CS162
Operating Systems and Systems Programming
Lecture 8

Locks, Semaphores, Monitors

September 20, 2017
Prof. Ion Stoica
http://cs162.eecs.Berkeley.edu

Review: Too Much Milk Solution #3

- Here is a possible two-note solution:

Thread A

```
leave note A;
while (note B) {\\X
    do nothing;
}
if (noMilk) {
    buy milk;
}
remove note A;
```

Thread B

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

- Does this work? Yes. Both can guarantee that:
  - It is safe to buy, or
  - Other will buy, ok to quit
- At X:
  - If no note B, safe for A to buy,
  - Otherwise wait to find out what will happen
- At Y:
  - If no note A, safe for B to buy
  - Otherwise, A is either buying or waiting for B to quit

Case 1

- "leave note A" happens before "if (noNote A)"

```
leave note A;
while (note B) {\\X
    do nothing;
};

if (noMilk) {
    buy milk;}
}
remove note A;
```

happened before

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```


Case 1

- "leave note A" happens before "if (noNote A)"

```
leave note A;
while (note B) {\\X
    do nothing;
};

if (noMilk) {
    buy milk;}
}
remove note A;
```

happened before

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

Case 1

- "`leave note A`" happens before "`if (noNote A)`"

```
leave note A;
while (note B) {\\X
    do nothing;
};
```

happened before

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

Wait for note B to be remove

```
if (noMilk) {
    buy milk;}
}
remove note A;
```


Case 2

- "`if (noNote A)`" happens before "`leave note A`"

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

happened before

```
leave note A;
while (note B) {\\X
    do nothing;
};
```

```
if (noMilk) {
    buy milk;}
}
remove note A;
```


Case 2

- "`if (noNote A)`" happens before "`leave note A`"

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

happened before

```
leave note A;
while (note B) {\\X
    do nothing;
};
```

```
if (noMilk) {
    buy milk;}
}
remove note A;
```


Case 2

- "`if (noNote A)`" happens before "`leave note A`"

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

happened before

```
leave note A;
while (note B) {\\X
    do nothing;
};
```

Wait for note B to be remove

```
if (noMilk) {
    buy milk;}
}
remove note A;
```

Review: Solution #3 discussion

- Our solution protects a single "Critical-Section" piece of code for each thread:

```
if (noMilk) {
   buy milk;
}
```

- Solution #3 works, but it's really unsatisfactory
  - Really complex – even for this simple an example
    - » Hard to convince yourself that this really works
  - A's code is different from B's – what if lots of threads?
    - » Code would have to be slightly different for each thread
  - While A is waiting, it is consuming CPU time
    - » This is called "busy-waiting"
- There's a better way
  - Have hardware provide higher-level primitives than atomic load & store
  - Build even higher-level programming abstractions on this hardware support

Too Much Milk: Solution #4

- Suppose we have some sort of implementation of a lock
  - `lock.Acquire()` – wait until lock is free, then grab
  - `lock.Release()` – Unlock, waking up anyone waiting
  - These must be atomic operations – if two threads are waiting for the lock and both see it's free, only one succeeds to grab the lock
- Then, our milk problem is easy:

```
milklock.Acquire();
if (nomilk)
   buy milk;
milklock.Release();
```

- Once again, section of code between `Acquire()` and `Release()` called a "Critical Section"
- Of course, you can make this even simpler: suppose you are out of ice cream instead of milk
  - Skip the test since you always need more ice cream ;-)

Where are we going with synchronization?

Programs	Shared Programs
Higher-level API	Locks Semaphores Monitors Send/Receive
Hardware	Load/Store Disable Ints Test&Set Compare&Swap

- We are going to implement various higher-level synchronization primitives using atomic operations
  - Everything is pretty painful if only atomic primitives are load and store
  - Need to provide primitives useful at user-level

Goals for Today

- Explore several implementations of locks
- Continue with Synchronization Abstractions
  - Semaphores, Monitors, and Condition variables
- Very Quick Introduction to scheduling

How to Implement Locks?

- Lock: prevents someone from doing something
  - Lock before entering critical section and before accessing shared data
  - Unlock when leaving, after accessing shared data
  - Wait if locked
    - » Important idea: all synchronization involves waiting
    - » Should *sleep* if waiting for a long time
- Atomic Load/Store: get solution like Milk #3
  - Pretty complex and error prone
- Hardware Lock instruction
  - Is this a good idea?
  - What about putting a task to sleep?
    - » How do you handle the interface between the hardware and scheduler?
  - Complexity?
    - » Done in the Intel 432 – each feature makes HW more complex and slow

Naïve use of Interrupt Enable/Disable

How can we build multi-instruction atomic operations?

