CS162
Operating Systems and Systems Programming
Lecture 8

Synchronization 3: Locks, Semaphores, Monitors

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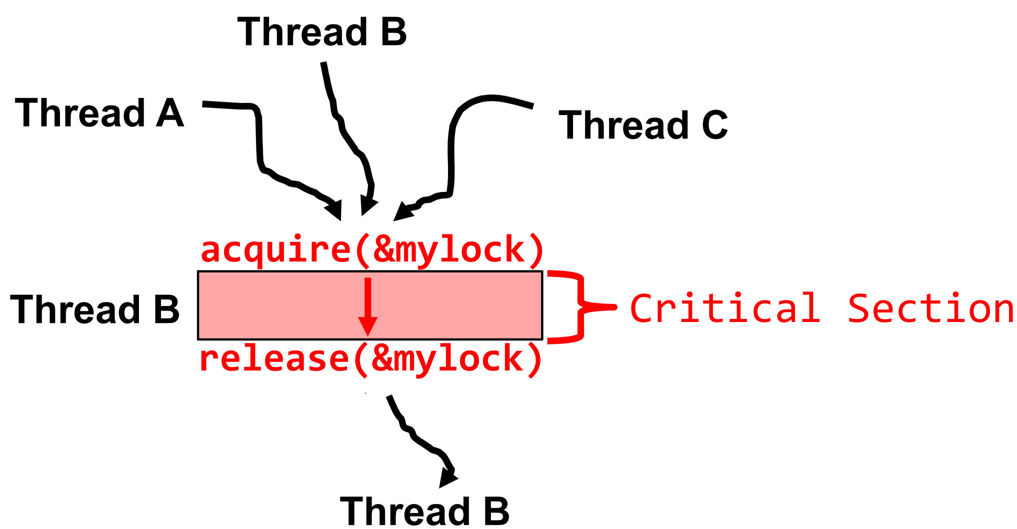
Recall: Fix banking problem with Locks!

- Identify critical sections (atomic instruction sequences) and add locking:

```
Deposit(acctId, amount) {
  acquire(&mylock)          // Wait if someone else in critical section!
  acct = GetAccount(actId);
  acct->balance += amount;
  StoreAccount(acct);
  release(&mylock)          // Release someone into critical section
}
```

Critical Section



Threads serialized by lock through critical section.
Only one thread at a time

- Must use SAME lock (`mylock`) with all of the methods (Withdraw, etc…)
  – Shared with all threads!

Recall: Motivating Example: "Too Much Milk"

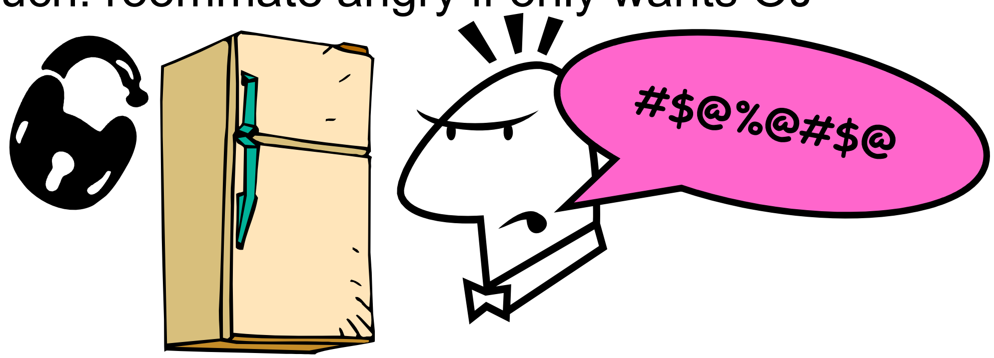
- Great thing about OS's – analogy between problems in OS and problems in real life
  - Help you understand real life problems better
  - But, computers are much stupider than people
- Example: People need to coordinate:

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

Solve with a lock?

