CS162
Operating Systems and Systems Programming
Lecture 9

Synchronization 3: Semaphores, Monitors and Readers/Writers

February 13th, 2024

Prof. John Kubiatowicz

http://cs162.eecs.Berkeley.edu

Recall: Atomic Instruction Operations

```
• test&set (&address) {          /* most architectures */
      result = M[address];       // return result from "address" and
      M[address] = 1;            // set value at "address" to 1
      return result;
  }
• swap (&address, register) {    /* x86 */
      temp = M[address];         // swap register's value to
      M[address] = register;     // value at "address"
      register = temp;           // value from "address" put back to register
      return temp;               // value from "address" considered return from swap
  }
• compare&swap (&address, reg1, reg2) { /* x86 (returns old value), 68000 */
      if (reg1 == M[address]) {  // If memory still == reg1,
          M[address] = reg2;     // then  put reg2 => memory
          return success;
      } else {                   // Otherwise do not change memory
          return failure;
      }
  }
• load-linked&store-conditional(&address) { /* R4000, alpha */
      loop:
          ll r1, M[address];
          movi r2, 1;              // Can do arbitrary computation
          sc r2, M[address];
          beqz r2, loop;
  }
```


Recall: Implementing Locks with test&set

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

```
// (Free) Can access this memory location from user space!
int mylock = 0; // Interface: acquire(&mylock);
                //            release(&mylock);
acquire(int *thelock) {
   while (test&set(thelock)); // Atomic operation!
}
release(int *thelock) {
   *thelock = 0;              // Atomic operation!
}
```

- Discussion:
  – Can have as many locks as memory locations!
  – If lock is free, only one thread will get to run test&set which reads 0 and sets lock=1
  – If lock is busy, test&set reads 1 and sets lock=1 (no change)
    It returns 1, so while loop continues.
  – When we set thelock = 0, someone else can get lock.
- Busy-Waiting: thread consumes cycles while waiting
  – For multiprocessors: every test&set() is a write, which makes value ping-pong around in cache (using lots of network BW)

Better Locks using test&set

- Can we build test&set locks without busy-waiting?
  – Mostly. Idea: only busy-wait to atomically check lock value

```
int guard = 0;  // Global Variable!
int mylock = 1; // Interface: acquire(&mylock);
                //            release(&mylock);

acquire(int *thelock) {
   // Short busy-wait time
   while (test&set(guard));
   if (*thelock == 1) {
      put thread on wait queue;
      go to sleep() & guard = 0 ????
      // guard == 0 on wakup;
   } else {
      *thelock = 1;
      guard = 0;
   }
}

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

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

Analysis: Lock Implementation using interrupts

Desired API

```
int mylock=0;

acquire(&mylock);
 …
 critical section;
 …
release(&mylock);
```

Naïve Implementation

```
acquire(int *thelock) {
  disable interrupts;
}

release(int *thelock)
{
  enable interrupts;
}
```

If one thread in critical section, no other activity (including OS) can run!

Lock argument not used!

Better Implementation

```
acquire(int *thelock) {
  // Short busy-wait time
  disable interrupts;
  if (*thelock == 1) {
    put thread on wait-queue;
    go to sleep() //See Lecture 8!
  } else {
    *thelock = 1;
    enable interrupts;
  }
}

release(int *thelock) {
  // Short busy-wait time
  disable interrupts;
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    *thelock = 0;
  }
  enable interrupts;
}
```


Analysis: Lock Implementation using test&set

Desired API

```
int mylock=0;

acquire(&mylock);
 …
 critical section;
 …
release(&mylock);
```

Naïve Implementation

```
int mylock = 0;
acquire(int *thelock) {
  while(test&set(thelock));
}

release(int *thelock) {
  *thelock = 0;
}
```

Threads waiting to enter critical section busy-wait!

Better Implementation??

```
int guard = 0; // global!
acquire(int *thelock) {
  // Short busy-wait time
  while(test&set(guard));
  if (*thelock == 1) {
    put thread on wait-queue;
    go to sleep()& guard = 0;
    // guard == 0 on wakeup
  } else {
    *thelock = 1;
    guard = 0;
  }
}
release(int *thelock) {
  // Short busy-wait time
  while (test&set(guard));
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    *thelock = 0;
  }
  guard = 0;
}
```


Linux `futex`: Fast Userspace Mutex

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

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

`uaddr` points to a 32-bit value in user space

`futex_op`

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

`timeout`

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

- `Interface to the kernel sleep() functionality!`
  - `Let thread put themselves to sleep – conditionally!`
- futex is not exposed in libc; it is used within the implementation of pthreads
  - Can be used to implement locks, semaphores, monitors, etc…

Example: First try: T&S and `futex`

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

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

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

}
```

- Properties:
  - Sleep interface by using futex – no busywaiting
- No overhead to acquire lock
  - Good!
- Every unlock has to call kernel to potentially wake someone up – even if none
  - Slows down the uncontested case where only one thread acquiring and releasing over and over…!

