CS162
Operating Systems and Systems Programming
Lecture 9

Synchronization (Con't)
Monitors and Readers/Writers example

February 19th, 2019

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Recall: Implement Locks by Disabling Interrupts

- Key idea: maintain a lock variable and impose mutual exclusion only during operations on that variable

```
int mylock = FREE;
Acquire(&mylock) - wait until lock is free, then grab
Release(&mylock) - Unlock, waking up anyone waiting
```

```
Acquire(int *lock) {
   disable interrupts;
   if (*lock == BUSY) {
      put thread on wait queue;
      Go to sleep() && Enab ints!
      // Ints disabled on wakeup
   } else {
      *lock = BUSY;
   }
   enable interrupts;
}
```

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

- Really only works in kernel – why?

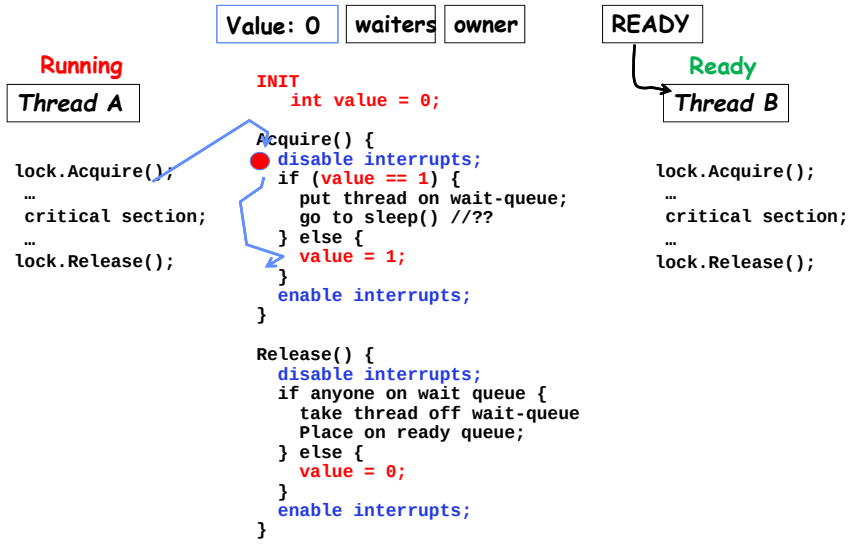
Recall: Two Implementations for T&S Lock

```
int guard = 0;
int mylock = FREE;
Acquire_Ver1() {
   // Short busy-wait time
   while (test&set(guard));
   if (mylock == BUSY) {
      put thread on wait queue;
      go to sleep() & guard = 0;
      // guard == 0 on wakeup!
   } else {
      mylock = BUSY;
      guard = 0; // Only success
   }
}
```

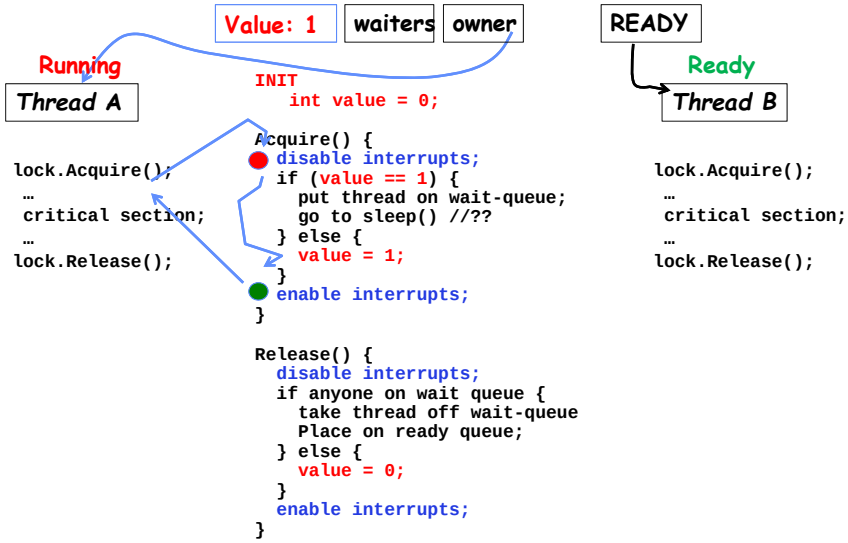
```
Acquire_Ver2() {
   // Short busy-wait time
   while (test&set(guard));
   if (mylock == BUSY) {
      put thread on wait queue;
      go to sleep() & guard = 0;
      // guard == 1 on wakeup!
   } else {
      mylock = BUSY;
   }
   guard = 0; // Success or fail!
}
```

- Brief busy-wait only to protect lock implementation
  - Note: sleep has to be sure to reset the guard variable
- Must understand value of guard on exiting sleep
  - Post – sleep guard value must be specified!
  - Only `Acquire_Ver2()` parallel to "disable interrupts" case!