- Recall: Lock prevents someone from doing something
  - Lock before entering critical section
  - Unlock when leaving
  - 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 OJ



- Of Course – We don't know how to make a lock yet
  - Let's see if we can answer this question!

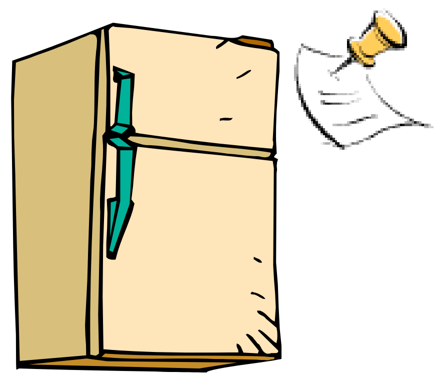
Too Much Milk: Correctness Properties

- Need to be careful about correctness of concurrent programs, since non-deterministic
  – Impulse is to start coding first, then when it doesn't work, pull hair out
  – Instead, think first, then code
  – Always write down behavior first
- What are the correctness properties for the "Too much milk" problem???
  – Never more than one person buys
  – Someone buys if needed
- First attempt: 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;
   }
}
```



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):

Thread A

```
if (noMilk) {


   if (noNote) {
     leave Note;
     buy Milk;
     remove Note;
   }
}
```

Thread B

```
if (noMilk) {
   if (noNote) {



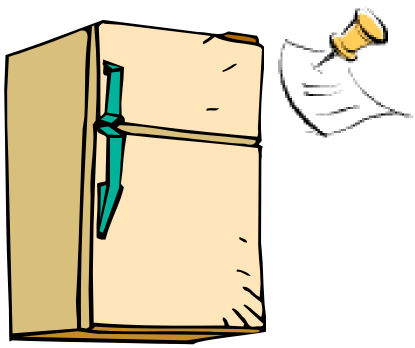


      leave Note;
      buy Milk;
      remove Note;
   }
}
```

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?
  - Still too much milk but only occasionally!
  - 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 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

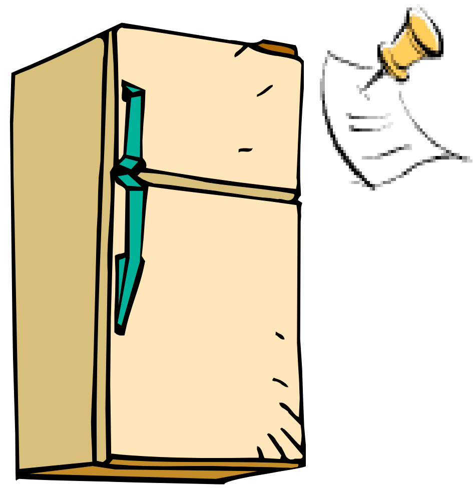
```
leave note A;
if (noNote B) {
   if (noMilk) {
      buy Milk;
   }
}
remove note A;
```

Thread B

```
leave note B;
if (noNoteA) {
   if (noMilk) {
      buy Milk;
   }
}
remove note B;
```

- Does this work?
- Possible for neither thread to buy milk
  – Context switches at exactly the wrong times can lead each to think that the other is going to buy
- Really insidious:
  – Extremely unlikely this would happen, but will at worse possible time
  – Probably something like this in UNIX

Too Much Milk Solution #2: problem!



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

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

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

happened before

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 removed

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

Case 2

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

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

This Generalizes to n Threads…

- Leslie Lamport's "Bakery Algorithm" (1974)

Computer Systems — G. Bell, D. Siewiorek, and S.H. Fuller, Editors

A New Solution of Dijkstra's Concurrent Programming Problem

Leslie Lamport
Massachusetts Computer Associates, Inc.

A simple solution to the mutual exclusion problem is presented which allows the system to continue to operate

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 got to be 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?

- Recall our target lock interface:
  - `acquire(&milklock)` – wait until lock is free, then grab
  - `release(&milklock)` – 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:

