CS162
Operating Systems and Systems Programming
Lecture 8

Concurrency

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https://cs162.org/

Slides based on prior slide decks from David Culler, Ion Stoica, John Kubiatowicz, Alison Norman and Lorenzo Alvisi

Higher-level Primitives for Synchronization

Goal of last few lectures:

- What is right abstraction for synchronizing threads that share memory?
- Want as high a level primitive as possible

We're building higher-level synchronization primitives from hardware instructions, starting with building locks

Recall: Atomic Read-Write Instructions

```
test&set (&address) {           /* most architectures */
    result = M[address];        // return result from “address” and
    M[address] = 1;             // set value at “address” to 1
    return result;
}

compare&swap (&address, reg1, reg2) { /* x86 (returns old value), 68000 */
    if (reg1 == M[address]) {   // If memory still == reg1,
        M[address] = reg2;      // then  put reg2 => memory
        return success;
    } else {                    // Otherwise do not change memory
        return failure;
    }
}
```

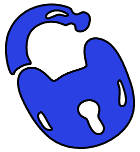
Recall: Simple locks using test&set

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

```
// Storage: just a memory location in userspace; 0 means "unlocked"
int mylock = 0; // Interface: acquire(&mylock);
                //            release(&mylock);

acquire(int *thelock) {
   while (test&set(thelock)); // Atomic operation!
}


release(int *thelock) {
   *thelock = 0;              // Atomic operation!
}
```

Better locks using test&set

Idea: only busy-wait to atomically check lock value, then put threads to sleep



```
int guard = 0; // Global Variable!
int mylock = FREE; // Interface: acquire(&mylock);
                   //            release(&mylock);

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

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

Linux futex: Fast Userspace Mutex

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

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

uaddr points to a 32-bit value in user space

futex_op

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

timeout

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

Linux futex: Fast Userspace Mutex

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

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

Interface to the kernel sleep() functionality!

– Let thread put themselves to sleep – conditionally!

futex is not exposed in libc; it is used within the implementation of pthreads

– Can be used to implement locks, semaphores, monitors, etc…

Example: First try: T&S and futex

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

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

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

}
```

Sleep interface by using futex – no busy-waiting

No overhead to acquire lock if unlocked

Every release() has to call kernel to potentially wake someone up, even if no waiters

Example: Try #2: T&S and futex

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

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

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

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

This is syscall-free in the uncontended case

- Temporarily falls back to syscalls if multiple waiters, or concurrent acquire/release

But it can be further optimized! See "Futexes are Tricky" by Ulrich Drepper

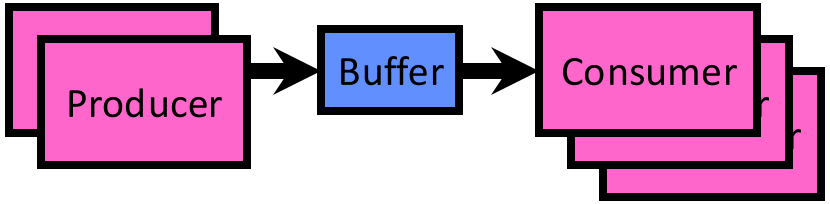
Where are we going with synchronization?

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

We are going to implement various higher-level synchronization primitives building up from atomic hardware operations

- Everything is too painful if the only atomic primitives are instructions

Example: Producer-Consumer with a Bounded Buffer



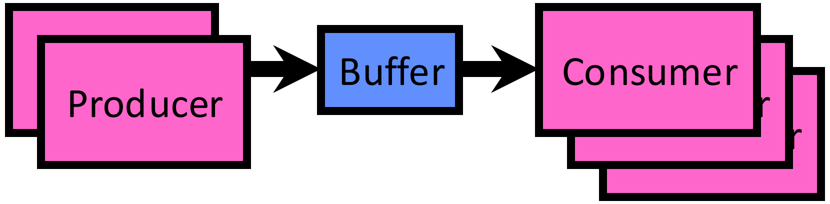
Problem Definition

- Producer(s) put things into a shared buffer
- Consumer(s) take them out
- Need synchronization to coordinate producer/consumer