In-Kernel Lock: Simulation



In-Kernel Lock: Simulation



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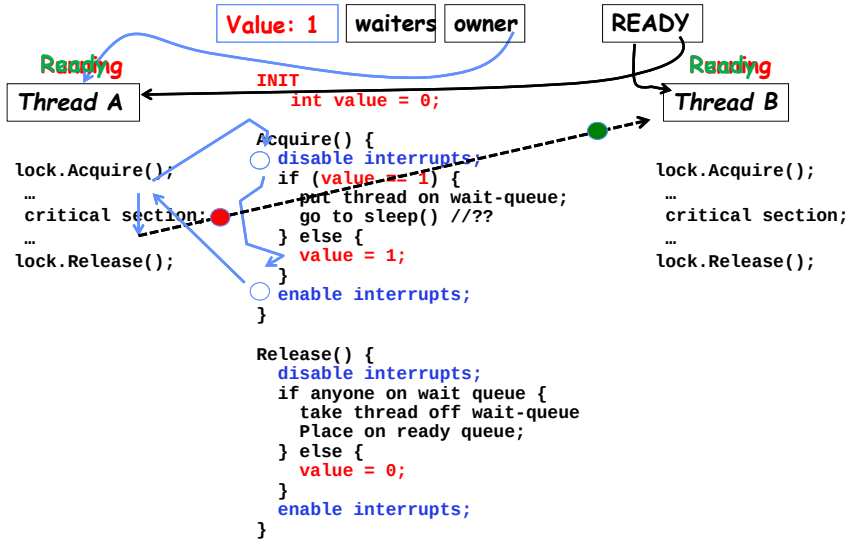
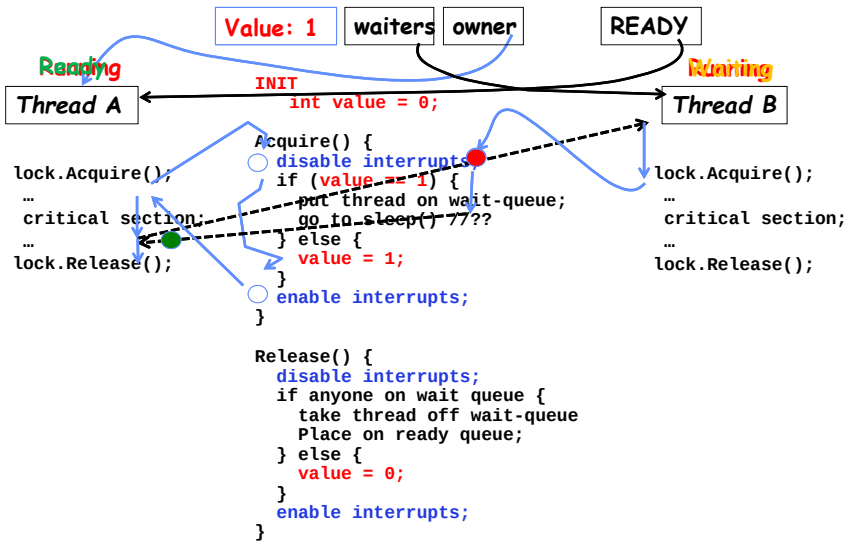