```
acquire(&milklock);
if (nomilk)
   buy milk;
release(&milklock);
```

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

Administrivia

- Midterm Next Thursday (February 16)!
  - No class on day of midterm
  - 7-9PM
- Project 1 Design Document Tomorrow!
- 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

Back to: 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?
    - » What is 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; }
```

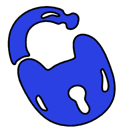
- Problems with this approach:
  - Can't let user do this! Consider following:

```
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.
  - *Prevent switching to other thread that might be trying to acquire lock!*
  - 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;
}
```

"Meta-" Critical Section

- Note: unlike previous solution, this "meta-"critical section 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;
}
```

Interrupt Re-enable in Going to Sleep

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

Enable Position

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

- Before Putting thread on the wait queue?

Interrupt Re-enable in Going to Sleep

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

Enable Position

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

- Before Putting thread on the wait queue?
  – Release can check the queue and not wake up thread

Interrupt Re-enable in Going to Sleep

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

Enable Position

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

- 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

Interrupt Re-enable in Going to Sleep

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

Enable Position

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

- 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!)

Interrupt Re-enable in Going to Sleep

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

Enable Position

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

- 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()?

- 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
                  context switch
    sleep return
     enable ints
          .
          .
```

In-Kernel Lock: Simulation

Value: 0 | waiters | owner | READY

Running
Thread A

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

```
INIT
   int value = 0;

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

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

Ready
Thread B

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

In-Kernel Lock: Simulation

Value: 1 | waiters | owner

READY

Running

Thread A

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

```
INIT
   int value = 0;

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

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

Ready

Thread B

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

In-Kernel Lock: Simulation

Value: 1 | waiters | owner

READY

Ready Running

Thread A

Ready Running

Thread B

```
INIT
    int value = 0;
```

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

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

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

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

In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Ready Running

Thread A

INIT

Waiting Running

Thread B

```
int value = 0;
```

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

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

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

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

In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Running — *Thread A*

Ready — *Thread B*

```
INIT
   int value = 0;

Acquire() {
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() ??
  } else {
    value = 1;
  }
  enable interrupts;
}

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

Thread A:

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

Thread B:

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

In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Running Ready — Thread A

Running Ready — Thread B

INIT
```
int value = 0;
```

Thread A:
```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

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

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

Thread B:
```
lock.Acquire();
 …
 critical section;
 …
lock.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 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

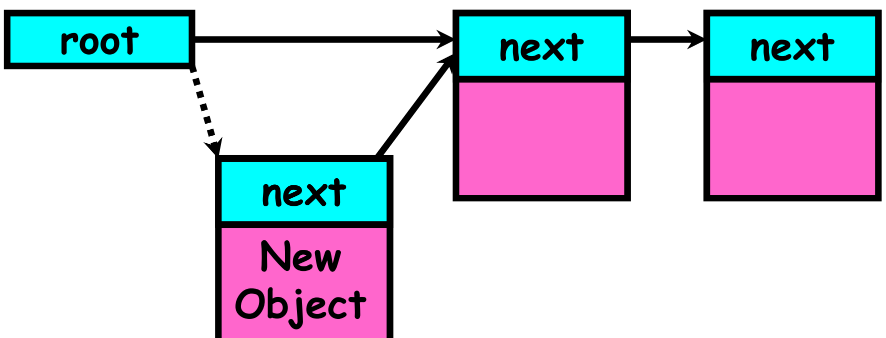
- ```
  test&set (&address) {           /* most architectures */
      result = M[address];        // return result from "address" and
      M[address] = 1;             // set value at "address" to 1
      return result;
  }
  ```
- ```
  swap (&address, register) {     /* x86 */
      temp = M[address];          // swap register's value to
      M[address] = register;      // value at "address"
      register = temp;
  }
  ```
- ```
  compare&swap (&address, reg1, reg2) { /* x86 (returns old value), 68000 */
      if (reg1 == M[address]) {   // If memory still == reg1,
          M[address] = reg2;      // then  put reg2 => memory
          return success;
      } else {                    // Otherwise do not change memory
          return failure;
      }
  }
  ```
- ```
  load-linked&store-conditional(&address) { /* R4000, alpha */
      loop:
          ll r1, M[address];
          movi r2, 1;              // Can do arbitrary computation
          sc r2, M[address];
          beqz r2, loop;
  }
  ```

Using of Compare&Swap for queues