Example: Try #2: T&S and futex

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

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

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

```
release(int *thelock, bool *maybe) {
   *thelock = 0;
   if (*maybe) {
      *maybe = false;
      // Try to wake up someone
      futex(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 considerably optimized!
  - See "Futexes are Tricky" by Ulrich Drepper

Try #3: Better, using more atomics

- Much better: Three (3) states:
  - UNLOCKED: No one has lock
  - LOCKED: One thread has lock
  - CONTESTED: Possibly more than one (with someone sleeping)
- Clean interface!
- Lock grabbed cleanly by either
  - compare&swap()
  - First swap()
- No overhead if uncontested!
- Could build semaphores in a similar way!

```
typedef enum { UNLOCKED,LOCKED,CONTESTED } Lock;
Lock mylock = UNLOCKED; // Interface: acquire(&mylock);
                        //            release(&mylock);

acquire(Lock *thelock) {
   // If unlocked, grab lock!
   if (compare&swap(thelock,UNLOCKED,LOCKED))
      return;

   // Keep trying to grab lock, sleep in futex
   while (swap(thelock,CONTESTED) != UNLOCKED))
      // Sleep unless someone releases here!
      futex(thelock, FUTEX_WAIT, CONTESTED);
}

release(Lock *thelock) {
   // If someone sleeping,
   if (swap(thelock,UNLOCKED) == CONTESTED)
      futex(thelock,FUTEX_WAKE,1);
}
```


Recall: Where are we going with synchronization?

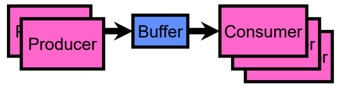
Programs	Shared Programs
Higher-level API	Locks Semaphores Monitors Send/Receive
Hardware	Load/Store Disable Ints Test&Set Compare&Swap

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

Administrivia

- Midterm This Thursday, 8-10pm (February 15)!
  - *In person:* Dwinelle 155 (here) or VLSB 2050
    - » Look on ED for which room you should go to
  - You are responsible for all materials up to and including today's lecture!
    - » Including Semaphores and Monitors
    - » I have a complete version of the synchronization lectures available on YouTube from my Fall 2020 class. [Note – the names of the lectures have changed slightly!]
- You get one (1) double-side page of *handwritten* notes
  - Hand drawn figures, hand written notes
  - No copying of figures directly from slides, no microfiche, etc
  - Redraw them if you want them on your notes!
- If you are sick, let us know.
  - Do not come to the midterm!
- No class on Thursday
  - I will have extra office hours during class time
- No section this week!
- No OH on Monday (it is a holiday!)

Producer-Consumer with a Bounded Buffer

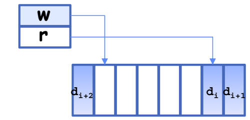


- Problem Definition
  - Producer(s) put things into a shared buffer
  - Consumer(s) take them out
  - Need synchronization to coordinate producer/consumer
- Don't want producer and consumer to have to work in lockstep, so put a fixed-size buffer between them
  - Need to synchronize access to this buffer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

- Example 1: GCC compiler
  - `cpp | cc1 | cc2 | as | ld`
- Example 2: Coke machine
  - Producer can put limited number of Cokes in machine
  - Consumer can't take Cokes out if machine is empty
- Others: Web servers, Routers, ….

Bounded 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?*

Bounded 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
}
```

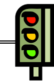
Will we ever come out of the wait loop?

Bounded 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 ?**

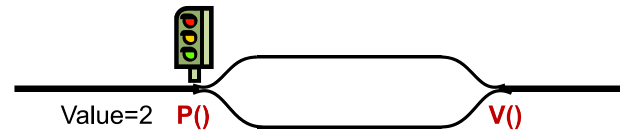
Better Primitive: Semaphores



- Semaphores are a kind of generalized lock
  - First defined by Dijkstra in late 60s
  - Main synchronization primitive used in original UNIX
- Definition: a Semaphore has a non-negative integer value and supports the following operations:
  - Set value when you initialize
  - `Down()` or `P()`: an atomic operation that waits for semaphore to become positive, then decrements it by 1
    - » Think of this as the wait() operation
  - `Up()` or `V()`: an atomic operation that increments the semaphore by 1, waking up a waiting P, if any
    - » This of this as the signal() operation
- Technically examining value after initialization is not allowed.