In-Kernel Lock: Simulation



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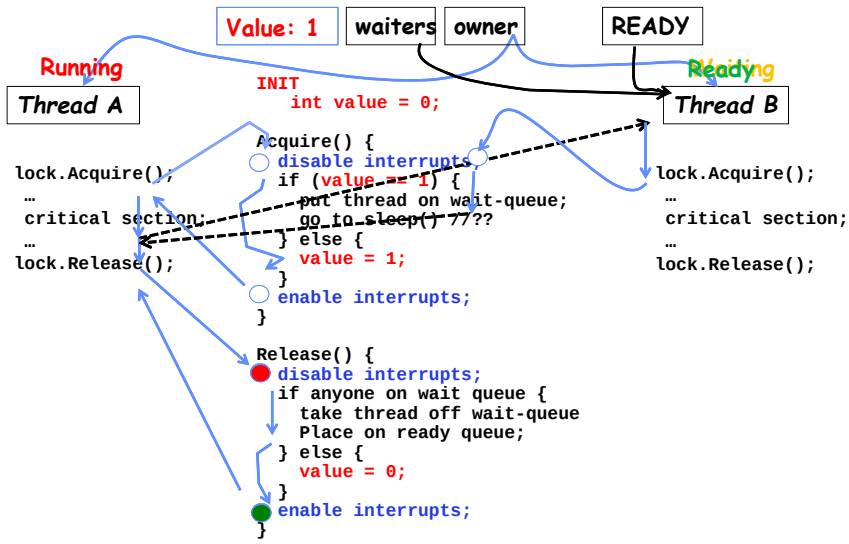
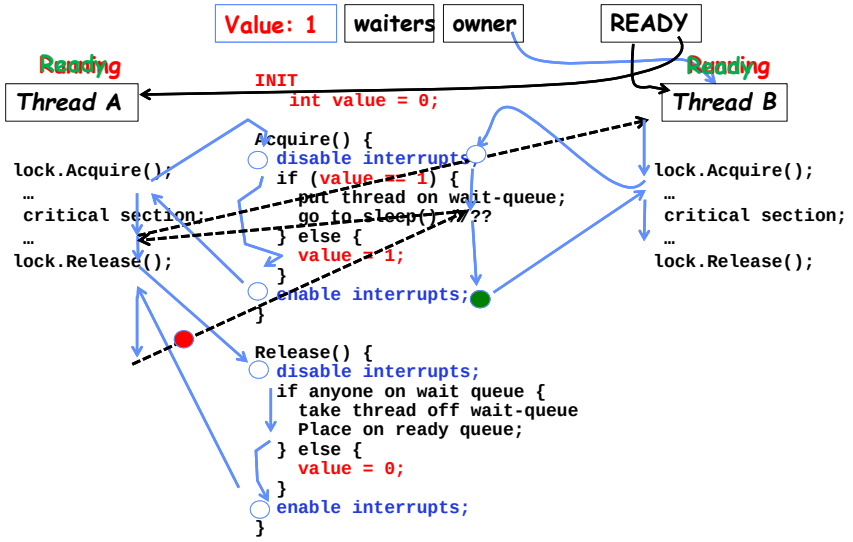
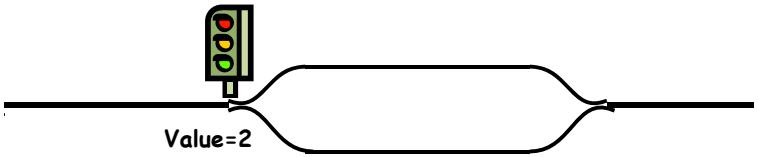


In-Kernel Lock: Simulation



Review: Semaphores

- 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
  - Only time can set integer directly is at initialization time
- Semaphore from railway analogy
  - Here is a semaphore initialized to 2 for resource control:



Review: 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;
}
```

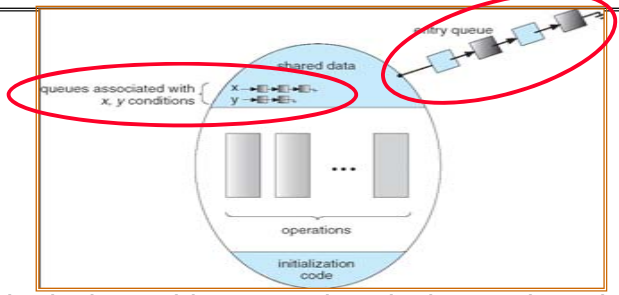

Review: Discussion about Solution

- Why asymmetry?
  - Producer does: `emptyBuffer.P(), fullBuffer.V()`
  - Consumer does: `fullBuffer.P(), emptyBuffer.V()`
- Is order of P's important?
  - Yes! Can cause deadlock
- Is order of V's important?
  - No, except that it might affect scheduling efficiency
- What if we have 2 producers or 2 consumers?
  - Still Works fine…

Motivation for Monitors and Condition Variables

- Semaphores are a huge step up; just think of trying to do the bounded buffer with only loads and stores
  - Problem is that semaphores are dual purpose:
    - » They are used for both mutex and scheduling constraints
    - » Example: the fact that flipping of P's in bounded buffer gives deadlock is not immediately obvious. How do you prove correctness to someone?
- Cleaner idea: Use *locks* for mutual exclusion and *condition variables* for scheduling constraints
- Definition: Monitor: a lock and zero or more condition variables for managing concurrent access to shared data
  - Some languages like Java provide this natively
  - Most others use actual locks and condition variables

Monitor with Condition Variables



- Lock: the lock provides mutual exclusion to shared data
  - Always acquire before accessing shared data structure
  - Always release after finishing with shared data
  - Lock initially free
- Condition Variable: a queue of threads waiting for something *inside* a critical section
  - Key idea: make it possible to go to sleep inside critical section by atomically releasing lock at time we go to sleep
  - Contrast to semaphores: Can't wait inside critical section

Simple Monitor Example (version 1)

- Here is an (infinite) synchronized queue

```
Lock lock;
Queue queue;

AddToQueue(item) {
   lock.Acquire();          // Lock shared data
   queue.enqueue(item);     // Add item
   lock.Release();          // Release Lock
}

RemoveFromQueue() {
   lock.Acquire();          // Lock shared data
   item = queue.dequeue();// Get next item or null
   lock.Release();          // Release Lock
   return(item);            // Might return null
}
```

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

Condition Variables

- How do we change the RemoveFromQueue() 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!
  - In Birrell paper, he says can perform signal() outside of lock – IGNORE HIM (this is only an optimization)

Complete Monitor Example (with cond. variable)

- Here is an (infinite) synchronized queue

```
Lock lock;
Condition dataready;
Queue queue;

