CS162
Operating Systems and Systems Programming
Lecture 7

Synchronization (Con't): Semaphores, Monitors, and Readers/Writers

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Acknowledgments: Lecture slides are from the Operating Systems course taught by John Kubiatowicz at Berkeley, with few minor updates/changes*. When slides are obtained from other sources, a reference will be noted on the bottom of that slide, in which case a full list of references is provided on the last slide.*

Review: Too Much Milk Solution #3

- Here is a possible two-note solution:

Thread A

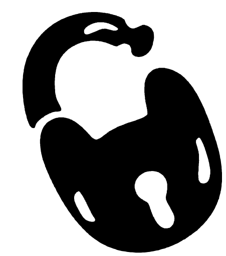
```
leave note A;
while (note B) {\\X
   do nothing;
}
if (noMilk) {
   buy milk;
}
remove note A;
```

Thread B

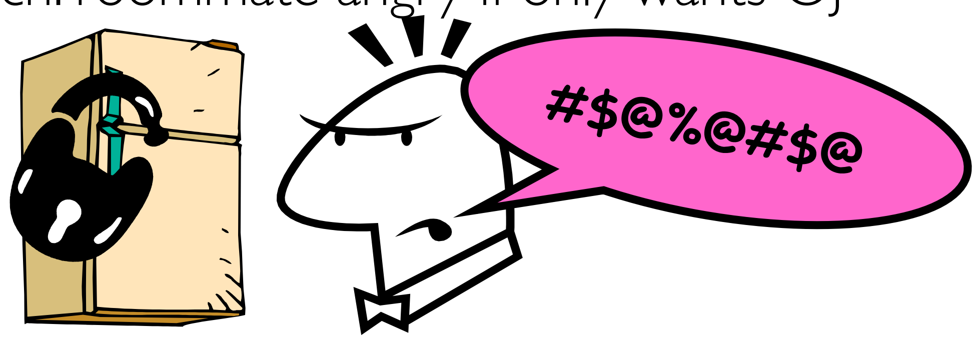
```
leave note B;
if (noNote A) {\\Y
   if (noMilk) {
      buy milk;
   }
}
remove note B;
```

- Does this work? Yes. Both can guarantee that:
  - It is safe to buy, or
  - Other will buy, ok to quit
- Solution #3 works, but it's really unsatisfactory
  - Really complex – even for this simple of 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"

Recall: What is a Lock?



- Lock: prevents someone from doing something
  - Lock before entering critical section and before accessing shared data
  - Unlock when leaving, after accessing shared data
  - Wait if locked
    - » Important idea: all synchronization involves waiting
- For example: fix the milk problem by putting a key on the refrigerator
  - Lock it and take key if you are going to go buy milk
  - Fixes too much: roommate angry if only wants OJ



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

Recall: Too Much Milk: Solution #4

- Suppose we have some sort of implementation of a lock
  - `lock.Acquire()` – wait until lock is free, then grab
  - `lock.Release()` – Unlock, waking up anyone waiting
  - These must be *atomic operations* – if two threads are waiting for the lock and both see it's free, only one succeeds to grab the lock
- Then, our milk problem is easy:

```
milklock.Acquire();
if (nomilk)
   buy milk;
milklock.Release();
```

- Once again, section of code between **`Acquire()`** and **`Release()`** called a "Critical Section"
- Of course, you can make this even simpler: suppose you are out of ice cream instead of milk
  - Skip the test since you always need more ice cream ;-)

Recall: Implement 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;
}
```

- Note – Can easily have many locks
  – Use an array of values, for instance!

Recall: 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        sleep return
           switch          enable ints
                                      .
                                      .
                                      .
                         disable int
              context          sleep
              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

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

Ready / Running

Thread A

Ready / Running

Thread B

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

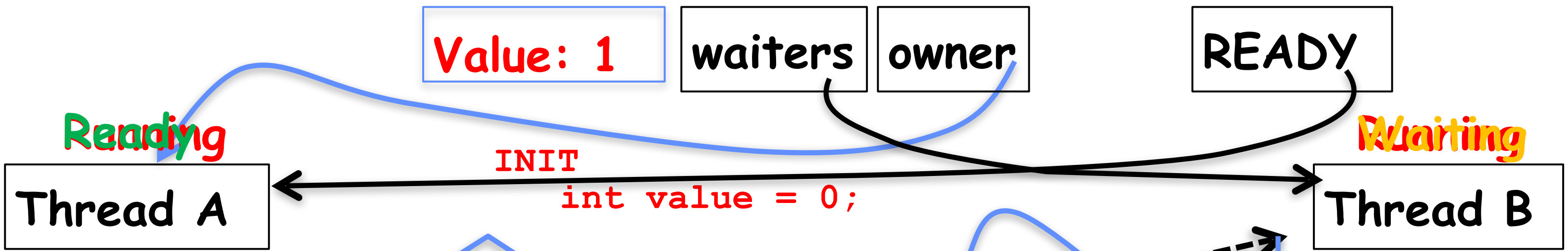
Thread A:
```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

