CS162
Operating Systems and Systems Programming
Lecture 8

Synchronization 3:
Locks, Semaphores, Monitors

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Recall: 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

Recall: Too Much Milk: Solution #4

- Solution #3 really complex and undesirable as a general solution
- 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);
```

Critical Section

Recall: 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 interrupts; }
LockRelease { enable interrupts; }
```

- 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?"

Recall: 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;
}
```

- Really only works in kernel – why?

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


In-Kernel Lock: Simulation

Value: 0 | waiters | owner | READY

Running: Thread A — Ready: Thread B

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


In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Running: Thread A — Ready: Thread B

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


In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Ready / Running: Thread A — Running / Ready: Thread B

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

In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Running / Ready — **Thread A** | Running / Waiting — **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();
```


In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Running — **Thread A** | Ready / Waiting — **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();
```


In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Ready / Running — **Thread A** | Ready / Running — **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

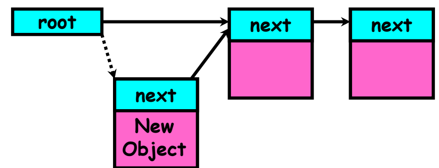
- test&set (&address) { /* most architectures */
```
test&set (&address) {          /* most architectures */
    result = M[address];       // return result from "address" and
    M[address] = 1;            // set value at "address" to 1
    return result;
}
```
- swap (&address, register) { /* x86 */
```
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 */
```
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 */
```
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 */
```
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));
}
```



Administrivia

- Midterm Next Thursday (February 17)!
  - No class on day of midterm
  - 7-9PM
- Project 1 Design Document due next Friday 2/11
- 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

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 ⇒ 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?

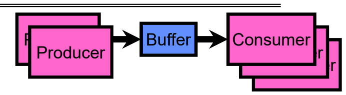
Programs	Shared Programs
Higher-level API	Locks Semaphores Monitors Send/Receive
Hardware	Load/Store Disable Ints Test&Set Compare&Swap

- 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

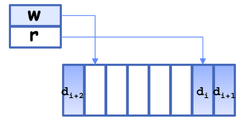


- Problem Definition
  - Producer(s) put things into a shared buffer
  - Consumer(s) take them out
  - Need synchronization to coordinate producer/consumer
- Don't want producer and consumer to have to work in lockstep, so put a fixed-size buffer between them
  - Need to synchronize access to this buffer
  - 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 – 2^{nd} cut

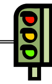
```
mutex buf_lock = <initially unlocked>

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

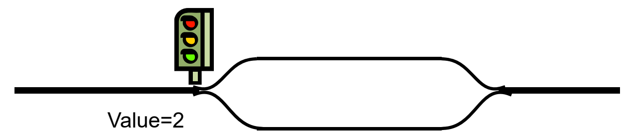
Semaphores



- 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;
}
```

Critical sections using mutex protect integrity of the queue

fullSlots signals coke

emptySlots signals space

Discussion about Solution

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

Decrease # of empty slots

Increase # of occupied slots

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;
}
```

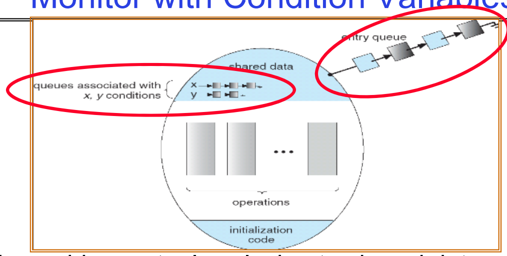

Semaphores are good but…Monitors are better!

- 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

Put waiting thread on ready queue

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

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!