CS162
Operating Systems and Systems Programming
Lecture 5

Semaphores, Conditional Variables

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Goals for Today

- Continue with Synchronization Abstractions
  - Monitors and condition variables
- Readers-Writers problem and solution
- Language Support for Synchronization

Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne. Many slides generated from lecture notes by Kubiatowicz.

Where are we going with synchronization?

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

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

Producer-consumer with a bounded buffer

- Problem Definition
  - Producer puts things into a shared buffer
  - Consumer takes them out
  - Need synchronization to coordinate producer/consumer
- Don't want producer and consumer to have to work in lockstep, so put a fixed-size buffer between them
  - Need to synchronize access to this buffer
  - Producer needs to wait if buffer is full
  - Consumer needs to wait if buffer is empty

- Example: Coke machine
  - Producer can put limited number of cokes in machine
  - Consumer can't take cokes out if machine is empty

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
  - P() stands for "*proberen*" (to test) and V() stands for "*verhogen*" (to increment) in Dutch

Correctness constraints for solution

- Correctness Constraints:
  - Consumer must wait for producer to fill slots, if empty (scheduling constraint)
  - Producer must wait for consumer to make room in buffer, if all full (scheduling constraint)
  - Only one thread can manipulate buffer queue at a time (mutual exclusion)
- General rule of thumb:
  Use a separate semaphore for each constraint
  - `Semaphore fullSlots; // consumer's constraint`
  - `Semaphore emptySlots;// producer's constraint`
  - `Semaphore mutex;  // mutual exclusion`

Full Solution to Bounded Buffer

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

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


Discussion about Solution

- Why asymmetry?
  - Producer does: `emptySlots.P(), fullSlots.V()`
  - Consumer does: `fullSlots.P(), emptySlots.V()`

  Decrease # of empty slots

  Increase # of occupied slots
- Is order of P's important?

  Decrease # of occupied slots

  Increase # of empty slots
- Is order of V's important?
- What if we have 2 producers or 2 consumers?
  - Do we need to change anything?

Solution for Bounded Buffer using Locks only

```
int fullSlots = 0;            // Initially, no coke
Lock lock = free;             // No one using machine

Producer(item) {
    lock.Acquire();
   if (fullSlots == bufSize) {
      lock.Release();
      return false;}       // No room for coke
   Enqueue(item);          // add new coke
   fullSlots++;
   lock.Release();
   return true;
}
Consumer() {
   lock.Acquire();
   if (fullSlots == 0) {
       lock.Release();
       return null;}         // no coke
    item = Dequeue();        // get coke
    fullSlots--;
    lock.Release();
    return item;
}
```

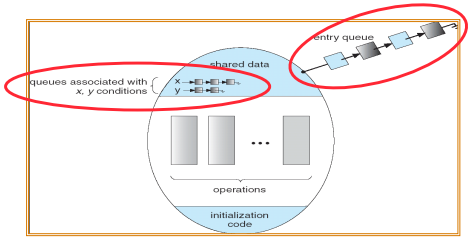

Motivation for Monitors and Condition Variables

- Semaphores are a huge step up; just think of trying to do the bounded buffer with only loads and stores
- Problem is that semaphores are dual purpose:
  - They are used for both mutex and scheduling constraints
  - Example: the fact that flipping of P's in bounded buffer gives deadlock is not immediately obvious. How do you prove correctness to someone?

Motivation for Monitors and Condition Variables

- Cleaner idea: Use *locks* for mutual exclusion and *condition variables* for scheduling constraints
- Monitor: a lock and zero or more condition variables for managing concurrent access to shared data
  - Some languages like Java provide this natively
  - Most others use actual locks and condition variables

Monitor with Condition Variables



- Lock: the lock provides mutual exclusion to shared data
  - Always acquire before accessing shared data structure
  - Always release after finishing with shared data
  - Lock initially free
- Condition Variable: a queue of threads waiting for something *inside* a critical section
  - Key idea: make it possible to go to sleep inside critical section by atomically releasing lock at time we go to sleep