- ```
  compare&swap (&address, reg1, reg2) { /* x86, 68000 */
      if (reg1 == M[address]) {
          M[address] = reg2;
          return success;
      } else {
          return failure;
      }
  }
  ```

  Here is an atomic add to linkedlist function:

  ```
  addToQueue(&object) {
      do {                     // repeat until no conflict
          ld r1, M[root]       // Get ptr to current head
          st r1, M[object]   // Save link in new object
      } until (compare&swap(&root,r1,object));
  }
  ```


  ```

Implementing Locks with test&set

- Simple lock that doesn't require entry into the kernel:

```
// (Free) Can access this memory location from user space!
int mylock = 0; // Interface: acquire(&mylock);
                //            release(&mylock);
acquire(int *thelock) {
   while (test&set(thelock)); // Atomic operation!
}
release(int *thelock) {
   *thelock = 0;              // Atomic operation!
}
```

- Simple explanation:
  - If lock is free, test&set reads 0 and sets lock=1, so lock is now busy. It returns 0 so while exits.
  - If lock is busy, test&set reads 1 and sets lock=1 (no change) It returns 1, so while loop continues.
  - When we set thelock = 0, someone else can get lock.
- Busy-Waiting: thread consumes cycles while waiting
  - For multiprocessors: every test&set() is a write, which makes value ping-pong around in cache (using lots of network BW)

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 $\Rightarrow$ no progress!
- Priority Inversion problem with original Martian rover
- For higher-level synchronization primitives (e.g. semaphores or 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!

Multiprocessor Spin Locks: test&test&set

- A better solution for multiprocessors:

```
// (Free) Can access this memory location from user space!
int mylock = 0; // Interface: acquire(&mylock);
                //            release(&mylock);
acquire(int *thelock) {
   do {
      while(*thelock);          // Wait until might be free (quick check/test!)
   } while(test&set(thelock)); // Atomic grab of lock (exit if succeeded)
}
release(int *thelock) {
   *thelock = 0;              // Atomic release of lock
}
```

- Simple explanation:
  – Wait until lock might be free (only reading – stays in cache)
  – Then, try to grab lock with test&set
  – Repeat if fail to actually get lock
- Issues with this solution:
  – Busy-Waiting: thread still consumes cycles while waiting
    » However, it does not impact other processors!

Better Locks using test&set

- Can we build test&set locks without busy-waiting?
  - Mostly. Idea: only busy-wait to atomically check lock value
  -
```
int guard = 0; // Global Variable!
int mylock = FREE; // Interface: acquire(&mylock);
                   //            release(&mylock);
```

```
acquire(int *thelock) {
   // Short busy-wait time
   while (test&set(guard));
   if (*thelock == BUSY) {
      put thread on wait queue;
      go to sleep() & guard = 0;
      // guard == 0 on wakup!
   } else {
      *thelock = BUSY;
      guard = 0;
   }
}
```

```
release(int *thelock) {
   // Short busy-wait time
   while (test&set(guard));
   if anyone on wait queue {
      take thread off wait queue
      Place on ready queue;
   } else {
      *thelock = 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?

Recap: Locks using interrupts

```
int mylock=0;

acquire(&mylock);
 …
 critical section;
 …
release(&mylock);
```

```
acquire(int *thelock) {
  disable interrupts;
}
```

```
release(int *thelock)
{
  enable interrupts;
}
```

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

Lock argument not used!

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

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

Recap: Locks using test & set

```
int mylock=0;

acquire(&mylock);
 …
 critical section;
 …
release(&mylock);
```

```
int mylock = 0;
acquire(int *thelock) {
  while(test&set(thelock));
}

release(int *thelock) {
  *thelock = 0;
}
```

Threads waiting to enter critical section busy-wait

```
int guard = 0; // global!