AddToQueue(item) {
   lock.Acquire();           // Get Lock
   queue.enqueue(item);      // Add item
   dataready.signal();       // Signal any waiters
   lock.Release();           // Release Lock
}

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


Administrivia

- Project 1 Design Document
  - Due tomorrow (Wednesday, 2/20) @ 11:59PM
- Midterm on Thursday 2/28 8pm-10pm
  - Room assignments TBD
- Closed book, no calculators, one double-side letter-sized page of handwritten notes
  - Covers Lectures 1-11 (up through Deadlock), readings, homework 1, and project 1

Mesa vs. Hoare monitors

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

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

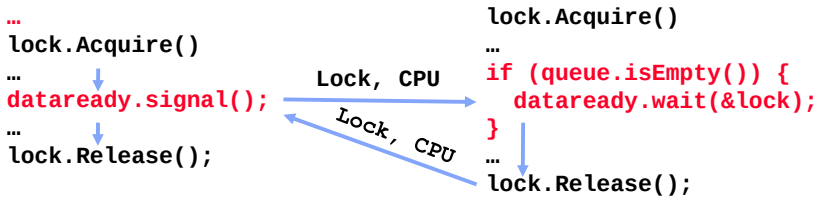
  - Why didn't we do this?

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

- Answer: depends on the type of scheduling
  - Hoare-style: Named after British logician Tony Hoare
  - Mesa-style: Named after Xerox-Park Mesa Operating System

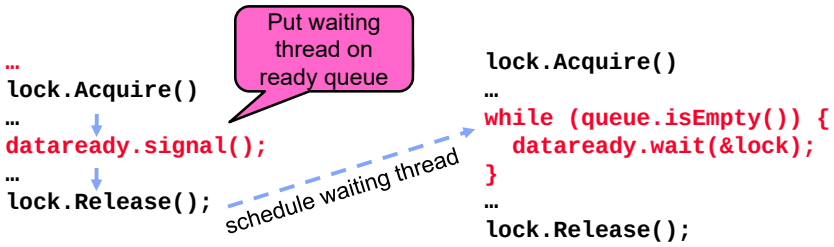
Hoare monitors

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



Mesa monitors

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



Mesa Monitor: Why "while()"?

- Why do we use "while()" instead of "if() with Mesa monitors?
  - Example illustrating what happens if we use "if()", e.g.,

```
if (queue.isEmpty()) {
  dataready.wait(&lock); // If nothing, sleep
}
```

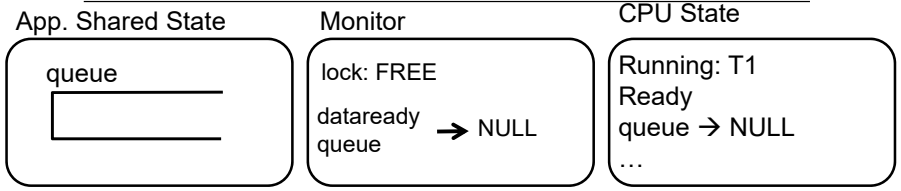
- We'll use the synchronized (infinite) queue example

```
AddToQueue(item) {
  lock.Acquire();
  queue.enqueue(item);
  dataready.signal();
  lock.Release();
}
```

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Replace "while" with "if"

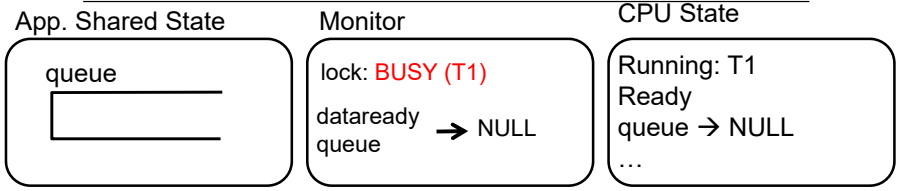
Mesa Monitor: Why "while()"?



T1 (Running)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

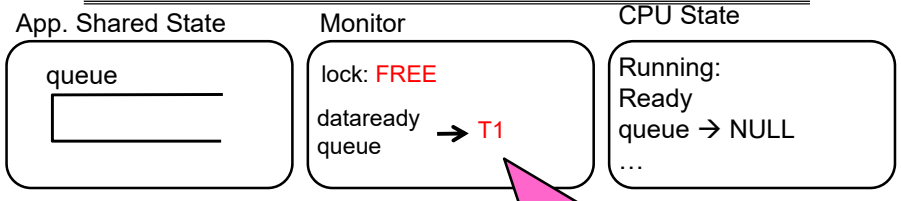

Mesa Monitor: Why "while()"?



T1 (Running)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Mesa Monitor: Why "while()"?