Don’t want producer and consumer to have to work in lockstep, so put a fixed-size buffer between them

- Need to synchronize access to this buffer
- Producer needs to wait if buffer is full
- Consumer needs to wait if buffer is empty

Producer-Consumer with a Bounded Buffer



Example 1: GCC compiler

- `cpp | cc1 | cc2 | as | ld`

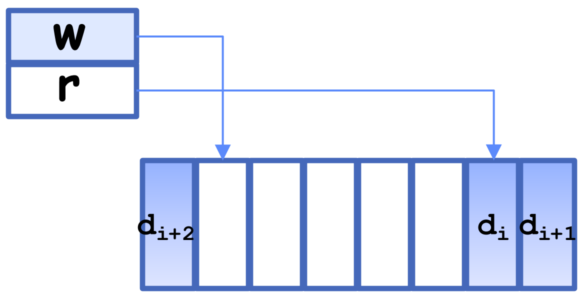
Example 2: Coke machine

- Producer can put limited number of Cokes in machine
- Consumer can't take Cokes out if machine is empty

Others: Web servers, Routers, ….

Circular Buffer Data Structure (sequential case)

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



Insert: write & bump write ptr (enqueue)

Remove: read & bump read ptr (dequeue)

How to tell if Full (on insert) Empty (on remove)?

And what do you do if it is?

What needs to be atomic?

Circular Buffer – first cut

```
mutex buf_lock = <initially unlocked>

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

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

Will we ever come out of the wait loop?

Circular Buffer – 2nd cut

```
mutex buf_lock = <initially unlocked>

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

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

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

Semaphores

Semaphores are a type of generalized lock

First defined by Dijkstra in late 60s

Main synchronization primitive in original UNIX

Semaphores

A Semaphore has a non-negative integer value and supports the following operations:

– Set starting value when you initialize

– Down() or P(): an atomic operation that waits for semaphore to become positive, then decrements it by 1

passeren?
prolaag?
procure

» Think of this as the wait() operation

– Up() or V(): an atomic operation that increments the semaphore by 1, waking up a waiting P, if any

vrijgave?
verhogen?
vacate

» This of this as the signal() operation

Semaphores Like Integers Except…

Semaphores are like integers, except:

– No negative values

– Only operations allowed are P and V – can't read or write value, except initially

– Operations must be atomic
  - » Two P's together can't decrement value below zero
  - » Thread going to sleep in P won't miss wakeup from V – even if both happen at same time

Two Uses of Semaphores

Mutual Exclusion (initial value = 1)

Also called “Binary Semaphore” or “mutex”.

Can be used for mutual exclusion, just like a lock:

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

Two Uses of Semaphores

Scheduling Constraints (initial value = 0)

Allow thread 1 to wait for a signal from thread 2

- thread 2 schedules thread 1 when a given event occurs

Example: suppose you had to implement ThreadJoin which must wait for thread to terminate:

```
Initial value of semaphore = 0
ThreadJoin {
   semaP(&mysem);
}
ThreadFinish {
   semaV(&mysem);
}
```

Bounded Buffer: Correctness constraints for solution

Correctness Constraints:

- Consumer must wait for producer to fill buffers, if none full (scheduling constraint)
- Producer must wait for consumer to empty buffers, if all full (scheduling constraint)
- Only one thread can manipulate buffer queue at a time (mutual exclusion)

Bounded Buffer: Correctness constraints for solution

General rule of thumb:

Use a separate semaphore for each constraint

```
– Semaphore fullBuffers; // consumer's constraint
– Semaphore emptyBuffers;// producer's constraint
– Semaphore mutex;       // mutual exclusion
```

Let’s drink coke!