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

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

Linux futex: Fast Userspace Mutex

```
#include <linux/futex.h>
#include <sys/time.h>

int futex(int *uaddr, int futex_op, int val,
          const struct timespec *timeout );
```

`uaddr` points to a 32-bit value in user space

`futex_op`

- `FUTEX_WAIT` – if `val == *uaddr` sleep till `FUTEX_WAIT`
  - » ***Atomic*** check that condition still holds after we disable interrupts (in kernel!)
- `FUTEX_WAKE` – wake up at most `val` waiting threads
- `FUTEX_FD`, `FUTEX_WAKE_OP`, `FUTEX_CMP_REQUEUE`: More interesting operations!

`timeout`

- ptr to a *timespec* structure that specifies a timeout for the op

- Interface to the kernel sleep() functionality!
  - Let thread put themselves to sleep – conditionally!
- futex is not exposed in libc; it is used within the implementation of pthreads
  - Can be used to implement locks, semaphores, monitors, etc…

Example: First try: T&S and futex

```
int mylock = 0; // Interface: acquire(&mylock);
                //            release(&mylock);

acquire(int *thelock) {
   while (test&set(thelock)) {
      futex(thelock, FUTEX_WAIT, 1);
   }
}

release(int *thelock) {
   thelock = 0; // unlock
   futex(&thelock, FUTEX_WAKE, 1);

}
```

- Properties:
  - Sleep interface by using futex – no busywaiting
- No overhead to acquire lock
  - Good!
- Every unlock has to call kernel to potentially wake someone up – even if none
  - Doesn't quite give us no-kernel crossings when uncontended…!

Example: Try #2: T&S and futex

```
bool maybe_waiters = false;
int mylock = 0; // Interface: acquire(&mylock,&maybe_waiters);
                //            release(&mylock,&maybe_waiters);
```

```
acquire(int *thelock, bool *maybe) {
   while (test&set(thelock)) {
      // Sleep, since lock busy!
      *maybe = true;
      futex(thelock, FUTEX_WAIT, 1);

      // Make sure other sleepers not stuck
      *maybe = true;
   }
}
```

```
release(int*thelock, bool *maybe) {
   thelock = 0;
   if (*maybe) {
      *maybe = false;
      // Try to wake up someone
      futex(&value, FUTEX_WAKE, 1);
   }
}
```

- This is syscall-free in the uncontended case
  - Temporarily falls back to syscalls if multiple waiters, or concurrent acquire/release
- But it can be considerably optimized!
  - See "Futexes are Tricky" by Ulrich Drepper

Try #3: Better, using more atomics

- Much better: Three (3) states:
  - UNLOCKED: No one has lock
  - LOCKED: One thread has lock
  - CONTESTED: Possibly more than one (with someone sleeping)
- Clean interface!
- Lock grabbed cleanly by either
  - compare_and_swap()
  - First swap()
- No overhead if uncontested!
- Could build semaphores in a similar way!

```
typedef enum { UNLOCKED,LOCKED,CONTESTED } Lock;
Lock mylock = UNLOCKED; // Interface: acquire(&mylock);
                        //            release(&mylock);

acquire(Lock *thelock) {
   // If unlocked, grab lock!
   if (compare&swap(thelock,UNLOCKED,LOCKED))
      return;

   // Keep trying to grab lock, sleep in futex
   while (swap(mylock,CONTESTED) != UNLOCKED))
      // Sleep unless someone releases hear!
      futex(thelock, FUTEX_WAIT, CONTESTED);
}

release(Lock *thelock) {
   // If someone sleeping,
   if (swap(thelock,UNLOCKED) == CONTESTED)
      futex(thelock,FUTEX_WAKE,1);
}
```

Recall: Where are we going with synchronization?