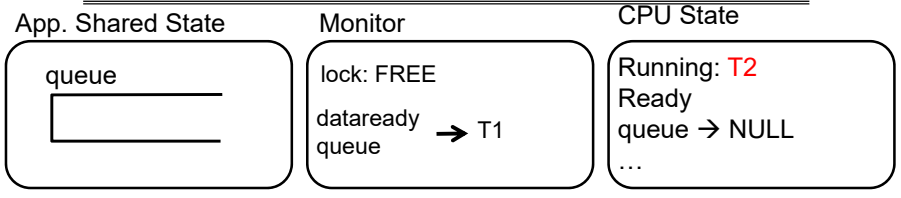


T1 (Waiting)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

wait(&lock) puts thread on dataready queue and releases lock

Mesa Monitor: Why "while()"?



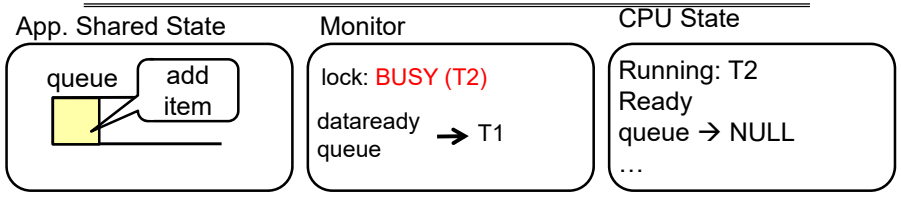
T1 (Waiting)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

T2 (Running)

```
AddToQueue(item) {
  lock.Acquire();
  queue.enqueue(item);
  dataready.signal();
  lock.Release();
}
```


Mesa Monitor: Why "while()"?



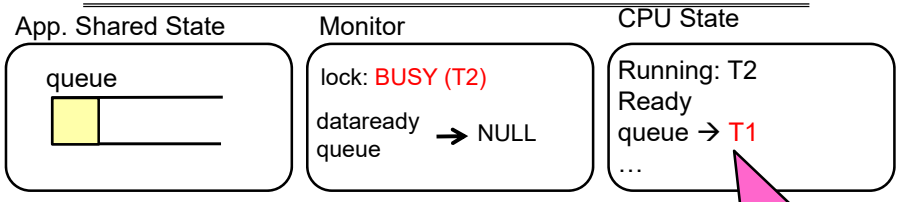
T1 (Waiting)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

T2 (Running)

```
AddToQueue(item) {
  lock.Acquire();
  queue.enqueue(item);
  dataready.signal();
  lock.Release();
}
```


Mesa Monitor: Why "while()"?



T1 (Ready)

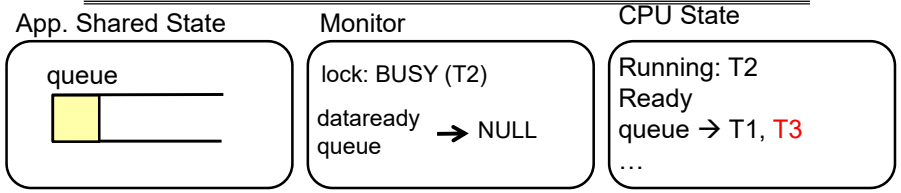
```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

T2 (Running)

```
AddToQueue(item) {
  lock.Acquire();
  queue.enqueue(item);
  dataready.signal();
  lock.Release();
}
```

signal() wakes up T1 and moves it on ready queue

Mesa Monitor: Why "while()"?



T1 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

T2 (Running)

```
AddToQueue(item) {
  lock.Acquire();
  queue.enqueue(item);
  dataready.signal();
  lock.Release();
}
```

T3 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```


Mesa Monitor: Why "while()"?

T1 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

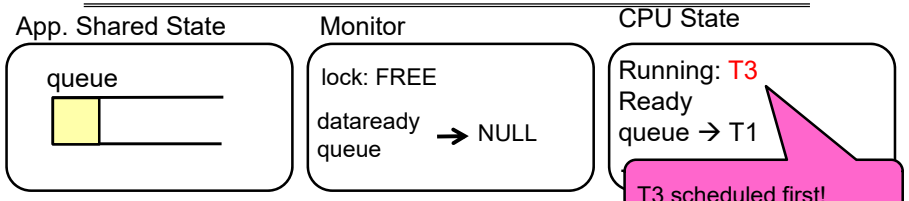
T2 (Terminate)