Thread B:
```
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;
}
```

In-Kernel Lock: Simulation




```
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;
}
```

Thread B:

```
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

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

Waiting / Ready
Thread B

```
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;
}
```

In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Running / Ready — **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;
}
```

Thread B:

```
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;
}
```

A Better Lock Implementation

- Interrupt-based solution works for single core, but costly
  - Kernel crossings/system calls required for users
  - Disruption of interrupt handling (by disabling interrupts)
- Doesn't work well on multi-core machines
  - Disable intr on all cores?

- Solution: Utilize hardware support for atomic operations
  - Operations work on *memory* which is *shared* between cores and doesn’t require system calls

Recall: 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) { /* 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;
  }
  ```

Recall: Implementing Locks with test&set

- Our first (simple!) cut at using atomic operations for locking:

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

- Simple explanation:
  – If lock is free, test&set reads 0 and sets value=1, so lock is now busy. It returns 0 so while exits.
  – If lock is busy, test&set reads 1 and sets value=1 (no change) It returns 1, so while loop continues.
  – When we set value = 0, someone else can get lock.
- Busy-Waiting: thread consumes cycles while waiting
  – This is not a good implementation for single core
  – 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
- Looking forward: For semaphores and 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:

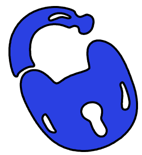
```
int mylock = 0; // Free
Acquire() {
   do {
      while(mylock);    // Wait until might be free
   } while(test&set(&mylock)); // exit if get lock
}

Release() {
   mylock = 0;
}
```

- 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
- Still have 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?
  – 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;
  }
}
```

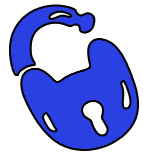
```
Release() {
  // Short busy-wait time
  while (test&set(guard));
  if anyone on wait queue {
    take thread off wait queue
    Place on ready queue;
  } else {
    value = FREE;
  }
  guard = 0;
```

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

Recall: Locks using Interrupts vs. test&set

Compare to "disable interrupt" solution

```
int value = FREE;
```



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

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

Basically we replaced:

- `disable interrupts` → `while (test&set(guard));`
- `enable interrupts` → `guard = 0;`

Recap: Locks using interrupts

```
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() && Enab Ints
   } 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 using test & set

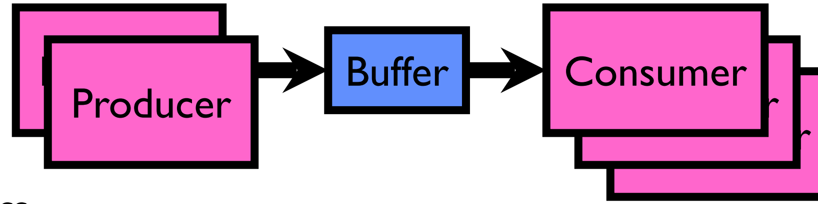
```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

```
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;
}
```

Producer-Consumer with a Bounded Buffer

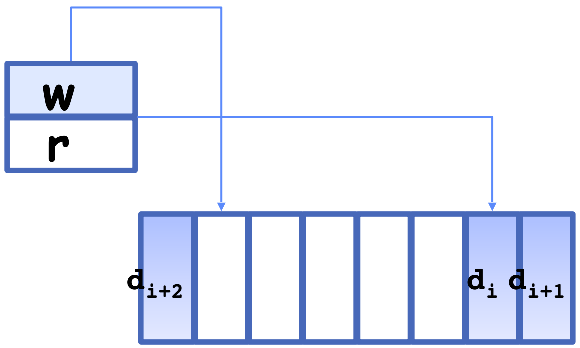


- Problem Definition
  - Producer(s) put things into a shared buffer
  - Consumer(s) take them out
  - Need synchronization to coordinate producer/consumer
- Don't want producer and consumer to have to work in lockstep, so put a fixed-size buffer between them
  - Need to synchronize access to this buffer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

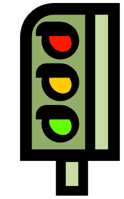
What happens when one is waiting for the other?

- Multiple cores ?
- Single core ?

