CS162
Operating Systems and Systems Programming
Lecture 7

Mutual Exclusion, Semaphores, Monitors, and Condition Variables

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Review: A 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

<u>Thread A</u>
```
i = 0;
while (i < 10)
   i = i + 1;
printf("A wins!");
```

<u>Thread B</u>
```
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? Could be either
- 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?

Hand Simulation Multiprocessor Example

Review: Too Much Milk Solution #3

- Here is a possible two-note solution:

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

<u>Thread B</u>
```
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

Goals for Today

- Hardware Support for Synchronization
- Higher-level Synchronization Abstractions
  - Semaphores, monitors, and condition variables
- Programming paradigms for concurrent programs

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

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 implement higher-level operations on top of atomic operations provided by hardware
  - Develop a "synchronization toolbox"
  - Explore some common programming paradigms

Where are we going with synchronization?

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

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

- Atomic Load/Store: get solution like Milk #3
  - Looked at this last lecture
  - Pretty complex and error prone
- Hardware Lock instruction
  - Is this a good idea?
  - Complexity?
    - » Done in the Intel 432
    - » Each feature makes hardware more complex and slow
  - What about putting a task to sleep?
    - » How do you handle the interface between the hardware and scheduler?

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;
}
```


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 (the lines from `if (value == BUSY) {` through the closing `}`)

- 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;
}
```

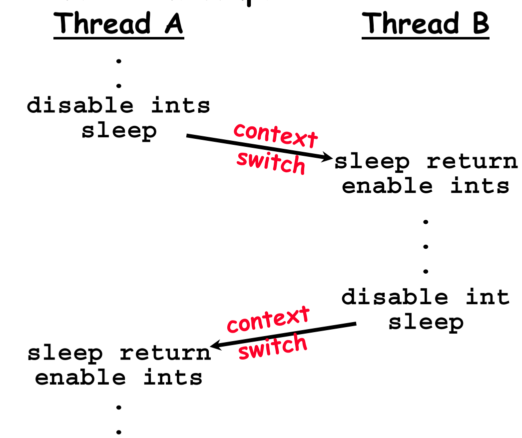
Enable Position → (before `put thread on wait queue;`)
Enable Position → (between `put thread on wait queue;` and `Go to sleep();`)
Enable Position → (after `Go to sleep();`)

Administrivia

- First Design Document due Monday 9/25
  - Subsequently need to schedule design review with TA (through web form)
  - Note that most of the design document grade comes from first version (some from final version)
- Design doc contents:
  - Architecture, correctness constraints, algorithms, pseudocode, testing strategy, and test case types
- CVS group accounts should be setup today or tomorrow
  - Check out the CVS Quick Start Guide for instructions on how to get your CVS repository working
  - If you change your key – need to let us know!

How to Re-enable After Sleep()?

- In Nachos, 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



Interrupt disable and enable across context switches

- An important point about structuring code:
  - In Nachos code you will see lots of comments about assumptions made concerning when interrupts disabled
  - This is an example of where modifications to and assumptions about program state can't be localized within a small body of code
  - In these cases it is possible for your program to eventually "acquire" bugs as people modify code
- Other cases where this will be a concern?
  - What about exceptions that occur after lock is acquired? Who releases the lock?

```
mylock.acquire();
a = b / 0;
mylock.release()
```


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
```
test&set (&address) {      /* most architectures */
    result = M[address];
    M[address] = 1;
    return result;
}
```
- swap
```
swap (&address, register) { /* x86 */
    temp = M[address];
    M[address] = register;
    register = temp;
}
```
- compare&swap
```
compare&swap (&address, reg1, reg2) { /* 68000 */
    if (reg1 == M[address]) {
        M[address] = reg2;
        return success;
    } else {
        return failure;
    }
}
```
- load-linked&store conditional
```
load-linked&store conditional(&address) {
    /* R4000, alpha */
    loop:
        ll r1, M[address];
        movi r2, 1;         /* Can do arbitrary comp */
        sc r2, M[address];
        beqz r2, loop;
}
```


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

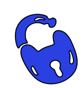
Problem: Busy-Waiting for Lock

- Positives for this solution
  - Machine can receive interrupts
  - User code can use this lock
  - Works on a multiprocessor
- Negatives
  - This is very inefficient 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;
    }
}
```

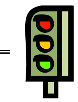
```
Release() {
    // Short busy-wait time
    while (test&set(guard));
    if anyone on wait queue {
        take thread off wait queue
        Place on ready queue;
    } else {
        value = FREE;
    }
    guard = 0;
```

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

Higher-level Primitives than Locks

- Goal of last couple of lectures:
  - 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
- 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

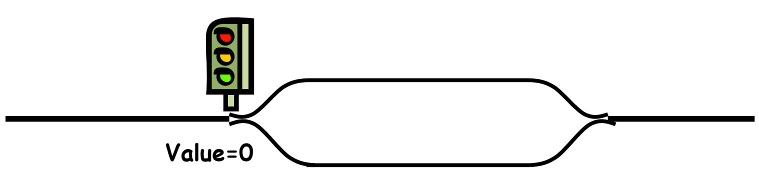
Semaphores



- 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)
  - 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();
}
```

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 fullBuffer = 0; // Initially, no coke
Semaphore emptyBuffers = numBuffers;
                          // Initially, num empty slots
Semaphore mutex = 1;      // No one using machine

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

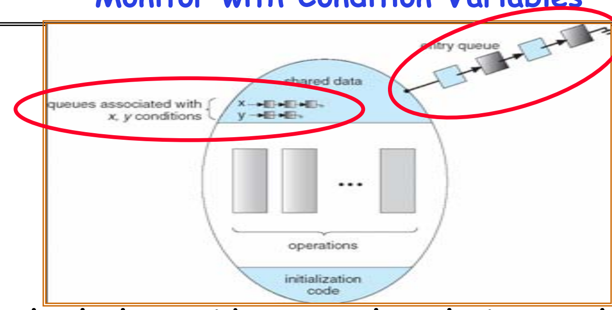

Discussion about Solution

- Why asymmetry?
  - Producer does: `emptyBuffer.P(), fullBuffer.V()`
  - Consumer does: `fullBuffer.P(), emptyBuffer.V()`
- Is order of P's important?
- Is order of V's important?
- What if we have 2 producers or 2 consumers?
  - Do we need to change anything?

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

- 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

- 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, comp&swap, load-linked/store 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
- Talked about Semaphores, Monitors, and Condition Variables
  - Higher level constructs that are harder to "screw up"