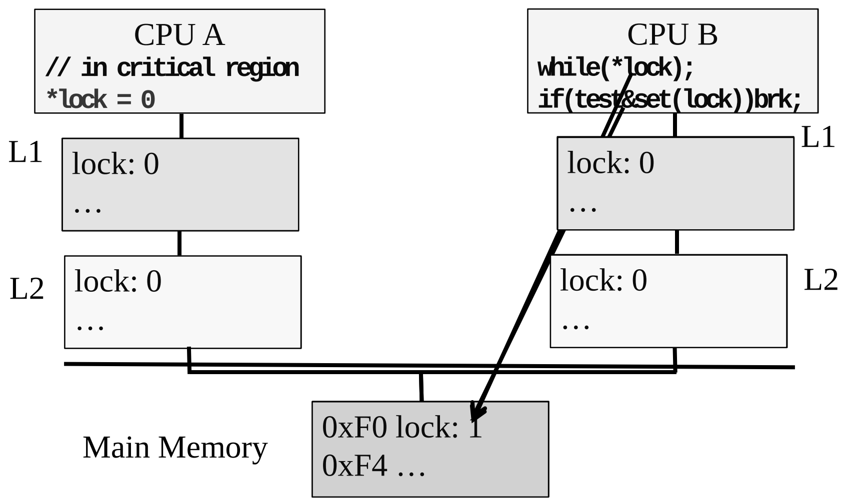


Test & Set with Memory Hierarchies

What happens to lock variable's cache line when different cpu's contend for the same lock?



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

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

Without busy-waiting, use a queue

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

```
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 implementation generally requires some level of hardware support
  - Atomic read-modify-write instructions
    - Uni- and multi-processor architectures
- Locks are good for mutual exclusion but weak for coordination, e.g., producer/consumer patterns.

Why Locks are Hard

- 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!