Higher-level Primitives than Locks

- 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 presents some ways of structuring sharing

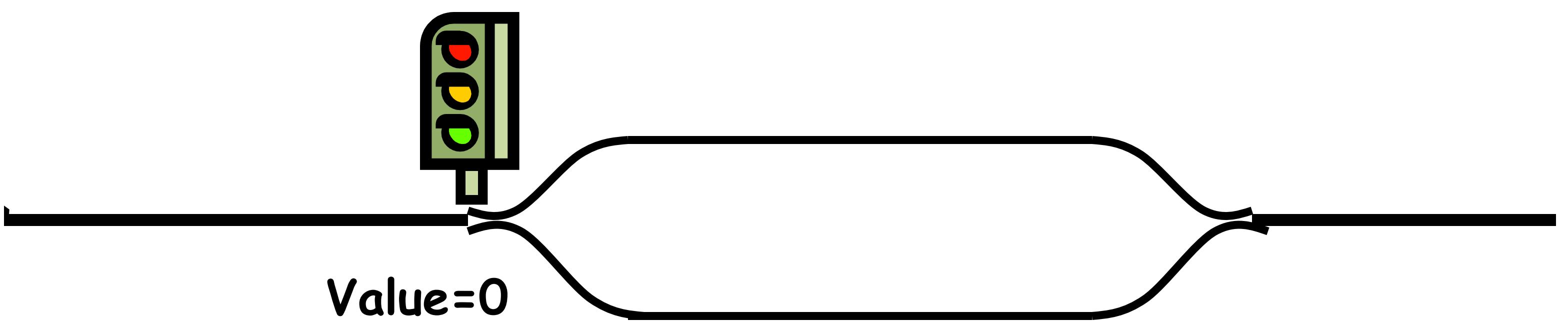
Semaphores



- 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 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
  - 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 {
            semaphore.P();
        }
        ThreadFinish {
            semaphore.V();
        }
```

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

```
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: **emptyBuffer.P(), fullBuffer.V()**
  - Consumer does: **fullBuffer.P(), emptyBuffer.V()**

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) {
    mutex.P();
    emptySlots.P();
    Enqueue(item);
    mutex.V();
    fullSlots.V();
}
Consumer() {
    fullSlots.P();
    mutex.P();
    item = Dequeue();
    mutex.V();
    emptySlots.V();
    return item;
}
```

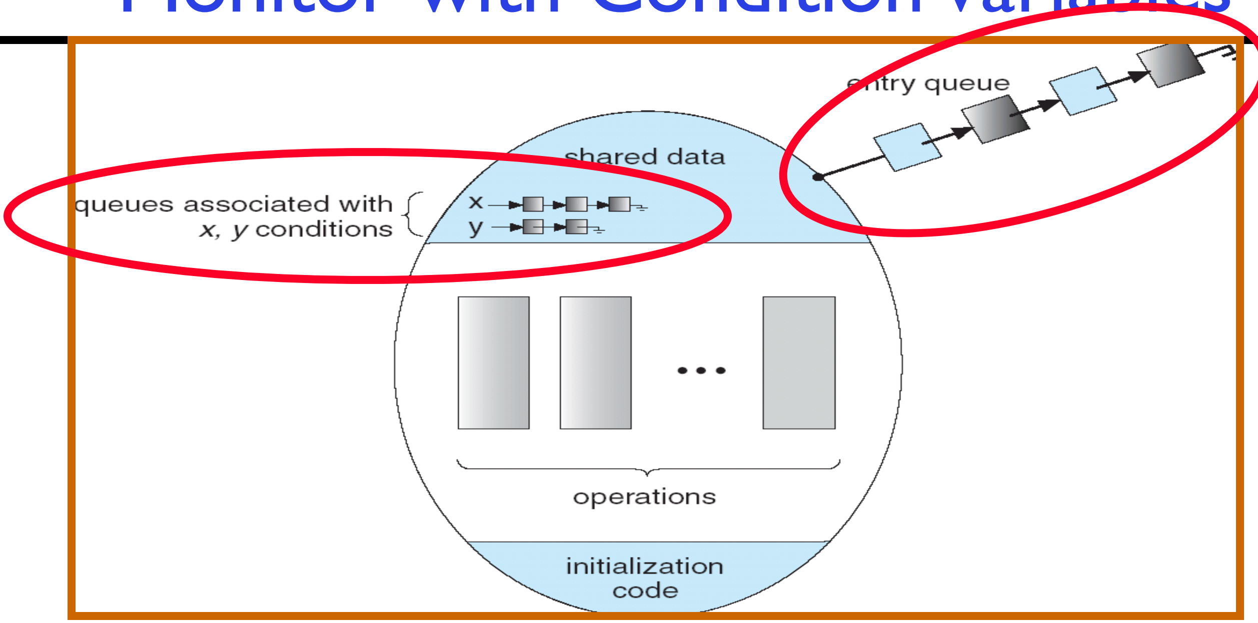
Semaphores are good but…Monitors are better!

- Semaphores are a huge step up; just think of trying to do the bounded buffer with only loads and stores
- 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;

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
}
```