- Recall: dispatcher gets control in two ways.
  - Internal: Thread does something to relinquish the CPU
  - External: Interrupts cause dispatcher to take CPU
- On a uniprocessor, can avoid context-switching by:
  - Avoiding internal events (although virtual memory tricky)
  - Preventing external events by disabling interrupts

Consequently, naïve Implementation of locks:

```
LockAcquire { disable Ints; }
LockRelease { enable Ints; }
```


Naïve use of Interrupt Enable/Disable: Problems

Can't let user do this! Consider following:

```
LockAcquire();
While(TRUE) {;}
```

Real-Time system—no guarantees on timing!

- Critical Sections might be arbitrarily long

What happens with I/O or other important events?

- "Reactor about to meltdown. Help?"

Better Implementation of Locks by Disabling Interrupts

Key idea: maintain a lock variable and impose mutual exclusion only during operations on that variable

```
int value = FREE;
```

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
      // Enable interrupts?
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

```
Release() {
   disable interrupts;
   if (anyone on wait queue) {
      take thread off wait queue
      Place on ready queue;
   } else {
      value = FREE;
   }
   enable interrupts;
}
```

New Lock Implementation: Discussion

- Why do we need to disable interrupts at all?
  - Avoid interruption between checking and setting lock value
  - Otherwise two threads could think that they both have lock

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
      // Enable interrupts?
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

Critical Section

- Note: unlike previous solution, the critical section (inside `Acquire()`) is very short
  - User of lock can take as long as they like in their own critical section: doesn't impact global machine behavior
  - Critical interrupts taken in time!

Interrupt Re-enable in Going to Sleep

- What about re-enabling ints when going to sleep?

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

Enable Position
Enable Position
Enable Position

How to Re-enable After Sleep()?

- In scheduler, since interrupts are disabled when you call sleep:
  - Responsibility of the next thread to re-enable ints
  - When the sleeping thread wakes up, returns to acquire and re-enables interrupts

```
Thread A                         Thread B
   .
   .
disable ints
   sleep
           context switch →  sleep return
                             enable ints
                                 .
                                 .
                                 .
                             disable int
                                sleep
sleep return  ← context switch
enable ints
   .
   .
```


Atomic Read-Modify-Write Instructions

- Problems with previous solution:
  - Can't give lock implementation to users
  - Doesn't work well on multiprocessor
    - » Disabling interrupts on all processors requires messages and would be very time consuming
- Alternative: atomic instruction sequences
  - These instructions read a value and write a new value atomically
  - Hardware is responsible for implementing this correctly
    - » on both uniprocessors (not too hard)
    - » and multiprocessors (requires help from cache coherence protocol)
  - Unlike disabling interrupts, can be used on both uniprocessors and multiprocessors

Examples of Read-Modify-Write

```
• test&set (&address) {       /* most architectures */
      result = M[address];    /* return result from "address" and
      M[address] = 1;            set value at "address" to 1 */
      return result;
  }

• swap (&address, register) { /* x86 */
      temp = M[address];      /* swap register's value to
      M[address] = register;     value at "address" */
      register = temp;
  }

• compare&swap (&address, reg1, reg2) { /* 68000 */
      if (reg1 == M[address]) {
          M[address] = reg2;
          return success;
      } else {
          return failure;
      }
  }
```


Implementing Locks with test&set

- Another flawed, but simple solution:

```
int value = 0; // Free
Acquire() {
   while (test&set(value)); // while busy
}
Release() {
   value = 0;
}
```

- Simple explanation:
  - If lock is free, test&set reads 0 and sets value=1, so lock is now busy It returns 0 so while exits
  - If lock is busy, test&set reads 1 and sets value=1 (no change) It returns 1, so while loop continues
  - When we set value = 0, someone else can get lock
- Busy-Waiting: thread consumes cycles while waiting

Problem: Busy-Waiting for Lock

- Positives for this solution
  - Machine can receive interrupts
  - User code can use this lock
  - Works on a multiprocessor
- Negatives
  - This is very inefficient as thread will consume cycles waiting
  - Waiting thread may take cycles away from thread holding lock (no one wins!)
  - Priority Inversion: If busy-waiting thread has higher priority than thread holding lock ⇒ no progress!
- Priority Inversion problem with original Martian rover
- For semaphores and monitors, waiting thread may wait for an arbitrary long time!
  - Thus even if busy-waiting was OK for locks, definitely not ok for other primitives
  - Homework/exam solutions should avoid busy-waiting!