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

Producer(item) {
    semaP(&emptySlots);       // Wait until space




}
Consumer() {
    semaP(&fullSlots);        // Check if there’s a coke




}
```

Let’s drink coke!


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

Producer(item) {
    semaP(&emptySlots);       // Wait until space
    Enqueue(item);



}
Consumer() {
    semaP(&fullSlots);        // Check if there’s a coke
    item = Dequeue();



}
```

Let's drink coke!


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

Producer(item) {
    semaP(&emptySlots);       // Wait until space
    Enqueue(item);
    semaV(&fullSlots);        // Tell consumers there is
                              // more coke


}
Consumer() {
    semaP(&fullSlots);        // Check if there's a coke
    item = Dequeue();
    semaV(&emptySlots);       // tell producer need more
    return item;
}
```

Let’s drink coke!


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

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

Let's drink coke!


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

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

`fullSlots` signals coke

`emptySlots` signals space

Critical sections using mutex protect integrity of the queue

Discussion About Solution

Why asymmetry?

– Producer does: **`semaP(&emptyBuffer), semaV(&fullBuffer)`**

– Consumer does: **`semaP(&fullBuffer), semaV(&emptyBuffer)`**

Does order matter? What if we decrement mutex before full/emptyBuffer?

Semaphores are good but…

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

Problem is that semaphores are dual purpose:

- They are used for both mutex and scheduling constraints
- Example: the fact that flipping of P's in bounded buffer gives deadlock is not immediately obvious. How do you prove correctness to someone?

Monitors are even nicer!

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

A monitor is a paradigm for concurrent programming

- Some languages, like Java, provide them natively
- Others use actual locks and condition var objects

Condition Variables

A queue of threads waiting for something (a condition) *inside* a critical section

Key idea: allow going to sleep inside the critical section by atomically releasing lock at time we go to sleep

Contrast to semaphores: Can’t wait inside critical section

Condition Variables

Operations on condition variables:

- `Wait(&lock)`: Atomically release lock and go to sleep. Re-acquire lock later, when returning from sleep.
- `Signal()`: Wake up one waiter, if any exists.
- `Broadcast()`: Wake up all waiters.

Rule: Must hold lock when doing condition variable ops!

Monitor with Condition Variables

Lock: the lock provides mutual exclusion to shared data

- Always acquire before accessing shared data structures
- Always release after finishing with shared data
- Lock is 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

Infinite Synchronized Buffer (with condition variable)

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

Infinite Synchronized Buffer (with condition variable)

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

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

Infinite Synchronized Buffer (with condition variable)

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

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

Consumer() {
   acquire(&buf_lock);              // Get Lock
   if (isEmpty(&queue)) {
      cond_wait(&buf_CV, &buf_lock); // If empty, sleep
   }
   item = dequeue(&queue);          // Get next item
   release(&buf_lock);              // Release Lock
   return(item);
}
```

Infinite Synchronized Buffer (with condition variable)

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


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


Consumer() {
   acquire(&buf_lock);                // Get Lock
   while (isEmpty(&queue)) {
      cond_wait(&buf_CV, &buf_lock); // If empty, sleep
   }
   item = dequeue(&queue);            // Get next item
   release(&buf_lock);                // Release Lock
   return(item);
}
```

Mesa vs. Hoare monitors

Need to be careful about precise definition of signal and wait.

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

Why didn't we do this?

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

Answer: depends on the type of scheduling

- Mesa-style: Named after Xerox-Parc Mesa Operating System
  - » Most OSes use Mesa scheduling!
- Hoare-style: Named after British logician Tony Hoare

Hoare monitors

Signaler gives up lock, CPU to waiter; waiter runs immediately

Then, Waiter gives up lock, processor back to signaler when it exits critical section or if it waits again

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

Lock, CPU

Lock, CPU

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

At first glance, this seems like good semantics

Waiter gets to run immediately, condition is still correct!

Mesa monitors

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

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

Put waiting thread on ready queue

schedule thread (sometime later!)

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

Practically, need to check condition again after wait
– By the time the waiter gets scheduled, condition may be false again
– – so, just check again with the "while" loop

Bounded Buffer – Attempt 4