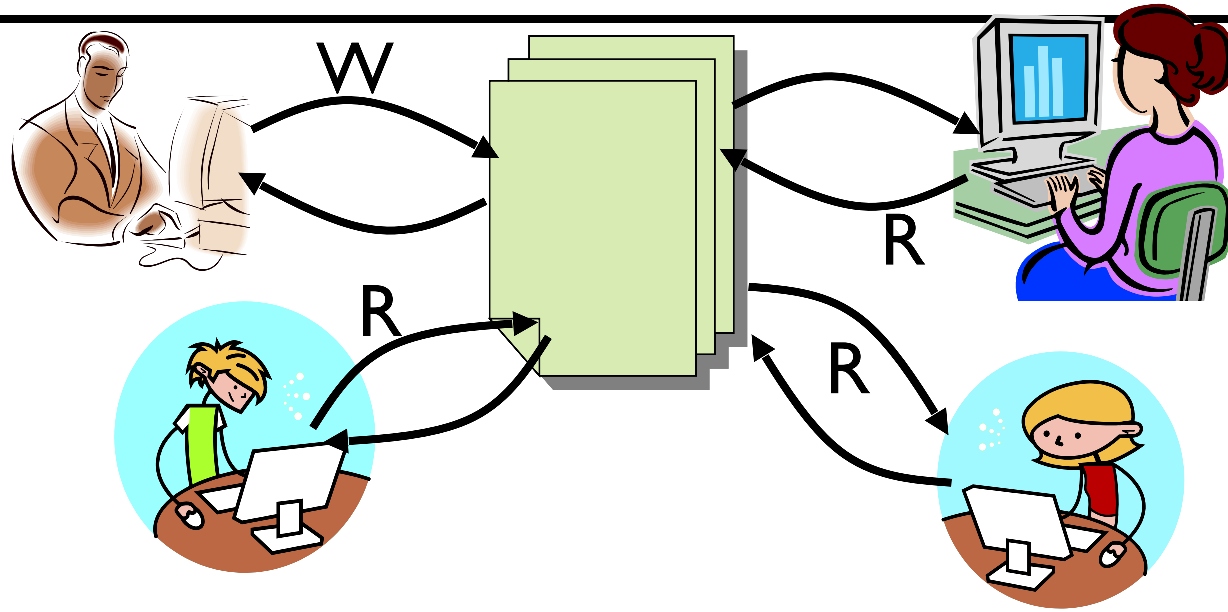
What does thread do when it is waiting?

- 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

Readers/Writers Problem



- Motivation: Consider a shared database
  - Two classes of users:
    - » Readers – never modify database
    - » Writers – read and modify database
  - Is using a single lock on the whole database sufficient?
    - » Like to have many readers at the same time
    - » Only one writer at a time

Basic Readers/Writers Solution

- Correctness Constraints:
  - Readers can access database when no writers
  - Writers can access database when no readers or writers
  - Only one thread manipulates state variables at a time
- Basic structure of a solution:
  - **`Reader()`**
    ```
    Wait until no writers
    Access data base
    Check out – wake up a waiting writer
    ```
  - **`Writer()`**
    ```
    Wait until no active readers or writers
    Access database
    Check out – wake up waiting readers or writer
    ```
  - State variables (Protected by a lock called "lock"):
    - » int AR: Number of active readers; initially = 0
    - » int WR: Number of waiting readers; initially = 0
    - » int AW: Number of active writers; initially = 0
    - » int WW: Number of waiting writers; initially = 0
    - » Condition okToRead = NIL
    - » Condition okToWrite = NIL

Code for a Reader

```
Reader() {
  // First check self into system
  lock.Acquire();
  while ((AW + WW) > 0) { // Is it safe to read?
    WR++;                 // No. Writers exist
    okToRead.wait(&lock); // Sleep on cond var
    WR--;                 // No longer waiting
  }
  AR++;                   // Now we are active!
  lock.release();
  // Perform actual read-only access
  AccessDatabase(ReadOnly);
  // Now, check out of system
  lock.Acquire();
  AR--;                   // No longer active
  if (AR == 0 && WW > 0)  // No other active readers
    okToWrite.signal();   // Wake up one writer
  lock.Release();
}
```

Code for a Writer

```
Writer() {
  // First check self into system
  lock.Acquire();
  while ((AW + AR) > 0) { // Is it safe to write?
    WW++;                 // No. Active users exist
    okToWrite.wait(&lock);  // Sleep on cond var
    WW--;                 // No longer waiting
  }
  AW++;                   // Now we are active!
  lock.release();
  // Perform actual read/write access
  AccessDatabase(ReadWrite);
  // Now, check out of system
  lock.Acquire();
  AW--;                   // No longer active
  if (WW > 0){            // Give priority to writers
    okToWrite.signal();   // Wake up one writer
  } else if (WR > 0) {    // Otherwise, wake reader
    okToRead.broadcast(); // Wake all readers
  }
  lock.Release();
}
```

