

CS162
Operating Systems and
Systems Programming
Lecture 9

Synchronization 4:
Semaphores, Monitors and Readers/Writers

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Recall: Atomic Read-Modify-Write

- `test&set (&address) {` `/* most architectures */`
 `result = M[address];` `// return result from "address" and`
 `M[address] = 1;` `// set value at "address" to 1`
 `return result;`
}
- `swap (&address, register) {` `/* x86 */`
 `temp = M[address];` `// swap register's value to`
 `M[address] = register;` `// value at "address"`
 `register = temp;`
}
- `compare&swap (&address, reg1, reg2) {` `/* 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: 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 = 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;  
}
```

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

Recall: 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...

Recall: Lock Using Atomic Instructions and Futex

- 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_and_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_and_swap(thelock, UNLOCKED, LOCKED))
        return;

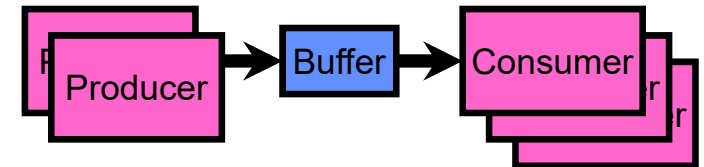
    // Keep trying to grab lock, sleep in futex
    while (swap(mylock, CONTESTED) != UNLOCKED)
        // Sleep unless someone releases here!
        futex(thelock, FUTEX_WAIT, CONTESTED);
}

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

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

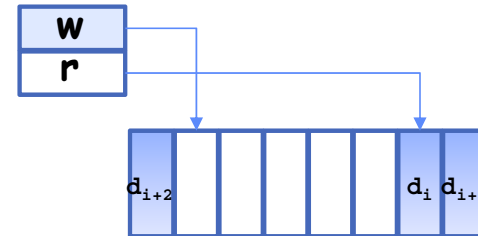
- Producer can put limited number of Cokes in machine
- Consumer can't take Cokes out if machine is empty

- 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);  
}
```



**Will we ever come out
of the wait loop?**

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


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);  
}
```

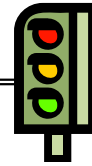
```
Consumer() {  
    acquire(&buf_lock);  
    while (buffer empty) {release(&buf_lock); acquire(&buf_lock);}  
    item = dequeue();  
    release(&buf_lock);  
    return item  
}
```

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

Higher-level Primitives than Locks

- What is right abstraction for synchronizing threads that share memory?
 - Want as high a level primitive as possible
- Good primitives and practices important!
 - Since execution is not entirely sequential, really hard to find bugs, since they happen rarely
 - UNIX is pretty stable now, but up until about mid-80s (10 years after started), systems running UNIX would crash every week or so – concurrency bugs
- Synchronization is a way of coordinating multiple concurrent activities that are using shared state
 - This lecture presents some ways to structuring sharing

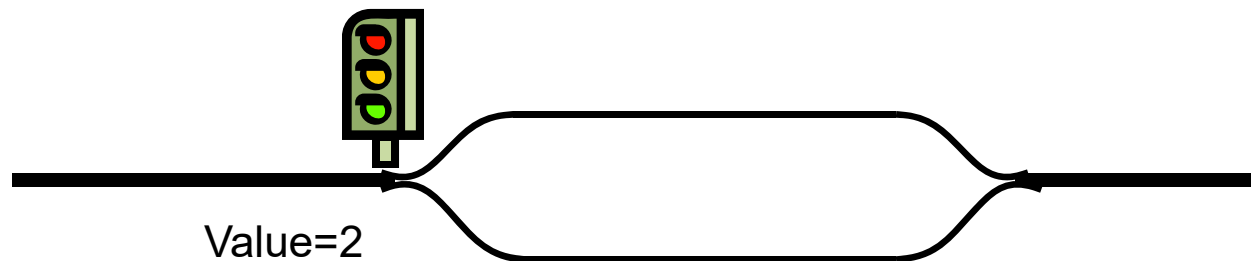
Semaphores



- Semaphores are a kind of generalized lock
 - First defined by Dijkstra in late 60s
 - Main synchronization primitive used in original UNIX
- Definition: a Semaphore has a **non-negative integer value** and supports the following 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
 - » Think 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

Critical sections
using mutex
protect integrity
of the queue

emptySlots
signals space

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;  
}
```