```
lock buf_lock = <initially unlocked>
condition isNotEmpty = <initially empty>
condition isNotFull = <initially empty>
```

Bounded Buffer – Attempt 4

```
lock buf_lock = <initially unlocked>
condition isNotEmpty = <initially empty>
condition isNotFull = <initially empty>

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

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

Again: Why the `while` Loop?

MESA semantics

For most operating systems, when a thread is woken up by signal(), it is simply put on the ready queue

It may or may not reacquire the lock immediately!

- Another thread could be scheduled first and "sneak in" to empty the queue
- Need a loop to re-check condition on wakeup

Is this busy waiting?

Basic Structure of *Mesa* Monitor Program

Monitors represent the synchronization logic of the program

- Wait if necessary
- Signal when change something so any waiting threads can proceed

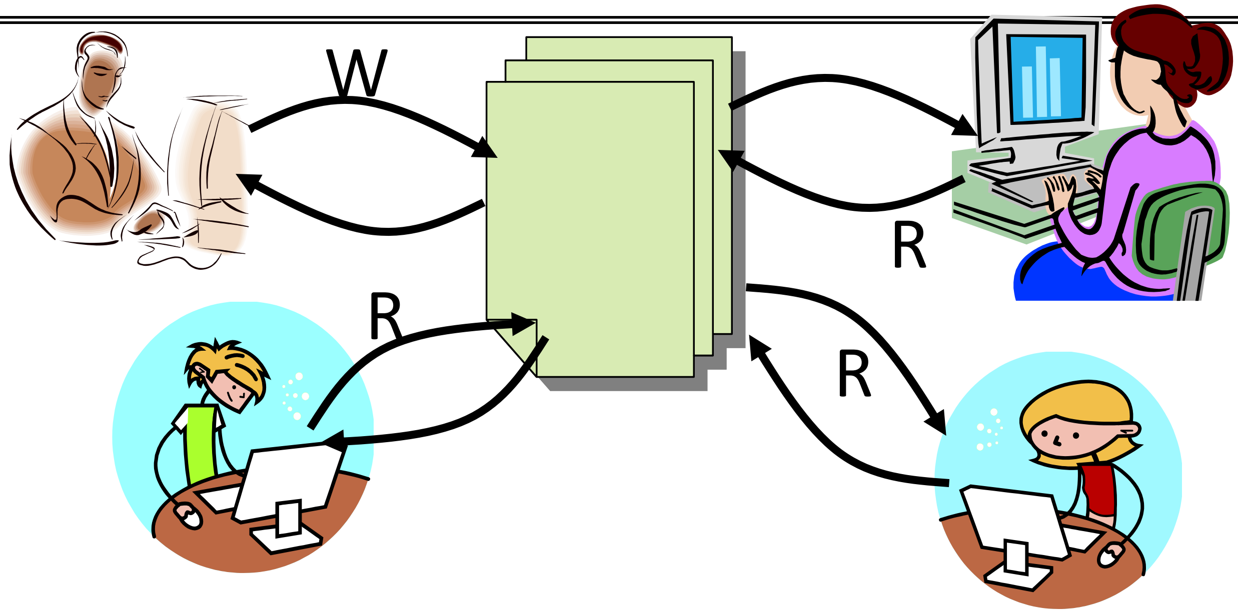
```
lock
while (need to wait) {
   condvar.wait();
}
unlock
```

Check and/or update state variables
Wait if necessary

```
do something so no need to wait

lock

condvar.signal();

unlock
```