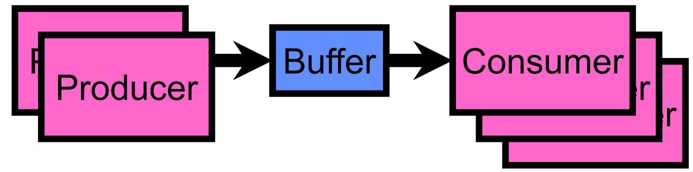
Programs	Shared Programs
Higher-level API	Locks Semaphores Monitors Send/Receive
Hardware	Load/Store Disable Ints Test&Set Compare&Swap

- 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

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

Producer-Consumer with a Bounded Buffer

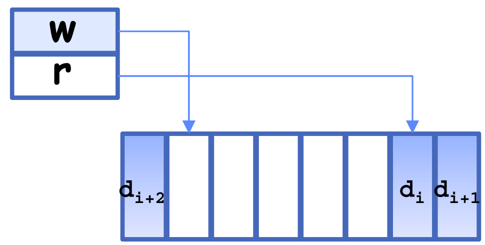


- Problem Definition
  – Producer(s) put things into a shared buffer
  – Consumer(s) take them out
  – Need synchronization to coordinate producer/consumer
- Don’t want producer and consumer to have to work in lockstep, so put a fixed-size buffer between them
  – Need to synchronize access to this buffer
  – 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
- Others: Web servers, Routers, ….

Circular Buffer Data Structure (sequential case)

```
typedef struct buf {
  int write_index;
  int read_index;
  <type> *entries[BUFSIZE];
} buf_t;
```



- Insert: write & bump write ptr (enqueue)
- Remove: read & bump read ptr (dequeue)
- *How to tell if Full (on insert) Empty (on remove)?*
- *And what do you do if it is?*
- *What needs to be atomic?*

Circular Buffer – first cut

```
mutex buf_lock = <initially unlocked>

Producer(item) {
  acquire(&buf_lock);
  while (buffer full) {}; // Wait for a free slot
  enqueue(item);
  release(&buf_lock);
}

Consumer() {
  acquire(&buf_lock);
  while (buffer empty) {}; // Wait for arrival
  item = dequeue();
  release(&buf_lock);
  return item
}
```

Will we ever come out of the wait loop?

Circular Buffer – 2nd cut

```
mutex buf_lock = <initially unlocked>

Producer(item) {
  acquire(&buf_lock);
  while (buffer full) {release(&buf_lock); acquire(&buf_lock);}
  enqueue(item);
  release(&buf_lock);
}

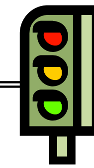

Consumer() {
  acquire(&buf_lock);
  while (buffer empty) {release(&buf_lock); acquire(&buf_lock);}
  item = dequeue();
  release(&buf_lock);
  return item
}
```

What happens when one is waiting for the other?
- Multiple cores ?
- Single core ?

Higher-level Primitives than Locks

- 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

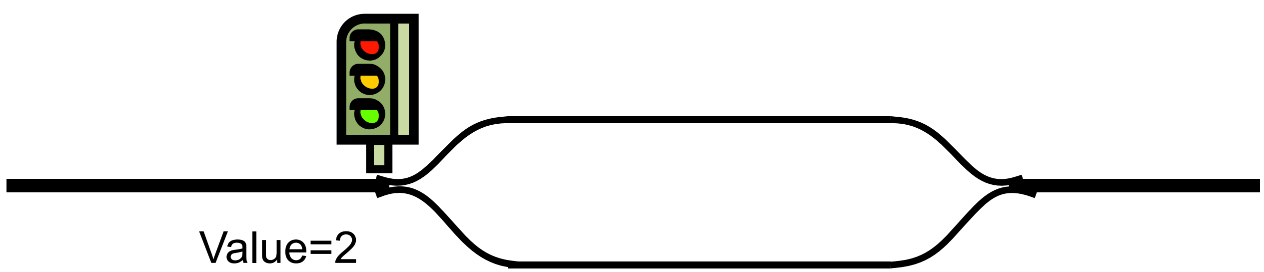
Semaphores



- 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 operations:
  - Set value when you initialize
  - `Down()` or `P()`: an atomic operation that waits for semaphore to become positive, then decrements it by 1
    - » Think of this as the wait() operation
  - `Up()` or `V()`: an atomic operation that increments the semaphore by 1, waking up a waiting P, if any
    - » This of this as the signal() operation
- Technically examining value after initialization is not allowed.