Simulation of Readers/Writers Solution

- Use an example to simulate the solution
- Consider the following sequence of operators:
  - R1, R2, W1, R3
- Initially: AR = 0, WR = 0, AW = 0, WW = 0

Simulation of Readers/Writers Solution

- R1 comes along (no waiting threads)
- AR = 0, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock)
    while ((AW + WW) > 0) { // Is it safe to read?
       WR++;                // No. Writers exist
       cond_wait(&okToRead,&lock);// Sleep on cond var
       WR--;                // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
       cond_signal(&okToWrite);
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- R1 comes along (no waiting threads)
- AR = 0, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 comes along (no waiting threads)
- AR = 1, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 comes along (no waiting threads)
- AR = 1, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 accessing dbase (no other threads)
- AR = 1, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R2 comes along (R1 accessing dbase)
- AR = 1, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
       WR++;                // No. Writers exist
       cond_wait(&okToRead,&lock);// Sleep on cond var
       WR--;                // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
       cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R2 comes along (R1 accessing dbase)
- AR = 1, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
        WR++;                // No. Writers exist
        cond_wait(&okToRead,&lock);// Sleep on cond var
        WR--;                // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
        cond_signal(&okToWrite);
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- R2 comes along (R1 accessing dbase)
- AR = 2, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R2 comes along (R1 accessing dbase)
- AR = 2, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- R1 and R2 accessing dbase
- AR = 2, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
}
```

Assume readers take a while to access database
Situation: Locks released, only AR is non-zero

Simulation of Readers/Writers Solution

- W1 comes along (R1 and R2 are still accessing dbase)
- AR = 2, WR = 0, AW = 0, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {   // Is it safe to write?
      WW++;                   // No. Active users exist
      cond_wait(&okToWrite,&lock);// Sleep on cond var
      WW--;                   // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
      cond_signal(&okToWrite);
    } else if (WR > 0) {
      cond_broadcast(&okToRead);
    }
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- W1 comes along (R1 and R2 are still accessing dbase)
- AR = 2, WR = 0, AW = 0, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {   // Is it safe to write?
        WW++;                 // No. Active users exist
        cond_wait(&okToWrite,&lock);// Sleep on cond var
        WW--;                 // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
        cond_signal(&okToWrite);
    } else if (WR > 0) {
        cond_broadcast(&okToRead);
    }
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- W1 comes along (R1 and R2 are still accessing dbase)
- AR = 2, WR = 0, AW = 0, WW = 1

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {  // Is it safe to write?
        WW++;                // No. Active users exist
        cond_wait(&okToWrite,&lock);// Sleep on cond var
        WW--;                // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
        cond_signal(&okToWrite);
    } else if (WR > 0) {
        cond_broadcast(&okToRead);
    }
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- R3 comes along (R1 and R2 accessing dbase, W1 waiting)
- AR = 2, WR = 0, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
        WR++;                // No. Writers exist
        cond_wait(&okToRead,&lock);// Sleep on cond var
        WR--;                // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
        cond_signal(&okToWrite);
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- R3 comes along (R1 and R2 accessing dbase, W1 waiting)
- AR = 2, WR = 0, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R3 comes along (R1 and R2 accessing dbase, W1 waiting)
- AR = 2, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
        WR++;                 // No. Writers exist
        cond_wait(&okToRead,&lock);// Sleep on cond var
        WR--;                 // No longer waiting
    }
    AR++;                     // Now we are active!
    lock.release();

    AccessDBase(ReadOnly);

    lock.Acquire();
    AR--;
    if (AR == 0 && WW > 0)
        okToWrite.signal();
    lock.Release();
}
```

Simulation of Readers/Writers Solution

- R3 comes along (R1, R2 accessing dbase, W1 waiting)
- AR = 2, WR = 1, AW = 0, WW = 1

```
Reader() {
    lock.Acquire();
    while ((AW + WW) > 0) {    // Is it safe to read?
      WR++;                     // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                     // No longer waiting
    }
    AR++;                       // Now we are active!
    lock.release();

    AccessDBase(ReadOnly);

    lock.Acquire();
    AR--;
    if (AR == 0 && WW > 0)
      okToWrite.signal();
    lock.Release();
  }
```