Semaphores Like Integers Except…

- Semaphores are like integers, except:
  - No negative values
  - Only operations allowed are P and V – can't read or write value, except initially
  - Operations must be atomic
    - » Two P's together can't decrement value below zero
    - » Thread going to sleep in P won't miss wakeup from V – even if both happen at same time
- POSIX adds ability to read value, but technically not part of proper interface!
- Semaphore from railway analogy
  - Here is a semaphore initialized to 2 for resource control:



Two Uses of Semaphores

Mutual Exclusion (initial value = 1)

- Also called "Binary Semaphore" or "mutex".
- Can be used for mutual exclusion, just like a lock:

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

Scheduling Constraints (initial value = 0)

- Allow thread 1 to wait for a signal from thread 2
  - thread 2 schedules thread 1 when a given event occurs
- Example: suppose you had to implement ThreadJoin which must wait for thread to terminate:

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


Revisit Bounded Buffer: Correctness constraints for solution

- Correctness Constraints:
  - Consumer must wait for producer to fill buffers, if none full (scheduling constraint)
  - Producer must wait for consumer to empty buffers, if all full (scheduling constraint)
  - Only one thread can manipulate buffer queue at a time (mutual exclusion)
- Remember why we need mutual exclusion
  - Because computers are stupid
  - Imagine if in real life: the delivery person is filling the machine and somebody comes up and tries to stick their money into the machine
- General rule of thumb: Use a separate semaphore for each constraint
  - `Semaphore fullBuffers; // consumer's constraint`
  - `Semaphore emptyBuffers;// producer's constraint`
  - `Semaphore mutex;       // mutual exclusion`

Bounded Buffer, 3rd cut (coke machine)

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

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

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)**

Decrease # of empty slots | Increase # of occupied slots | Decrease # of occupied slots | Increase # of empty slots

- Is order of P's important?
- Is order of V's important?
- What if we have 2 producers or 2 consumers?

```
Producer(item) {
  semaP(&mutex);
  semaP(&emptySlots);
  Enqueue(item);
  semaV(&mutex);
  semaV(&fullSlots);
}
Consumer() {
  semaP(&fullSlots);
  semaP(&mutex);
  item = Dequeue();
  semaV(&mutex);
  semaV(&emptySlots);
  return item;
}
```

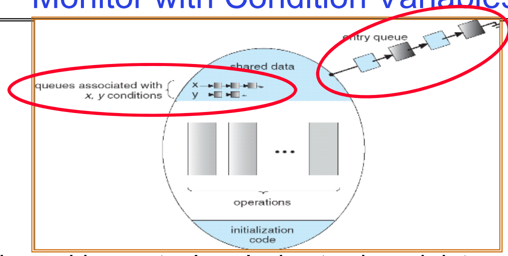

Semaphores are good but…Monitors are better!

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

Condition Variables

- How do we change the consumer() routine to wait until something is on the queue?
  - Could do this by keeping a count of the number of things on the queue (with semaphores), but error prone
- Condition Variable: a queue of threads waiting for something *inside* a critical section
  - Key idea: allow sleeping inside critical section by atomically releasing lock at time we go to sleep
  - Contrast to semaphores: Can't wait inside critical section
- Operations:
  - `Wait(&lock)`: Atomically release lock and go to sleep. Re-acquire lock later, before returning.
  - `Signal()`: Wake up one waiter, if any
  - `Broadcast()`: Wake up all waiters
- Rule: Must hold lock when doing condition variable ops!

Monitor with Condition Variables



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

Infinite Synchronized Buffer (with condition variable)

- Here is an (infinite) synchronized queue:

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

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

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


Mesa vs. Hoare monitors

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

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

  – Why didn't we do this?

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

- Answer: depends on the type of scheduling
  – Mesa-style: Named after Xerox-Park Mesa Operating System
    » Most OSes use Mesa Scheduling!
  – Hoare-style: Named after British logician Tony Hoare

Hoare monitors

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

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

Lock, CPU

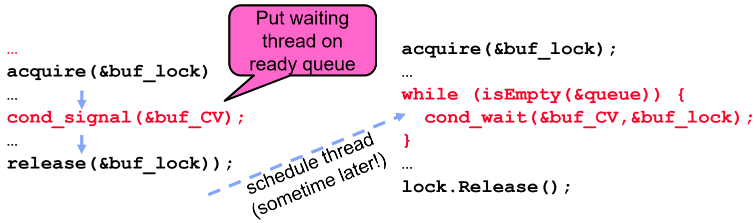
Lock, CPU

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

- On first glance, this seems like good semantics
  – Waiter gets to run immediately, condition is still correct!
- Most textbooks talk about Hoare scheduling
  – However, hard to do, not really necessary!
  – Forces a lot of context switching (inefficient!)