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 initially
  - Operations must be atomic
    - » Two P's together can't decrement value below zero
    - » Thread going to sleep in P won't miss wakeup from V – even if both happen at same time
- POSIX adds ability to read value, but technically not part of proper interface!
- 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” or “mutex”.
- Can be used for mutual exclusion, just like a lock:

```
semaP(&mysem);
  // Critical section goes here
semaV(&mysem);
```

Scheduling Constraints (initial value = 0)

- Allow thread 1 to wait for a signal from thread 2
  - 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 {
   semaP(&mysem);
}
ThreadFinish {
   semaV(&mysem);
}
```

Revisit Bounded Buffer: 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 (coke machine)


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

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

fullSlots signals coke

emptySlots signals space

Critical sections using mutex protect integrity of the queue

Discussion about Solution

Decrease # of empty slots

Increase # of occupied slots

- Why asymmetry?
  - Producer does: **`semaP(&emptyBuffer), semaV(&fullBuffer)`**
  - Consumer does: **`semaP(&fullBuffer), semaV(&emptyBuffer)`**

Decrease # of occupied slots

Increase # of empty slots

- Is order of P's important?
- Is order of V's important?
- What if we have 2 producers or 2 consumers?

```
Producer(item) {
  semaP(&mutex);
  semaP(&emptySlots);
  Enqueue(item);
  semaV(&mutex);
  semaV(&fullSlots);
}
Consumer() {
  semaP(&fullSlots);
  semaP(&mutex);
  item = Dequeue();
  semaV(&mutex);
  semaV(&emptySlots);
  return item;
}
```

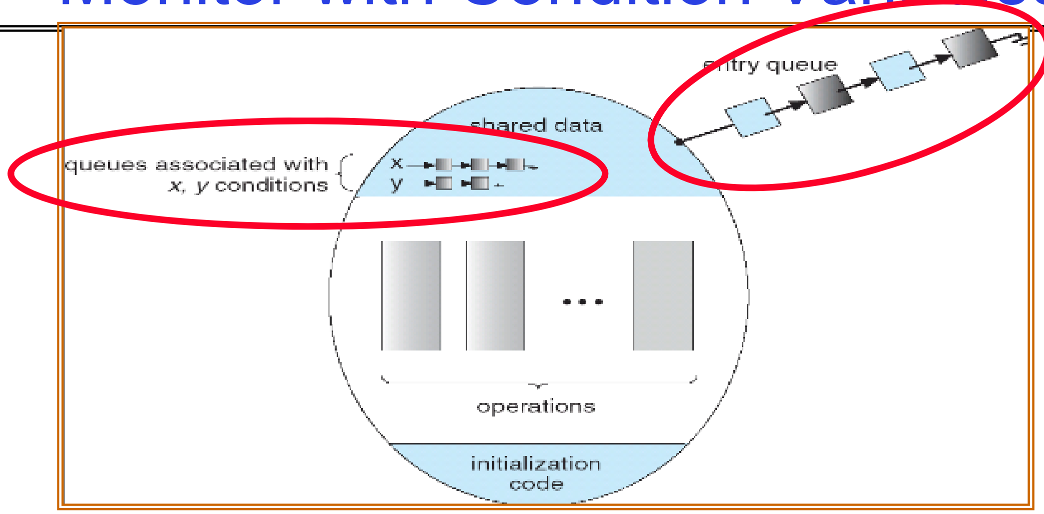
Semaphores are good but…Monitors are better!

- Semaphores are a huge step up; just think of trying to do the bounded buffer with only loads and stores or even with locks!
- 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
- A "Monitor" is a paradigm for concurrent programming!
  - Some languages support monitors explicitly

Condition Variables

- How do we change the consumer() 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!

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

Synchronized Buffer (with condition variable)

- Here is an (infinite) synchronized queue:

```
lock buf_lock;                     // Initially unlocked
condition buf_CV;                  // Initially empty
queue queue;                       // Actual queue!