Simulation of Readers/Writers Solution

- R1 and R2 accessing dbase, W1 and R3 waiting
- AR = 2, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
```

Status:

- R1 and R2 still reading
- W1 and R3 waiting on okToWrite and okToRead, respectively

Simulation of Readers/Writers Solution

- R2 finishes (R1 accessing dbase, W1 and R3 waiting)
- AR = 2, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R2 finishes (R1 accessing dbase, W1 and R3 waiting)
- AR = 1, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R2 finishes (R1 accessing dbase, W1 and R3 waiting)
- AR = 1, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
       WR++;                 // No. Writers exist
       cond_wait(&okToRead,&lock);// Sleep on cond var
       WR--;                 // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
       cond_signal(&okToWrite);
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- R2 finishes (R1 accessing dbase, W1 and R3 waiting)
- AR = 1, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 finishes (W1 and R3 waiting)
- AR = 1, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 finishes (W1, R3 waiting)
- AR = 0, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {   // Is it safe to read?
      WR++;                    // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                    // No longer waiting
    }
    AR++;                      // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 finishes (W1, R3 waiting)
- AR = 0, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 signals a writer (W1 and R3 waiting)
- AR = 0, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    lock.Release();
}
```

Simulation of Readers/Writers Solution

- W1 gets signal (R3 still waiting)
- AR = 0, WR = 1, AW = 0, WW = 1

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {  // Is it safe to write?
      WW++;                   // No. Active users exist
      cond_wait(&okToWrite,&lock);// Sleep on cond var
      WW--;                   // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
      cond_signal(&okToWrite);
    } else if (WR > 0) {
      cond_broadcast(&okToRead);
    }
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- W1 gets signal (R3 still waiting)
- AR = 0, WR = 1, AW = 0, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {  // Is it safe to write?
        WW++;                // No. Active users exist
        cond_wait(&okToWrite,&lock);// Sleep on cond var
        WW--;                // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
        cond_signal(&okToWrite);
    } else if (WR > 0) {
        cond_broadcast(&okToRead);
    }
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- W1 gets signal (R3 still waiting)
- AR = 0, WR = 1, AW = 1, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {  // Is it safe to write?
        WW++;                // No. Active users exist
        cond_wait(&okToWrite,&lock);// Sleep on cond var
        WW--;                // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
        cond_signal(&okToWrite);
    } else if (WR > 0) {
        cond_broadcast(&okToRead);
    }
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- W1 accessing dbase (R3 still waiting)
- AR = 0, WR = 1, AW = 1, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {  // Is it safe to write?
       WW++;                 // No. Active users exist
       cond_wait(&okToWrite,&lock);// Sleep on cond var
       WW--;                 // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
       cond_signal(&okToWrite);
    } else if (WR > 0) {
       cond_broadcast(&okToRead);
    }
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- W1 finishes (R3 still waiting)
- AR = 0, WR = 1, AW = 1, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {   // Is it safe to write?
        WW++;                 // No. Active users exist
        okToWrite.wait(&lock);// Sleep on cond var
        WW--;                 // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
        cond_signal(&okToWrite);
    } else if (WR > 0) {
        cond_broadcast(&okToRead);
    }
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- W1 finishes (R3 still waiting)
- AR = 0, WR = 1, AW = 0, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {  // Is it safe to write?
        WW++;                // No. Active users exist
        okToWrite.wait(&lock);// Sleep on cond var
        WW--;                // No longer waiting
    }
    AW++;
    release(&);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
        cond_signal(&okToWrite);
    } else if (WR > 0) {
        cond_broadcast(&okToRead);
    }
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- W1 finishes (R3 still waiting)
- AR = 0, WR = 1, AW = 0, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {  // Is it safe to write?
      WW++;                  // No. Active users exist
      cond_wait(&okToWrite,&lock);// Sleep on cond var
      WW--;                  // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
      cond_signal(&okToWrite);
    } else if (WR > 0) {
      cond_broadcast(&okToRead);
    }
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- W1 signaling readers (R3 still waiting)
- AR = 0, WR = 1, AW = 0, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {  // Is it safe to write?
      WW++;                  // No. Active users exist
      cond_wait(&okToWrite,&lock);// Sleep on cond var
      WW--;                  // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
      cond_signal(&okToWrite);
    } else if (WR > 0) {
      cond_broadcast(&okToRead);
    }
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R3 gets signal (no waiting threads)
- AR = 0, WR = 1, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R3 gets signal (no waiting threads)
- AR = 0, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
      WR++;                   // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                   // No longer waiting
    }
    AR++;                     // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R3 accessing dbase (no waiting threads)
- AR = 1, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
        WR++;                 // No. Writers exist
        cond_wait(&okToRead,&lock);// Sleep on cond var
        WR--;                 // No longer waiting
    }
    AR++;                     // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
        cond_signal(&okToWrite);
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- R3 finishes (no waiting threads)
- AR = 1, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R3 finishes (no waiting threads)
- AR = 0, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDbase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Questions

- Can readers starve? Consider Reader() entry code:

```
while ((AW + WW) > 0) { // Is it safe to read?
  WR++;                 // No. Writers exist

cond_wait(&okToRead,&lock);// Sleep on cond var
  WR--;                 // No longer waiting
  }
AR++;                   // Now we are active!
```