```
AddToQueue(item) {
  lock.Acquire();
  queue.enqueue(item);
  dataready.signal();
  lock.Release();
}
```

T3 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```


Mesa Monitor: Why "while()"?



T1 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

T3 (Running)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
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  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```
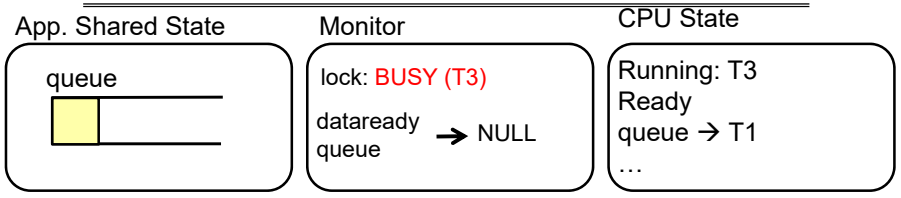


Mesa Monitor: Why "while()"?



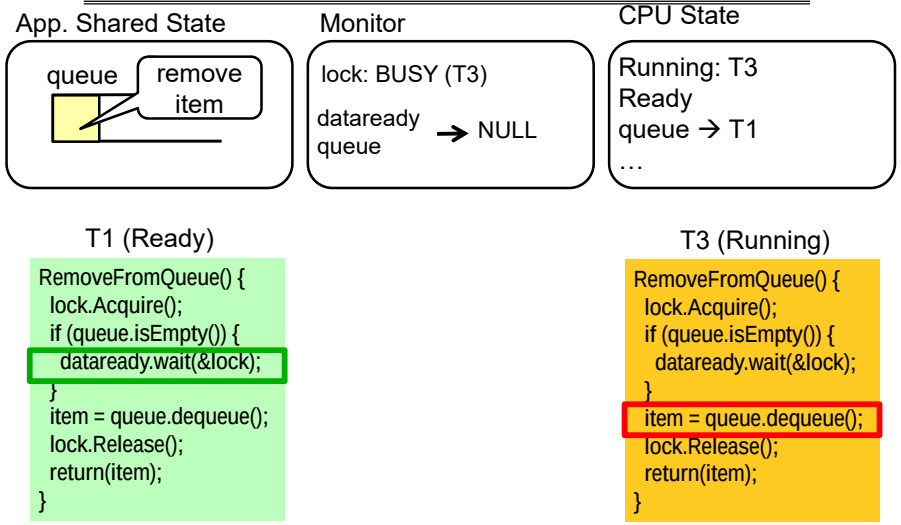
T1 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

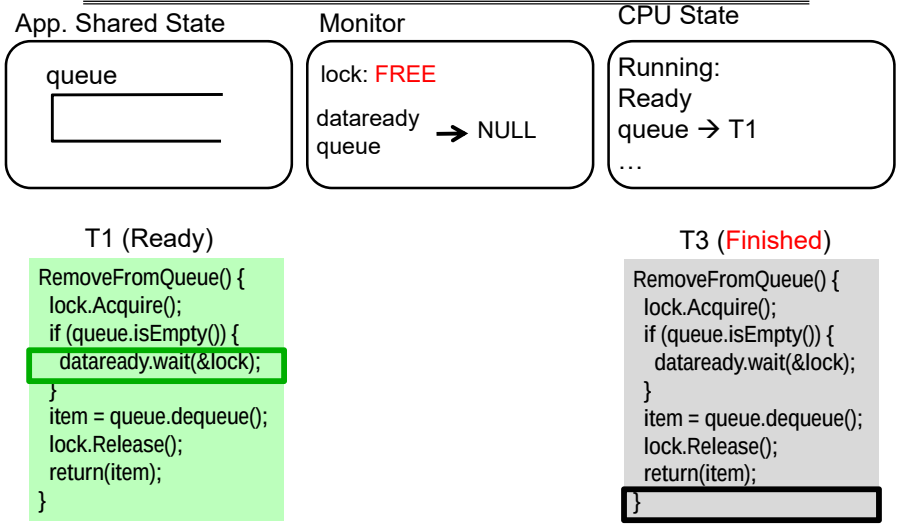
T3 (Running)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Mesa Monitor: Why "while()"?



Mesa Monitor: Why "while()"?



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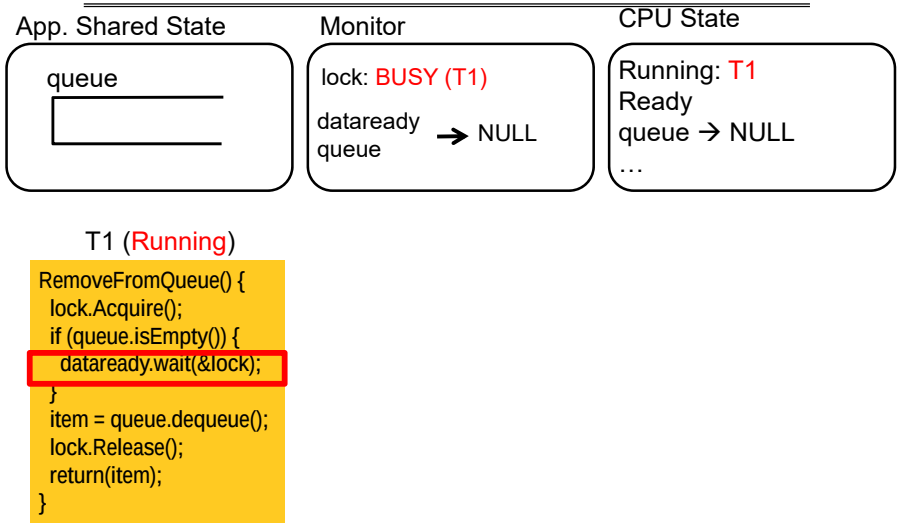
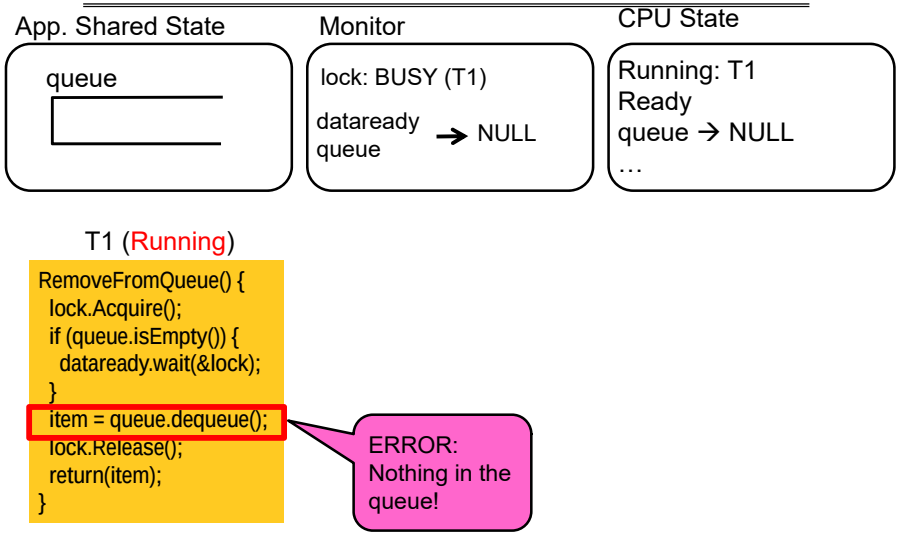


Mesa Monitor: Why "while()"?



Mesa Monitor: Why "while()"?

App. Shared State | Monitor | CPU State

queue

lock: BUSY (T1)
datareadyqueue → NULL

Running: T1
Ready
queue → NULL
…

T1 (Running)