Producer(item) {
   acquire(&buf_lock);             // Get Lock
   enqueue(&queue,item);           // Add item
   cond_signal(&buf_CV);           // Signal any waiters
   release(&buf_lock);             // Release Lock
}

Consumer() {
   acquire(&buf_lock);             // Get Lock
   while (isEmpty(&queue)) {
      cond_wait(&buf_CV, &buf_lock); // If empty, sleep
   }
   item = dequeue(&queue);         // Get next item
   release(&buf_lock);             // 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 (isEmpty(&queue)) {
  cond_wait(&buf_CV,&buf_lock); // If nothing, sleep
}
item = dequeue(&queue);   // Get next item
```

  – Why didn't we do this?

```
if (isEmpty(&queue)) {
  cond_wait(&buf_CV,&buf_lock); // If nothing, sleep
}
item = dequeue(&queue);   // Get next item
```

- Answer: depends on the type of scheduling
  – Mesa-style: Named after Xerox-Park Mesa Operating System
    » Most OSes use Mesa Scheduling!
  – Hoare-style: Named after British logician Tony Hoare

Hoare monitors

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

```
…
acquire(&buf_lock);
…
cond_signal(&buf_CV);
…
release(&buf_lock);
```

Lock, CPU

Lock, CPU

```
acquire(&buf_lock);
…
if (isEmpty(&queue)) {
  cond_wait(&buf_CV,&buf_lock);
}
…
release(&buf_lock);
```

- On first glance, this seems like good semantics
  – Waiter gets to run immediately, condition is still correct!
- Most textbooks talk about Hoare scheduling
  – However, hard to do, not really necessary!
  – Forces a lot of context switching (inefficient!)

Mesa monitors

- Signaler keeps lock and processor
- Waiter placed on ready queue with no special priority

```
…
acquire(&buf_lock)
…
cond_signal(&buf_CV);
…
release(&buf_lock));
```

Put waiting thread on ready queue

schedule thread (sometime later!)

```
acquire(&buf_lock);
…
while (isEmpty(&queue)) {
  cond_wait(&buf_CV,&buf_lock);
}
…
lock.Release();
```

- Practically, need to check condition again after wait
  - By the time the waiter gets scheduled, condition may be false again – so, just check again with the "while" loop
- Most real operating systems do this!
  - More efficient, easier to implement
  - Signaler's cache state, etc still good

Circular Buffer – 3rd cut (Monitors, pthread-like)

```
lock buf_lock = <initially unlocked>
condition producer_CV = <initially empty>
condition consumer_CV = <initially empty>

Producer(item) {
  acquire(&buf_lock);
  while (buffer full) { cond_wait(&producer_CV, &buf_lock); }
  enqueue(item);
  cond_signal(&consumer_CV);
  release(&buf_lock);
}

Consumer() {
  acquire(buf_lock);
  while (buffer empty) { cond_wait(&consumer_CV, &buf_lock); }
  item = dequeue();
  cond_signal(&producer_CV);
  release(buf_lock);
  return item
}
```

What does thread do when it is waiting?
- Sleep, not busywait!

Again: Why the `while` Loop?

- MESA semantics
- For most operating systems, when a thread is woken up by `signal()`, it is simply put on the ready queue
- It may or may not reacquire the lock immediately!
  - Another thread could be scheduled first and "sneak in" to empty the queue
  - Need a loop to re-check condition on wakeup

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, load-locked & 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
- Showed primitive for constructing user-level locks
  - Packages up functionality of sleeping

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()`
- Monitors represent the logic of the program
  - Wait if necessary
  - Signal when change something so any waiting threads can proceed
- Next time: More complex monitor example
  - Readers/Writers in depth!