- What if we erase the condition check in Reader exit?

```
AR--;                   // No longer active
if (AR == 0 && WW > 0)  // No other active readers
  cond_signal(&okToWrite);// Wake up one writer
```

- Further, what if we turn the signal() into broadcast()

```
AR--;                   // No longer active
cond_broadcast(&okToWrite); // Wake up sleepers
```

- Finally, what if we use only one condition variable (call it "**okContinue**") instead of two separate ones?
  - Both readers and writers sleep on this variable
  - Must use broadcast() instead of signal()

Use of Single CV: okContinue

```
Reader() {
    // check into system
    acquire(&lock);
    while ((AW + WW) > 0) {
        WR++;
        cond_wait(&okContinue);
        WR--;
    }
    AR++;
    release(&lock);

    // read-only access
    AccessDbase(ReadOnly);

    // check out of system
    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
        cond_signal(&okContinue);
    release(&lock);
}
```

```
Writer() {
    // check into system
    acquire(&lock);
    while ((AW + AR) > 0) {
        WW++;
        cond_wait(&okContinue);
        WW--;
    }
    AW++;
    release(&lock);

    // read/write access
    AccessDbase(ReadWrite);

    // check out of system
    acquire(&lock);
    AW--;
    if (WW > 0){
        cond_signal(&okContinue);
    } else if (WR > 0) {
        cond_broadcast(&okContinue);
    }
    release(&lock);
}
```

What if we turn `okToWrite` and `okToRead` into `okContinue`
(i.e. use only one condition variable instead of two)?

Use of Single CV: okContinue

```
Reader() {
    // check into system
    acquire(&lock);
    while ((AW + WW) > 0) {
        WR++;
        cond_wait(&okContinue);
        WR--;
    }
    AR++;
    release(&lock);

    // read-only access
    AccessDbase(ReadOnly);

    // check out of system
    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
        cond_signal(&okContinue);
    release(&lock);
}
```

```
Writer() {
    // check into system
    acquire(&lock);
    while ((AW + AR) > 0) {
        WW++;
        cond_wait(&okContinue);
        WW--;
    }
    AW++;
    release(&lock);

    // read/write access
    AccessDbase(ReadWrite);

    // check out of system
    acquire(&lock);
    AW--;
    if (WW > 0){
        cond_signal(&okContinue);
    } else if (WR > 0) {
        cond_broadcast(&okContinue);
    }
    release(&lock);
}
```

Consider this scenario:
- **R1 arrives**
- **W1, R2 arrive while R1 still reading → W1 and R2 wait for R1 to finish**
- **Assume R1's signal is delivered to R2 (not W1)**

Use of Single CV: okContinue

```
Reader() {
    // check into system
    acquire(&lock);
    while ((AW + WW) > 0) {
        WR++;
        okContinue.wait(&lock);
        WR--;
    }
    AR++;
    release(&lock);

    // read-only access
    AccessDbase(ReadOnly);

    // check out of system
    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
        okContinue.broadcast();
    release(&lock);
}
```

```
Writer() {
    // check into system
    acquire(&lock);
    while ((AW + AR) > 0) {
        WW++;
        okContinue.wait(&lock);
        WW--;
    }
    AW++;
    release(&lock);

    // read/write access
    AccessDbase(ReadWrite);

    // check out of system
    acquire(&lock);
    AW--;
    if (WW > 0 || WR > 0){
        okContinue.broadcast();
    }
    release(&lock);
}
```

Need to change to broadcast()!

Must broadcast() to sort things out!

Can we construct Monitors from Semaphores?

- Locking aspect is easy: Just use a mutex
- Can we implement condition variables this way?

```
Wait()   { semaphore.P(); }
Signal() { semaphore.V(); }
```

- Does this work better?

```
Wait(Lock lock) {
  lock.Release();
  semaphore.P();
  lock.Acquire();
}
Signal() { semaphore.V(); }
```

  – No: Condition vars have no history, semaphores have history:
    » What if thread signals and no one is waiting?
    » What if thread later waits?
    » What if thread V's and no one is waiting?
    » What if thread later does P?

Construction of Monitors from Semaphores (con't)

- Problem with previous try:
  - P and V are commutative – result is the same no matter what order they occur
  - Condition variables are NOT commutative
- Does this fix the problem?

```
    Wait(Lock lock) {
      lock.Release();
      semaphore.P();
      lock.Acquire();
  }
  Signal() {
      if semaphore queue is not empty
         semaphore.V();
  }
```

  - Not legal to look at contents of semaphore queue
  - There is a race condition – signaler can slip in after lock release and before waiter executes semaphore.P()
- It is actually possible to do this correctly
  - Complex solution for Hoare scheduling in book

