CS162
Operating Systems and Systems Programming
Lecture 5

Semaphores, Conditional Variables

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Goals for Today

- Atomic instruction sequence
- Continue with Synchronization Abstractions
  - Semaphores, Monitors and condition variables

Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne. Slides courtesy of Anthony D. Joseph, John Kubiatowicz, AJ Shankar, George Necula, Alex Aiken, Eric Brewer, Ras Bodik, Ion Stoica, Doug Tygar, and David Wagner.

Atomic Read-Modify-Write instructions

- Problems with interrupt-based lock 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

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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
  - Inefficient: busy-waiting thread will consume cycles waiting
  - Waiting thread may take cycles away from thread holding lock!
  - 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!
  - Even if 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?

Locks using test&set vs. Interrupts

- Compare to "disable interrupt" solution (last lecture)

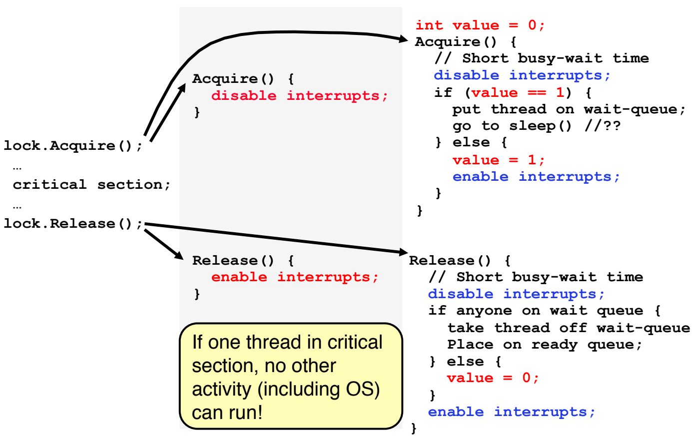
```
int value = FREE;

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



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

```
Acquire() {
  disable interrupts;
}
```

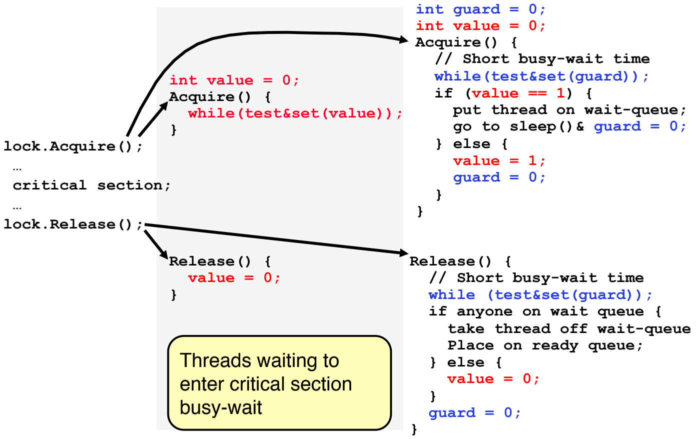
```
Release() {
  enable interrupts;
}
```

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



```
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;
}
```

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**

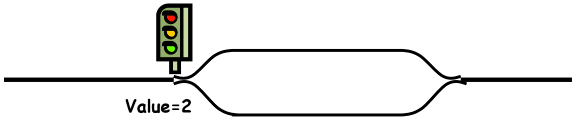
- We are going to implement various higher-level synchronization primitives using atomic operations
  - Everything is pretty painful if only atomic primitives are load and store
  - Need to provide primitives useful at user-level

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)
  - – Allow thread 1 to wait for a signal from thread 2, i.e., thread 2 schedules thread 1 when a given constrained is satisfied
  - – 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: 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 slots, if empty (scheduling constraint)
  - – Producer must wait for consumer to make room in buffer, if all full (scheduling constraint)
  - – Only one thread can manipulate buffer queue at a time (mutual exclusion)
- General rule of thumb:
  Use a separate semaphore for each constraint

```
– Semaphore fullSlots; // consumer's constraint
– Semaphore emptySlots;// 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

Increase # of occupied slots

Decrease # of occupied slots

Increase # of empty slots

Discussion about Solution

- Is order of P's important?
- Is order of V's important?
  - No, except that it might affect scheduling efficiency
- 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;
}
```

5min Break

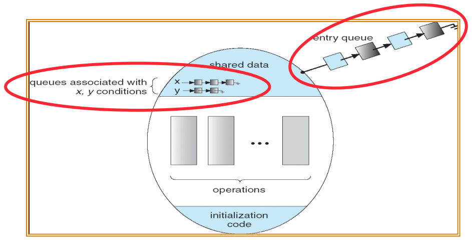
Motivation for Monitors and Condition Variables

- 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?

Motivation for Monitors and Condition Variables

- Cleaner idea: Use *locks* for mutual exclusion and *condition variables* for scheduling constraints
- 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

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Simple Monitor Example

- 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
}
```

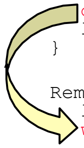
- Not very interesting use of "Monitor"
  - It only uses a lock with no condition variables
  - Cannot put consumer to sleep if no work!

Condition Variables

- 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!

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);
}
```

Mesa vs. Hoare monitors

- Need to be careful about precise definition of signal and wait. Consider a piece of our dequeue code:

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

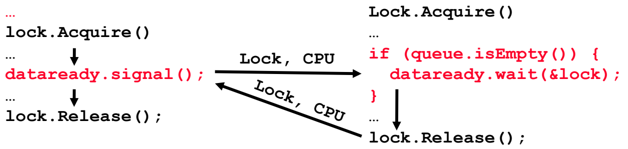
  - Why didn't we do this?

```
if (queue.isEmpty()) {
  dataready.wait(&lock); // If nothing, sleep
}
item = queue.dequeue();// Get next item
```

- Answer: depends on the type of scheduling
  - Hoare-style
  - Mesa-style

Hoare monitors

- Signaler gives up lock, CPU to waiter; waiter runs immediately
- Waiter gives up lock, processor back to signaler when it exits critical section or if it waits again
- Most textbooks



```
…
lock.Acquire()
…
dataready.signal();
…
lock.Release();
```

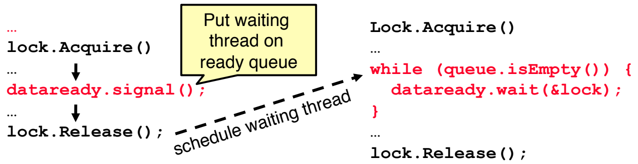
Lock, CPU

Lock, CPU

```
Lock.Acquire()
…
if (queue.isEmpty()) {
  dataready.wait(&lock);
}
…
lock.Release();
```

Mesa monitors

- Signaler keeps lock and processor
- Waiter placed on ready queue with no special priority
- Practically, need to check condition again after wait
- Most real operating systems



```
…
lock.Acquire()
…
dataready.signal();
…
lock.Release();
```

```
Lock.Acquire()
…
while (queue.isEmpty()) {
  dataready.wait(&lock);
}
…
lock.Release();
```

Summary

- Locks construction based on atomic seq. of instructions
  - Must be very careful not to waste/tie up machine resources
    - » Shouldn't spin wait for long
  - Key idea: Separate lock variable, use hardware mechanisms to protect modifications of that variable
- Semaphores
  - Generalized locks
  - Two operations: P(), V()
- 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()`