```
RemoveFromQueue() {
  lock.Acquire();
  while (queue.isEmpty())
  {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Replace "if" with "while"

Mesa Monitor: Why "while()"?

App. Shared State | Monitor | CPU State

queue

lock: BUSY (T1)
datareadyqueue → NULL

Running: T1
Ready
queue → NULL
…

T1 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  while (queue.isEmpty())
  {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Check again: Is queue empty?

Mesa Monitor: Why "while()"?

App. Shared State | Monitor | CPU State

queue

lock: FREE
datareadyqueue → T1

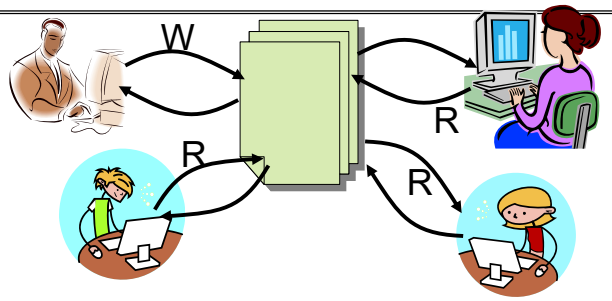
Running: T1
Ready
queue → NULL
…

T1 (Waiting)

```
RemoveFromQueue() {
  lock.Acquire();
  while (queue.isEmpty())
  {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

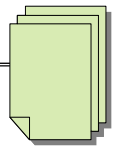
Yup! Back to Sleep

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() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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

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() {
    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++;
    lock.release();

    AccessDBase(ReadWrite);

    lock.Acquire();
    AW--;
    if (WW > 0){
      okToWrite.signal();
    } else if (WR > 0) {
      okToRead.broadcast();
    }
    lock.Release();
  }
```


Simulation of Readers/Writers Solution

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

```
Writer() {
    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++;
    lock.release();

    AccessDBase(ReadWrite);

    lock.Acquire();
    AW--;
    if (WW > 0){
      okToWrite.signal();
    } else if (WR > 0) {
      okToRead.broadcast();
    }
    lock.Release();
  }
```

Simulation of Readers/Writers Solution

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

```
Writer() {
    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++;
    lock.release();

    AccessDBase(ReadWrite);

    lock.Acquire();
    AW--;
    if (WW > 0){
      okToWrite.signal();
    } else if (WR > 0) {
      okToRead.broadcast();
    }
    lock.Release();
  }
```


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

- R3 comes along (R1 and 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
      okToRead.wait(&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
      okToRead.wait(&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() {
    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();

    AccessDBase(ReadOnly);

    lock.Acquire();
    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() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Writer() {
    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++;
    lock.release();

    AccessDBase(ReadWrite);

    lock.Acquire();
    AW--;
    if (WW > 0){
      okToWrite.signal();
    } else if (WR > 0) {
      okToRead.broadcast();
    }
    lock.Release();
  }
```


Simulation of Readers/Writers Solution

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