Monitor Conclusion

- Monitors represent the logic of the program
  - Wait if necessary
  - Signal when change something so any waiting threads can proceed
- Basic structure of monitor-based program:

```
 lock
while (need to wait) {
    condvar.wait();
}
unlock
```

Check and/or update state variables
Wait if necessary

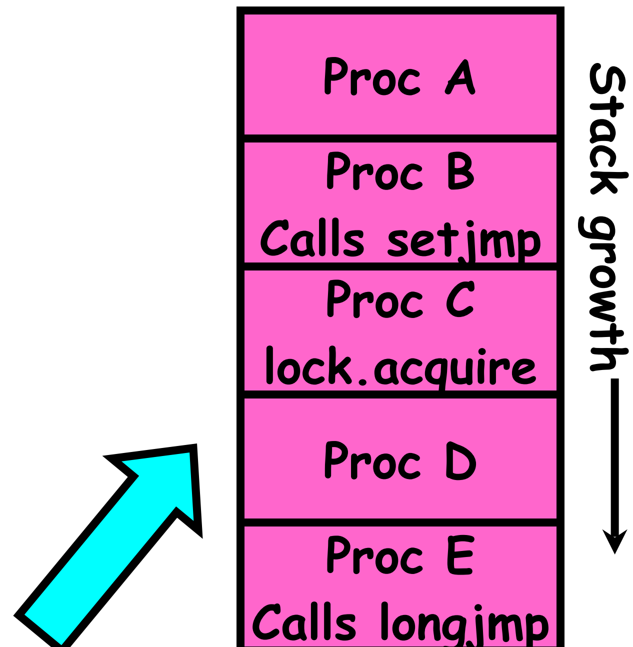
```
do something so no need to wait

lock

  condvar.signal();

unlock
```

Check and/or update state variables

C-Language Support for Synchronization

- C language: Pretty straightforward synchronization
  - Just make sure you know *all* the code paths out of a critical section

```
int Rtn() {
      lock.acquire();
      …
      if (exception) {
          lock.release();
          return errReturnCode;
      }
      …
      lock.release();
      return OK;
}
```



  - Watch out for `setjmp/longjmp`!
    - » Can cause a non-local jump out of procedure
    - » In example, procedure E calls longjmp, poping stack back to procedure B
    - » If Procedure C had lock.acquire, problem!

C++ Language Support for Synchronization

- Languages with exceptions like C++
  - Languages that support exceptions are problematic (easy to make a non-local exit without releasing lock)
  - Consider:

```
        void Rtn() {
          lock.acquire();
          …
          DoFoo();
          …
          lock.release();
        }
        void DoFoo() {
          …
          if (exception) throw errException;
          …
        }
```

  - Notice that an exception in DoFoo() will exit without releasing the lock!

C++ Language Support for Synchronization (con't)

- Must catch all exceptions in critical sections
  - Catch exceptions, release lock, and re-throw exception:

```
void Rtn() {
   lock.acquire();
   try {
      …
      DoFoo();
      …
   } catch (…) {       // catch exception
      lock.release(); // release lock
      throw;          // re-throw the exception
   }
   lock.release();
}
void DoFoo() {
   …
   if (exception) throw errException;
   …
}
```

  - Even Better: auto_ptr<T> facility. See C++ Spec.
    - » Can deallocate/free lock regardless of exit method

Java Language Support for Synchronization

- Java has explicit support for threads and thread synchronization
- Bank Account example:

```
class Account {
   private int balance;
   // object constructor
   public Account (int initialBalance) {
      balance = initialBalance;
   }
   public synchronized int getBalance() {
      return balance;
   }
   public synchronized void deposit(int amount) {
      balance += amount;
   }
}
```

  – Every object has an associated lock which gets automatically acquired and released on entry and exit from a *synchronized* method.

Java Language Support for Synchronization (con't)

- Java also has *synchronized* statements:

```
synchronized (object) {
      …
}
```

  – Since every Java object has an associated lock, this type of statement acquires and releases the object's lock on entry and exit of the body
  – Works properly even with exceptions:

```
   synchronized (object) {
   …
   DoFoo();
   …
}
void DoFoo() {
   throw errException;
}
```

Java Language Support for Synchronization (con't 2)

- In addition to a lock, every object has a single condition variable associated with it
  - How to wait inside a synchronization method of block:
    - `void wait(long timeout); // Wait for timeout`
    - `void wait(long timeout, int nanoseconds); //variant`
    - `void wait();`
  - How to signal in a synchronized method or block:
    - `void notify();    // wakes up oldest waiter`
    - `void notifyAll(); // like broadcast, wakes everyone`
  - Condition variables can wait for a bounded length of time. This is useful for handling exception cases:

```
   t1 = time.now();
while (!ATMRequest()) {
   wait (CHECKPERIOD);
   t2 = time.new();
   if (t2 – t1 > LONG_TIME) checkMachine();
}
```

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

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