Better Locks using test&set

- Can we build test&set locks without busy-waiting?
  - Can't entirely, but can minimize!
  - Idea: only busy-wait to atomically check lock value

```
int guard = 0;
int value = FREE;
```

```
Acquire() {
   // Short busy-wait time
   while (test&set(guard));
   if (value == BUSY) {
      put thread on wait queue;
      go to sleep() & guard = 0;
   } else {
      value = BUSY;
      guard = 0;
   }
}

Release() {
   // Short busy-wait time
   while (test&set(guard));
   if anyone on wait queue {
      take thread off wait queue
      Place on ready queue;
   } else {
      value = FREE;
   }
   guard = 0;
```

- Note: sleep has to be sure to reset the guard variable
  - Why can't we do it just before or just after the sleep?

Locks using Interrupts vs. test&set

Compare to "disable interrupt" solution

```
int value = FREE;

Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
      // Enable interrupts?
   } else {
      value = BUSY;
   }
   enable interrupts;
}

Release() {
   disable interrupts;
   if (anyone on wait queue) {
      take thread off wait queue
      Place on ready queue;
   } else {
      value = FREE;
   }
   enable interrupts;
}
```

Basically replace

- `disable interrupts` → `while (test&set(guard));`
- `enable interrupts` → `guard = 0;`

Recap: Locks using interrupts

```
lock.Acquire();
…
critical section;
…
lock.Release();
```

```
Acquire() {
   disable interrupts;
}

Release() {
   enable interrupts;
}
```

If one thread in critical section, no other activity (including OS) can run!

```
int value = 0;
Acquire() {
   // Short busy-wait time
   disable interrupts;
   if (value == 1) {
      put thread on wait-queue;
      go to sleep() //??
   } else {
      value = 1;
      enable interrupts;
   }
}

Release() {
   // Short busy-wait time
   disable interrupts;
   if anyone on wait queue {
      take thread off wait-queue
      Place on ready queue;
   } else {
      value = 0;
   }
   enable interrupts;
}
```


Recap: Locks using test & wait

```
lock.Acquire();
…
critical section;
…
lock.Release();
```

```
int value = 0;
Acquire() {
   while(test&set(value));
}

Release() {
   value = 0;
}
```

Threads waiting to enter critical section busy-wait

```
int guard = 0;
int value = 0;
Acquire() {
   // Short busy-wait time
   while(test&set(guard));
   if (value == 1) {
      put thread on wait-queue;
      go to sleep()& guard = 0;
   } else {
      value = 1;
      guard = 0;
   }
}

Release() {
   // Short busy-wait time
   while (test&set(guard));
   if anyone on wait queue {
      take thread off wait-queue
      Place on ready queue;
   } else {
      value = 0;
   }
   guard = 0;
}
```


Administrivia

- Midterm Thursday 9/28 6:30-8PM
- Project 1 Design Document due today
- Project 1 Design reviews upcoming
  - High-level discussion of your approach
    - » What will you modify?
    - » What algorithm will you use?
    - » How will things be linked together, etc.
    - » Do not need final design (complete with all semicolons!)
  - You *will* be asked about testing
    - » Understand testing framework
    - » Are there things you are doing that are not tested by tests we give you?
- *Do your own work!*
  - Please do not try to find solutions from previous terms
  - We will be on the look out for anyone doing this…today

BREAK

Higher-level Primitives than Locks

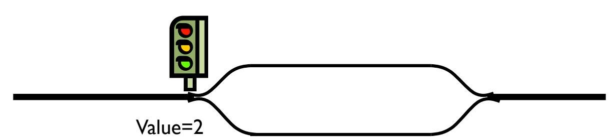
- Goal of last couple of lectures:
  - What is right abstraction for synchronizing threads that share memory?
  - Want as high a level primitive as possible
- Good primitives and practices important!
  - Since execution is not entirely sequential, really hard to find bugs, since they happen rarely
  - UNIX is pretty stable now, but up until about mid-80s (10 years after started), systems running UNIX would crash every week or so – concurrency bugs
- Synchronization is a way of coordinating multiple concurrent activities that are using shared state
  - This lecture and the next presents a some ways of structuring sharing