```
Writer() {
    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++;
    lock.release();

    AccessDBase(ReadWrite);

    lock.Acquire();
    AW--;
    if (WW > 0){
      okToWrite.signal();
    } else if (WR > 0) {
      okToRead.broadcast();
    }
    lock.Release();
  }
```

Simulation of Readers/Writers Solution

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

```
Writer() {
    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++;
    lock.release();

    AccessDBase(ReadWrite);

    lock.Acquire();
    AW--;
    if (WW > 0){
      okToWrite.signal();
    } else if (WR > 0) {
      okToRead.broadcast();
    }
    lock.Release();
  }
```


Simulation of Readers/Writers Solution

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

```
Writer() {
    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++;
    lock.release();

    AccessDBase(ReadWrite);

    lock.Acquire();
    AW--;
    if (WW > 0){
      okToWrite.signal();
    } else if (WR > 0) {
      okToRead.broadcast();
    }
    lock.Release();
  }
```


Simulation of Readers/Writers Solution

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

```
Writer() {
    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++;
    lock.release();

    AccessDBase(ReadWrite);

    lock.Acquire();
    AW--;
    if (WW > 0){
      okToWrite.signal();
    } else if (WR > 0) {
      okToRead.broadcast();
    }
    lock.Release();
  }
```


Simulation of Readers/Writers Solution

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

```
Writer() {
    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++;
    lock.release();

    AccessDBase(ReadWrite);

    lock.Acquire();
    AW--;
    if (WW > 0){
      okToWrite.signal();
    } else if (WR > 0) {
      okToRead.broadcast();
    }
    lock.Release();
  }
```

Simulation of Readers/Writers Solution

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

```
Writer() {
    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++;
    lock.release();

    AccessDBase(ReadWrite);

    lock.Acquire();
    AW--;
    if (WW > 0){
      okToWrite.signal();
    } else if (WR > 0) {
      okToRead.broadcast();
    }
    lock.Release();
  }
```


Simulation of Readers/Writers Solution

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

```
Writer() {
    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++;
    lock.release();

    AccessDBase(ReadWrite);

    lock.Acquire();
    AW--;
    if (WW > 0){
      okToWrite.signal();
    } else if (WR > 0) {
      okToRead.broadcast();
    }
    lock.Release();
  }
```


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDBase(ReadOnly);

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


Simulation of Readers/Writers Solution

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

```
Reader() {
    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();

    AccessDbase(ReadOnly);

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


Questions

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

```
    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!
```

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

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

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

```
    AR--;                    // No longer active
    okToWrite.broadcast();   // 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
    lock.Acquire();
    while ((AW + WW) > 0) {
      WR++;
      okContinue.wait(&lock);
      WR--;
    }
    AR++;
    lock.release();

    // read-only access
    AccessDbase(ReadOnly);

    // check out of system
    lock.Acquire();
    AR--;
    if (AR == 0 && WW > 0)
      okContinue.signal();
    lock.Release();
  }
```

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

    // read/write access
    AccessDbase(ReadWrite);

    // check out of system
    lock.Acquire();
    AW--;
    if (WW > 0){
      okContinue.signal();
    } else if (WR > 0) {
      okContinue.broadcast();
    }
    lock.Release();
  }
```

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
    lock.Acquire();
    while ((AW + WW) > 0) {
      WR++;
      okContinue.wait(&lock);
      WR--;
    }
    AR++;
    lock.release();

    // read-only access
    AccessDbase(ReadOnly);

    // check out of system
    lock.Acquire();
    AR--;
    if (AR == 0 && WW > 0)
      okContinue.signal();
    lock.Release();
  }
```

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

    // read/write access
    AccessDbase(ReadWrite);

    // check out of system
    lock.Acquire();
    AW--;
    if (WW > 0){
      okContinue.signal();
    } else if (WR > 0) {
      okContinue.broadcast();
    }
    lock.Release();
  }
```

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
    lock.Acquire();
    while ((AW + WW) > 0) {
      WR++;
      okContinue.wait(&lock);
      WR--;
    }
    AR++;
    lock.release();

    // read-only access
    AccessDbase(ReadOnly);

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

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

    // read/write access
    AccessDbase(ReadWrite);

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

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(); }
```

:

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
  - Can you come up with simpler Mesa-scheduled solution?

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

do something so no need to wait

lock

condvar.signal();

unlock
```

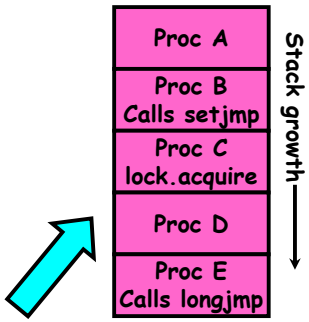
Check and/or update state variables Wait if necessary

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();
}
```

  - Not all Java VMs equivalent!
    - » Different scheduling policies, not necessarily preemptive!

Summary

- 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