Mesa monitors

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



- Practically, need to check condition again after wait
  – By the time the waiter gets scheduled, condition may be false again – so, just check again with the "while" loop
- Most real operating systems do this!
  – More efficient, easier to implement
  – Signaler's cache state, etc still good

Bounded Buffer – 4rd cut (Monitors, pthread-like)

```
lock buf_lock = <initially unlocked>
condition producer_CV = <initially empty>
condition consumer_CV = <initially empty>

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

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

What does thread do when it is waiting?
- Sleep, not busywait!

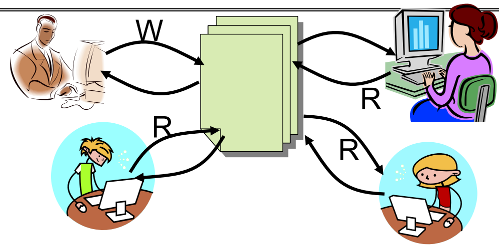
Again: Why the `while` Loop?

- MESA semantics
- For most operating systems, when a thread is woken up by `signal()`, it is simply put on the ready queue
- It may or may not reacquire the lock immediately!
  – Another thread could be scheduled first and "sneak in" to empty the queue
  – Need a loop to re-check condition on wakeup
- Is this busy waiting?

OS Library Monitor Pattern: *pthreads*

```
// Locks
int pthread_mutex_init(pthread_mutex_t *mutex,
                       const pthread_mutexattr_t *attr);

int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);

// Condition Variables
int pthread_cond_init(pthread_cond_t *cond,
                      const pthread_mutexattr_t *attr);
int pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex);
int pthread_cond_signal(pthread_cond_t *cond);
int pthread_cond_broadcast(pthread_cond_t *cond);
```

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 Structure of *Mesa* Monitor Program

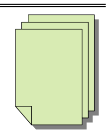
- Monitors represent the synchronization logic of the program
  - Wait if necessary
  - Signal when change something so any waiting threads can proceed
- Basic structure of mesa monitor-based program:

```
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 (beside the lock/while/unlock block)

Check and/or update state variables (beside the condvar.signal() block)

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
  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
```

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

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

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

Use of Single CV: **okContinue**

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

    // read-only access
    AccessDbase(ReadOnly);

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

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

    // read/write access
    AccessDbase(ReadWrite);

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

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

Use of Single CV: **okContinue**

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

    // read-only access
    AccessDbase(ReadOnly);

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

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

    // read/write access
    AccessDbase(ReadWrite);

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

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

Use of Single CV: okContinue

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

    // read-only access
    AccessDbase(ReadOnly);

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

Need to change to broadcast()!

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

    // read/write access
    AccessDbase(ReadWrite);

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

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 *thesema)   { semaP(thesema); }
Signal(Semaphore *thesema) { semaV(thesema); }
```

- Does this work better?

```
Wait(Lock *thelock, Semaphore *thesema) {
   release(thelock);
   semaP(thesema);
   acquire(thelock);
}
Signal(Semaphore *thesema) {
  semaV(thesema);
}
```


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 *thelock, Semaphore *thesema) {
   release(thelock);
   semaP(thesema);
   acquire(thelock);
}
Signal(Semaphore *thesema) {
   if semaphore queue is not empty
      semaV(thesema);
}
```

  - 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?

Mesa Monitor Conclusion

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

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

do something so no need to wait

lock

condvar.signal();

unlock
```

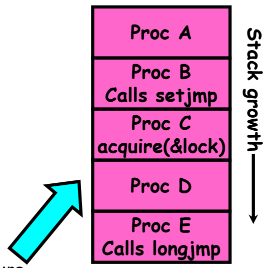
Check and/or update state variables Wait if necessary (for the lock/while/unlock block)

Check and/or update state variables (for condvar.signal())

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() {
   acquire(&lock);
   …
   if (exception) {
      release(&lock);
      return errReturnCode;
   }
   …
   release(&lock);
   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!

Concurrency and Synchronization in C

- Harder 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();
}
```

- Is goto a solution???

```
void Rtn() {
  lock1.acquire();
  …
  if (error) {
    goto release_lock1_and_return;
  }
  …
  lock2.acquire();
  …
  if (error) {
    goto release_both_and_return;
  }
  …
release_both_and_return:
  lock2.release();
release_lock1_and_return:
  lock1.release();
}
```


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;
   …
}
```

Much better: 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 when 'lock' goes out of scope
}
```


Python `with` Keyword

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

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

Conclusion

- 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
  - Monitors supported natively in a number of languages
- Readers/Writers Monitor example
  - Shows how monitors allow sophisticated controlled entry to protected code