CS162
Operating Systems and Systems Programming
Lecture 4

Synchronization, Atomic operations, Locks, Semaphores

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Anthony D. Joseph and Ion Stoica
http://inst.eecs.berkeley.edu/~cs162

Review: Event Programming – Analogy

- Once upon a time (before cell-phones)

- Ann calls Bank of America to verify her account…
- … she is put on hold…
- … Mary, her roommate, waits for an important phone call

- Is there a better solution?
- Yes! Ann can ask the clerk to call her back ;-)

- Event programming:
  - Non-blocking I/O call: returns immediately after I/O call
  - Program periodically checks or interrupted when I/O completes

Review: Another Concurrent Program Example

- Two threads, A and B, compete with each other
  - One tries to increment a shared counter
  - The other tries to decrement the counter

Thread A	Thread B

i = 0;
while (i < 10)
  i = i + 1;
printf("A wins!");
	i = 0;
	while (i > -10)
	  i = i – 1;
	printf("B wins!");

- Assume that memory loads and stores are atomic, but incrementing and decrementing are *not* atomic
- Who wins?
- Is it guaranteed that someone wins? Why or why not?
- What it both threads have their own CPU running at same speed? Is it guaranteed that it goes on forever?

Goals for Today

- Synchronization
- Hardware Support for Synchronization
- Higher-level Synchronization Abstractions
  - Semaphores

Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne. Many slides generated by Kubiatowicz.

Motivation: “Too much milk”

- Great thing about OS’s – analogy between problems in OS and problems in real life
  - Help you understand real life problems better
  - But, computers are much stupider than people
- Example: People need to coordinate:

Time	Person A	Person B
3:00	Look in Fridge. Out of milk	
3:05	Leave for store	
3:10	Arrive at store	Look in Fridge. Out of milk
3:15	Buy milk	Leave for store
3:20	Arrive home, put milk away	Arrive at store
3:25		Buy milk
3:30		Arrive home, put milk away

Definitions

- Synchronization: using atomic operations to ensure cooperation between threads
  - For now, only loads and stores are atomic
  - We’ll show its hard to build anything useful with only reads and writes
- Mutual Exclusion: ensuring that only one thread does a particular thing at a time
  - One thread *excludes* the other while doing its task
- Critical Section: piece of code that only one thread can execute at once
  - Critical section is the result of mutual exclusion
  - Critical section and mutual exclusion are two ways of describing the same thing

More Definitions

- 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
- For example: fix the milk problem by putting a key on the refrigerator
  - Lock it and take key if you are going to go buy milk
  - Fixes too much: roommate angry if only wants orange juice

  - Of Course – We don’t know how to make a lock yet

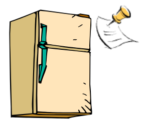
Too Much Milk: Correctness Properties

- Need to be careful about correctness of concurrent programs, since non-deterministic
  - Always write down behavior first
  - Impulse is to start coding first, then when it doesn’t work, pull hair out
  - Instead, think first, then code
- What are the correctness properties for the “Too much milk” problem?
  - Never more than one person buys
  - Someone buys if needed
- Restrict ourselves to use only atomic load and store operations as building blocks

Too Much Milk: Solution #1

- Use a note to avoid buying too much milk:
  - Leave a note before buying (kind of "lock")
  - Remove note after buying (kind of "unlock")
  - Don't buy if note (wait)
- Suppose a computer tries this (remember, only memory read/ write are atomic):

```
if (noMilk) {
   if (noNote) {
      leave Note;
      buy milk;
      remove note;
   }
}
```



- Result?

Too Much Milk: Solution #1

- Still too much milk but only occasionally!

```
  Thread A                Thread B
if (noMilk)
  if (noNote) {
                        if (noMilk)
                          if (noNote) {
    leave Note;
    buy milk;
    remove note;
  }
}
                            leave Note;
                            buy milk;
                            …
```

- Thread can get context switched after checking milk and note but before buying milk!
- Solution makes problem worse since fails intermittently
  - Makes it really hard to debug…
  - Must work despite what the thread dispatcher does!

Too Much Milk: Solution #1½

- Clearly the Note is not quite blocking enough
  - Let's try to fix this by placing note first
- Another try at previous solution:

```
leave Note;
if (noMilk) {
   if (noNote) {
      buy milk;
   }
}
remove note;
```

- What happens here?
  - Well, with human, probably nothing bad
  - With computer: no one ever buys milk

Too Much Milk Solution #2

- How about labeled notes?
  - Now we can leave note before checking
- Algorithm looks like this:

```
Thread A                    Thread B
leave note A;               leave note B;
if (noNote B) {             if (noNote A) {
   if (noMilk) {               if (noMilk) {
      buy Milk;                   buy Milk;
   }                           }
}                           }
remove note A;              remove note B;
```

- Does this work?