Check and/or update state variables

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 database
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
```

Basic Readers/Writers Solution

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

Code for a Writer

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

Simulation of Readers/Writers Solution

Use an example to simulate the solution

Consider the following sequence of operators:

– R1, R2, W1, R3

Initially: AR = 0, WR = 0, AW = 0, WW = 0

Simulation of Readers/Writers Solution

R1 comes along (no waiting threads)

AR = 0, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R1 comes along (no waiting threads)

AR = 0, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R1 comes along (no waiting threads)

AR = 1, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R1 comes along (no waiting threads)

AR = 1, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R1 accessing dbase (no other threads)

AR = 1, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R2 comes along (R1 accessing dbase)

AR = 1, WR = 0, AW = 0, WW = 0

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

   AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R2 comes along (R1 accessing dbase)

AR = 1, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R2 comes along (R1 accessing dbase)

AR = 2, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R2 comes along (R1 accessing dbase)

AR = 2, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R1 and R2 accessing dbase

AR = 2, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadOnly);

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

Assume readers take a while to access database

Situation: Locks released, only AR is non-zero

Simulation of Readers/Writers Solution

W1 comes along (R1 and R2 are still accessing dbase)

AR = 2, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadWrite);

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

Simulation of Readers/Writers Solution

W1 comes along (R1 and R2 are still accessing dbase)

AR = 2, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadWrite);

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

Simulation of Readers/Writers Solution

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

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

    AccessDBase(ReadWrite);

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

Simulation of Readers/Writers Solution

R3 comes along (R1 and R2 accessing dbase, W1 waiting)

AR = 2, WR = 0, AW = 0, WW = 1

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R3 comes along (R1 and R2 accessing dbase, W1 waiting)

AR = 2, WR = 0, AW = 0, WW = 1

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R3 comes along (R1 and R2 accessing dbase, W1 waiting)

AR = 2, WR = 1, AW = 0, WW = 1

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R3 comes along (R1, R2 accessing dbase, W1 waiting)

AR = 2, WR = 1, AW = 0, WW = 1

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R1 and R2 accessing dbase, W1 and R3 waiting

AR = 2, WR = 1, AW = 0, WW = 1

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

    AccessDBase(ReadOnly);

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

Status:

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

Simulation of Readers/Writers Solution

R2 finishes (R1 accessing dbase, W1 and R3 waiting)

AR = 2, WR = 1, AW = 0, WW = 1

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R2 finishes (R1 accessing dbase, W1 and R3 waiting)

AR = 1, WR = 1, AW = 0, WW = 1

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R2 finishes (R1 accessing dbase, W1 and R3 waiting)

AR = 1, WR = 1, AW = 0, WW = 1

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R2 finishes (R1 accessing dbase, W1 and R3 waiting)

AR = 1, WR = 1, AW = 0, WW = 1

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R1 finishes (W1 and R3 waiting)

AR = 1, WR = 1, AW = 0, WW = 1

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R1 finishes (W1, R3 waiting)

AR = 0, WR = 1, AW = 0, WW = 1

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R1 finishes (W1, R3 waiting)

AR = 0, WR = 1, AW = 0, WW = 1

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R1 signals a writer (W1 and R3 waiting)

AR = 0, WR = 1, AW = 0, WW = 1

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

W1 gets signal (R3 still waiting)

AR = 0, WR = 1, AW = 0, WW = 1

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

    AccessDBase(ReadWrite);

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

Simulation of Readers/Writers Solution

W1 gets signal (R3 still waiting)

AR = 0, WR = 1, AW = 0, WW = 0

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

    AccessDBase(ReadWrite);

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

Simulation of Readers/Writers Solution

W1 gets signal (R3 still waiting)

AR = 0, WR = 1, AW = 1, WW = 0

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

    AccessDBase(ReadWrite);

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

Simulation of Readers/Writers Solution

W1 accessing dbase (R3 still waiting)

AR = 0, WR = 1, AW = 1, WW = 0

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

    AccessDBase(ReadWrite);

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

Simulation of Readers/Writers Solution

W1 finishes (R3 still waiting)

AR = 0, WR = 1, AW = 1, WW = 0

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

    AccessDBase(ReadWrite);

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

Simulation of Readers/Writers Solution

W1 finishes (R3 still waiting)

AR = 0, WR = 1, AW = 0, WW = 0

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

   AccessDBase(ReadWrite);

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

Simulation of Readers/Writers Solution

W1 finishes (R3 still waiting)

AR = 0, WR = 1, AW = 0, WW = 0

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

    AccessDBase(ReadWrite);

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

Simulation of Readers/Writers Solution

W1 signaling readers (R3 still waiting)

AR = 0, WR = 1, AW = 0, WW = 0

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

    AccessDBase(ReadWrite);

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

Simulation of Readers/Writers Solution

R3 gets signal (no waiting threads)

AR = 0, WR = 1, AW = 0, WW = 0

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R3 gets signal (no waiting threads)

AR = 0, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R3 accessing dbase (no waiting threads)

AR = 1, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R3 finishes (no waiting threads)

AR = 1, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadOnly);

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

Simulation of Readers/Writers Solution

R3 finishes (no waiting threads)

AR = 0, WR = 0, AW = 0, WW = 0

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

    AccessDBase(ReadOnly);

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

Questions

Can readers starve? Consider Reader() entry code:

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

What if we erase the condition check in Reader exit?

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

Questions

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

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

Finally, what if we use only one condition variable (call it "**okContinue**") instead of two separate ones?

- Both readers and writers sleep on this variable
- Must use broadcast() instead of signal()

Code for a Reader

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

Code for a Writer

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

Mesa Monitor Conclusion

Monitors represent the synchronization logic of the program

- Wait if necessary
- Signal when change something so any waiting threads can proceed

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

Check and/or update state variables
Wait if necessary