Semaphores

- Semaphores are a kind of generalized lock
  - First defined by Dijkstra in late 60s
  - Main synchronization primitive used in original UNIX
- Definition: a Semaphore has a non-negative integer value and supports the following two operations:
  - P(): an atomic operation that waits for semaphore to become positive, then decrements it by 1
    - » Think of this as the wait() operation
  - V(): an atomic operation that increments the semaphore by 1, waking up a waiting P, if any
    - » This of this as the signal() operation
  - Note that P() stands for "*proberen*" (to test) and V() stands for "*verhogen*" (to increment) in Dutch

Semaphores Like Integers Except

- Semaphores are like integers, except
  - No negative values
  - Only operations allowed are P and V – can't read or write value, except to set it initially
  - Operations must be atomic
    - » Two P's together can't decrement value below zero
    - » Similarly, thread going to sleep in P won't miss wakeup from V – even if they both happen at same time
- Semaphore from railway analogy
  - Here is a semaphore initialized to 2 for resource control:



Two Uses of Semaphores

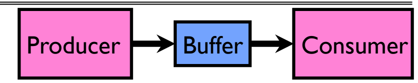
Mutual Exclusion (initial value = 1)
- Also called "Binary Semaphore".
- Can be used for mutual exclusion:

```
semaphore.P();
// Critical section goes here
semaphore.V();
```

Scheduling Constraints (initial value = 0)
- Allow thread 1 to wait for a signal from thread 2, i.e., thread 2 schedules thread 1 when a given event occurs
- Example: suppose you had to implement ThreadJoin which must wait for thread to terminate:

```
Initial value of semaphore = 0
ThreadJoin {
    semaphore.P();
}
ThreadFinish {
    semaphore.V();
}
```


Producer-Consumer with a Bounded Buffer



- Problem Definition
  - Producer puts things into a shared buffer
  - Consumer takes them out
  - Need synchronization to coordinate producer/consumer
- Don't want producer and consumer to have to work in lockstep, so put a fixed-size buffer between them
  - Need to synchronize access to this buffer
  - Producer needs to wait if buffer is full
  - Consumer needs to wait if buffer is empty

- Example 1: GCC compiler
  - `cpp | cc1 | cc2 | as | ld`
- Example 2: Coke machine
  - Producer can put limited number of Cokes in machine
  - Consumer can't take Cokes out if machine is empty

Correctness constraints for solution

- Correctness Constraints:
  - Consumer must wait for producer to fill buffers, if none full (scheduling constraint)
  - Producer must wait for consumer to empty buffers, if all full (scheduling constraint)
  - Only one thread can manipulate buffer queue at a time (mutual exclusion)
- Remember why we need mutual exclusion
  - Because computers are stupid
  - Imagine if in real life: the delivery person is filling the machine and somebody comes up and tries to stick their money into the machine
- General rule of thumb:
  Use a separate semaphore for each constraint
  - `Semaphore fullBuffers; // consumer's constraint`
  - `Semaphore emptyBuffers;// producer's constraint`
  - `Semaphore mutex;       // mutual exclusion`

Full Solution to Bounded Buffer

```
Semaphore fullSlots = 0;  // Initially, no coke
Semaphore emptySlots = bufSize;
                          // Initially, num empty slots
Semaphore mutex = 1;      // No one using machine

Producer(item) {
    emptySlots.P();           // Wait until space
    mutex.P();                // Wait until machine free
    Enqueue(item);
    mutex.V();
    fullSlots.V();            // Tell consumers there is
                              // more coke
}
Consumer() {
    fullSlots.P();            // Check if there's a coke
    mutex.P();                // Wait until machine free
    item = Dequeue();
    mutex.V();
    emptySlots.V();           // tell producer need more
    return item;
}
```

Discussion about Solution

Why asymmetry?

- Producer does: `emptySlots.P(), fullSlots.V()`
- Consumer does: `fullSlots.P(), emptySlots.V()`

Decrease # of empty slots (emptySlots.P)
Increase # of occupied slots (fullSlots.V)
Decrease # of occupied slots (fullSlots.P)
Increase # of empty slots (emptySlots.V)

Discussion about Solution (cont'd)

Is order of P's important?

Is order of V's important?