Simple Monitor Example

- Here is an (infinite) synchronized queue

```
Lock lock;
Queue queue;

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

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

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

Condition Variables

- Condition Variable: a queue of threads waiting for something *inside* a critical section
  - Key idea: allow sleeping inside critical section by atomically releasing lock at time we go to sleep
  - Contrast to semaphores: Can't wait inside critical section
- Operations:
  - `Wait(&lock)`: Atomically release lock and go to sleep. Re-acquire lock later, before returning.
  - `Signal()`: Wake up one waiter, if any
  - `Broadcast()`: Wake up all waiters
- Rule: Must hold lock when doing condition variable ops!

Complete Monitor Example (with condition variable)

- Here is an (infinite) synchronized queue

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

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

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


Mesa vs. Hoare monitors

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

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

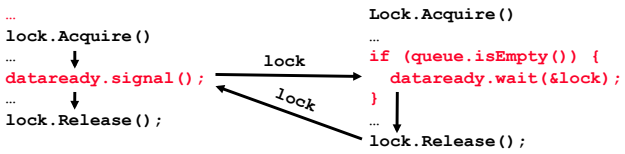
  - Why didn't we do this?

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

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

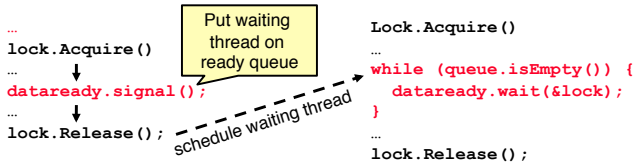
Hoare monitors

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

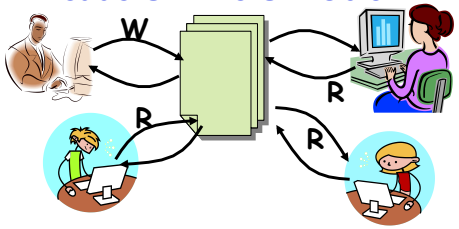


Mesa monitors

- 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

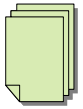


Readers/Writers Problem



- 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();
}
```


Announcements

- Project 1 will be posted Thursday afternoon.
- Find a group or be dropped!
- Two new discussion section slots:
  - 5-6pm: 320 Soda Hall
  - 6-7pm: 320 Soda Hall
- We'll announce by Friday which morning sections will move slots

5min Break

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
- 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
- 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
- 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
- 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
- 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
- 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
- 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
- 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
- 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
- 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();
  }
```

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

- 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();
  }
```

W1 cannot start because of readers, so goes to sleep

Simulation of Readers/Writers Solution

- R3 comes along (R1, 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, 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, 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

- R2 finishes (R1 accessing dbase, W1, 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, 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, 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, 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 = 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 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();
  }
```

All reader finished, signal writer – note R3 still waiting

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();
  }
```

Got signal from R1

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 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 = 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 = 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();
  }
```

No waiting writer, signal reader R3

Simulation of Readers/Writers Solution

- R1 finishes (W1, R3 waiting)
- 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();
  }
```

Got signal from W1

Simulation of Readers/Writers Solution

- R1 finishes (W1, R3 waiting)
- 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 finishes (W1, R3 waiting)
- 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();
  }
```

DONE!

Read/Writer Questions

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

    // read-only
    AccessDbase

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

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

    // read/write access
    AccessDbase(ReadWrite);

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

What if we remove this line?

Read/Writer Questions

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

    // read-only
    AccessDbase

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

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

    // read/write access
    AccessDbase(ReadWrite);

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

What if we turn signal to broadcast?

Read/Writer Questions

```
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?

Read/Writer Questions

```
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();
  }
```

- R1 arrives
- W1, R2 arrive while R1 reads
- R1 signals R2

Read/Writer Questions

```
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){
       okContinue.signal();
    } else if (WR > 0) {
       okContinue.broadcast();
    }
    lock.Release();
  }
```

Need to change to broadcast!
Why?

Summary

- 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()`
- Readers/Writers
  - Readers can access database when no writers
  - Writers can access database when no readers
  - Only one thread manipulates state variables at a time
- Language support for synchronization:
  - Java provides synchronized keyword and one condition-variable per object (with `wait()` and `notify()`)