```
do something so no need to wait

lock

condvar.signal();

unlock
```

Check and/or update state variables

C-Language Support for Synchronization

Pretty straightforward, just functions to call

But make sure you know *all* the code paths out of a critical section!

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

Concurrency and Synchronization in C

Harder to track what to release with more locks

```
void Rtn() {
  lock1.acquire();
  …
  if (error) {
    lock1.release();
    return;
  }
  …
  lock2.acquire();
  …
  if (error) {
    lock2.release()
    lock1.release();
    return;
  }
  …
  lock2.release();
  lock1.release();
}
```

C++ Language Support for Synchronization

Languages that support exceptions are problematic (easy to make a non-local exit without releasing lock)

```
void Rtn() {
   lock.acquire();
   …
   DoFoo();
   …
   lock.release();
}
void DoFoo() {
   …
   if (bad stuff) throw Exception;
   …
}
```

An exception in DoFoo() will exit Rtn() 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;
   …
}
```

Much better pattern: C++ Lock Guards

```
#include <mutex>
int global_i = 0;
std::mutex global_mutex;

void safe_increment() {
  std::lock_guard<std::mutex> lock(global_mutex);
  …
  global_i++;
  // Mutex released in the destructor of "lock"
}
```

Python `with` Keyword

More versatile than we show here (can be used to close files, connections, etc.)

```
lock = threading.Lock()
…
with lock: # Automatically calls acquire()
  some_var += 1
  …
# release() called however we leave the “with” block
```

Java synchronized Keyword

Every Java object has an associated lock:

- Lock is acquired on entry and released on exit from a synchronized method
- Lock is properly released if exception occurs inside a synchronized method
- Mutex execution of synchronized methods (beware deadlock)

```
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;
   }
}
```

Java Support for Monitors

Along with a lock, every object has a single condition variable associated with it

To wait inside a synchronized method:

- `void wait();`
- `void wait(long timeout);`

To signal while in a synchronized method:

- `void notify();`
- `void notifyAll();`

Where are we going with synchronization?

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

Implement various higher-level synchronization primitives using atomic operations