Too Much Milk Solution #2

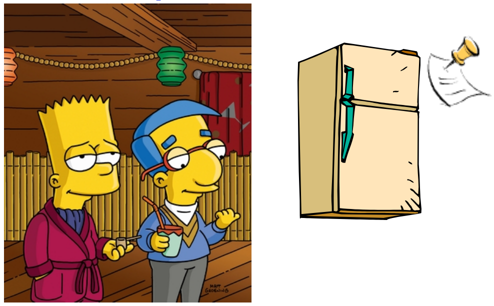
- Possible for neither thread to buy milk!

Thread A | Thread B

```
Thread A                              Thread B
leave note A;
                                      leave note B;
                                      if (noNote A) {
                                         if (noMilk) {
                                            buy Milk;
                                         }
                                      }
if (noNote B) {
   if (noMilk) {
      buy Milk;
      …
                                      remove note B;
```

- Really insidious:
  – Unlikely that this would happen, but will at worse possible time

Too Much Milk Solution #2: problem!



- *I'm* not getting milk, *You're* getting milk
- This kind of lockup is called "starvation!"

Review: Too Much Milk Solution #3

- Here is a possible two-note solution:

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

- 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

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 better (higher-level) primitives than atomic load and store
  – Build even higher-level programming abstractions on this new hardware support

High-Level Picture

- The abstraction of threads is good:
  - Maintains sequential execution model
  - Allows simple parallelism to overlap I/O and computation
- Unfortunately, still too complicated to access state shared between threads
  - Consider "too much milk" example
  - Implementing a concurrent program with only loads and stores would be tricky and error-prone
- Today, we'll start implementing higher-level operations on top of atomic operations provided by hardware
  - Develop a "synchronization toolbox"
  - Explore some common programming paradigms

Too Much Milk: Solution #4

- Suppose we have some sort of implementation of a lock (more in a moment).
  - `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"

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?
    - » Each feature makes hardware 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; }
```

- Problems with this approach:
  - 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;
}
```


5min Break

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?

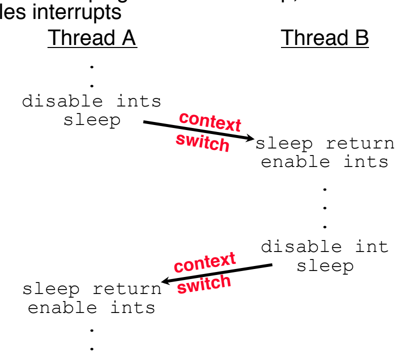
```
Acquire() {
  disable interrupts;
  if (value == BUSY) {
    put thread on wait queue;
    Go to sleep();
  } else {
    value = BUSY;
  }
  enable interrupts;
}
```

Enable Position
Enable Position
Enable Position

- Before Putting thread on the wait queue?
  - Release can check the queue and not wake up thread
- After putting the thread on the wait queue
  - Release puts the thread on the ready queue, but the thread still thinks it needs to go to sleep
  - Misses wakeup and still holds lock (deadlock!)
- Want to put it after sleep(). But – how?

How to Re-enable After Sleep()?

- Since ints 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



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 from memory 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];
      M[address] = 1;
      return result;
  }

• swap (&address, register) { /* x86 */
      temp = M[address];
      M[address] = register;
      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

- Simple solution:

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

```
test&set (&address) {
  result = M[address];
  M[address] = 1;
  return result;
}
```

- 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

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 because the busy-waiting 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 length of time!
  - Thus even if busy-waiting was OK for locks, definitely not ok for other primitives
  - Homework/exam solutions should not have 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?

Better Locks using 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;`

Higher-level Primitives than Locks

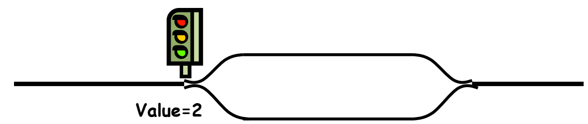
- Synchronization is a way of coordinating multiple concurrent activities that are using shared state
  - This lecture and the next presents a couple of ways of structuring the sharing
  - What is the right abstraction for synchronizing threads that share memory?
  - Want as high a level primitive as 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

Semaphores

- Semaphores are a kind of generalized locks
  - 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)
  - Locks are fine for mutual exclusion, but what if you want a thread to wait for something?
  - Example: suppose you had to implement ThreadJoin which must wait for thread to terminiate:

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


Summary

- 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
- 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
- Semaphores: Higher level constructs that are harder to "screw up"