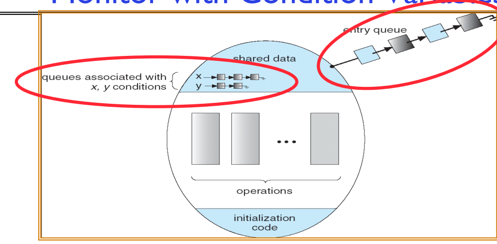
What if we have 2 producers or 2 consumers?

```
Producer(item) {
    mutex.P();
    emptySlots.P();
    Enqueue(item);
    mutex.V();
    fullSlots.V();
}
Consumer() {
    fullSlots.P();
    mutex.P();
    item = Dequeue();
    mutex.V();
    emptySlots.V();
    return item;
}
```


Motivation for Monitors and Condition Variables

- Semaphores are a huge step up; just think of trying to do the bounded buffer with only loads and stores
  - Problem is that semaphores are dual purpose:
    - » They are used for both mutex and scheduling constraints
    - » Example: the fact that flipping of P's in bounded buffer gives deadlock is not immediately obvious. How do you prove correctness to someone?
- Cleaner idea: Use *locks* for mutual exclusion and *condition variables* for scheduling constraints
- Definition: Monitor: a lock and zero or more condition variables for managing concurrent access to shared data
  - Some languages like Java provide this natively
  - Most others use actual locks and condition variables

Monitor with Condition Variables



- Lock: the lock provides mutual exclusion to shared data
  - Always acquire before accessing shared data structure
  - Always release after finishing with shared data
  - Lock initially free
- Condition Variable: a queue of threads waiting for something *inside* a critical section
  - Key idea: make it possible to go to sleep inside critical section by atomically releasing lock at time we go to sleep
  - Contrast to semaphores: Can't wait inside critical section

Simple Monitor Example (version 1)

- Here is an (infinite) synchronized queue

```
Lock lock;
Queue queue;

AddToQueue(item) {
   lock.Acquire();          // Lock shared data
   queue.enqueue(item);     // Add item
   lock.Release();          // Release Lock
}

RemoveFromQueue() {
   lock.Acquire();          // Lock shared data
   item = queue.dequeue();// Get next item or null
   lock.Release();          // Release Lock
   return(item);            // Might return null
}
```

- Not very interesting use of "Monitor"
  - It only uses a lock with no condition variables
  - Cannot put consumer to sleep if no work!

Condition Variables

- How do we change the RemoveFromQueue() routine to wait until something is on the queue?
  - Could do this by keeping a count of the number of things on the queue (with semaphores), but error prone
- Condition Variable: a queue of threads waiting for something *inside* a critical section
  - Key idea: allow sleeping inside critical section by atomically releasing lock at time we go to sleep
  - Contrast to semaphores: Can't wait inside critical section
- Operations:
  - `Wait(&lock)`: Atomically release lock and go to sleep. Re-acquire lock later, before returning.
  - `Signal()`: Wake up one waiter, if any
  - `Broadcast()`: Wake up all waiters
- Rule: Must hold lock when doing condition variable ops!
  - In Birrell paper, he says can perform signal() outside of lock – IGNORE HIM (this is only an optimization)

Complete Monitor Example (with condition variable)

- Here is an (infinite) synchronized queue

```
Lock lock;
Condition dataready;
Queue queue;

AddToQueue(item) {
   lock.Acquire();             // Get Lock
   queue.enqueue(item);        // Add item
   dataready.signal();         // Signal any waiters
   lock.Release();             // Release Lock
}

RemoveFromQueue() {
   lock.Acquire();             // Get Lock
   while (queue.isEmpty()) {
      dataready.wait(&lock); // If nothing, sleep
   }
   item = queue.dequeue();     // Get next item
   lock.Release();             // Release Lock
   return(item);
}
```


Summary (1/2)

- Important concept: Atomic Operations
  - An operation that runs to completion or not at all
  - These are the primitives on which to construct various synchronization primitives
- Talked about hardware atomicity primitives:
  - Disabling of Interrupts, test&set, swap, compare&swap, conditional
- Showed several constructions of Locks
  - Must be very careful not to waste/tie up machine resources
    - » Shouldn't disable interrupts for long
    - » Shouldn't spin wait for long
  - Key idea: Separate lock variable, use hardware mechanisms to protect modifications of that variable

Summary (2/2)

- Semaphores: Like integers with restricted interface
  - Two operations:
    - » `P()`: Wait if zero; decrement when becomes non-zero
    - » `V()`: Increment and wake a sleeping task (if exists)
    - » Can initialize value to any non-negative value
  - Use separate semaphore for each constraint
- Monitors: A lock plus one or more condition variables
  - Always acquire lock before accessing shared data
  - Use condition variables to wait inside critical section
    - » Three Operations: `Wait()`, `Signal()`, and `Broadcast()`