Administrivia

- Midterm This Thursday, 7-9pm (February 16)!
 - *In person*: 150 Wheeler unless you have alternative from us
 - You are responsible for all materials up to and including today's lecture!
 - » Including Semaphores and Monitors
- 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
- Do not seek out information about projects or homework from previous terms!
 - This includes solutions, rubrics, any other information!
 - Something like this constitutes academic dishonesty

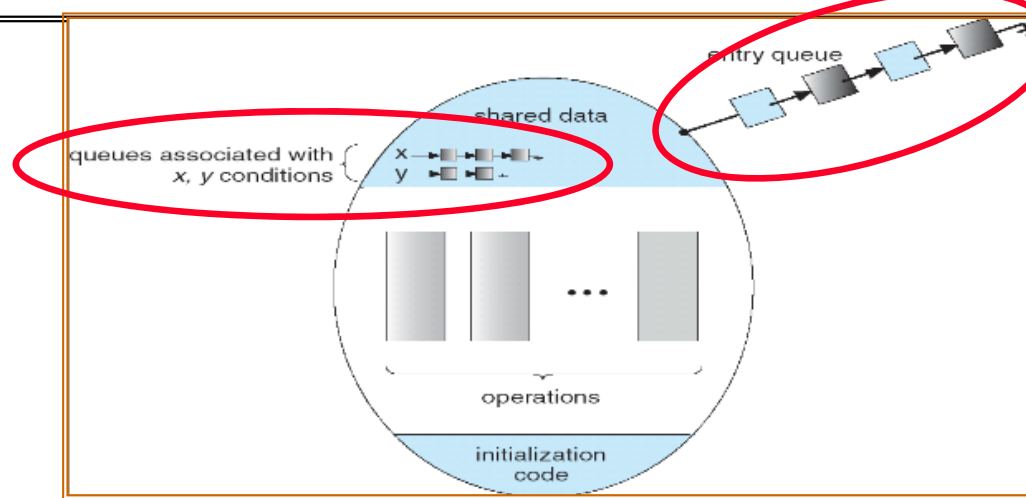
Semaphores are good but...Monitors are better!

- 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
```

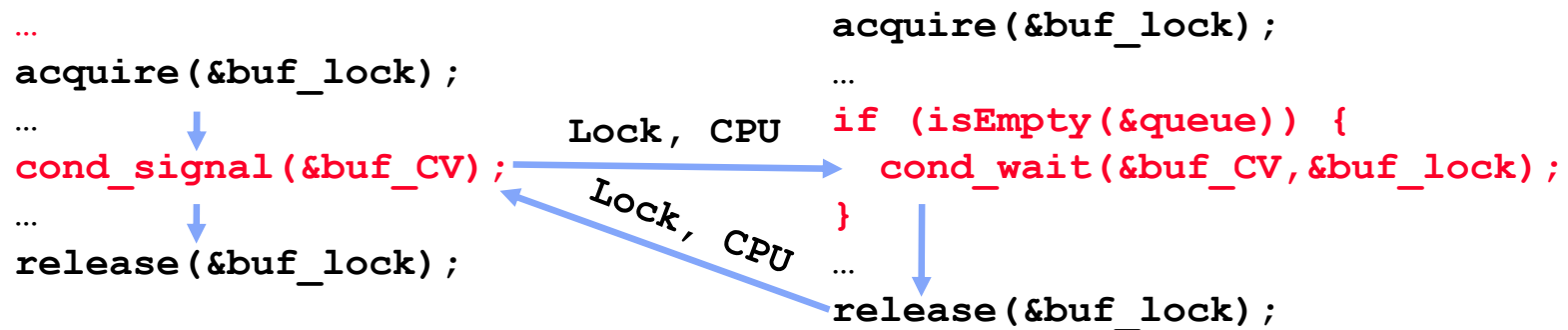
- Why didn't we do this?

```
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

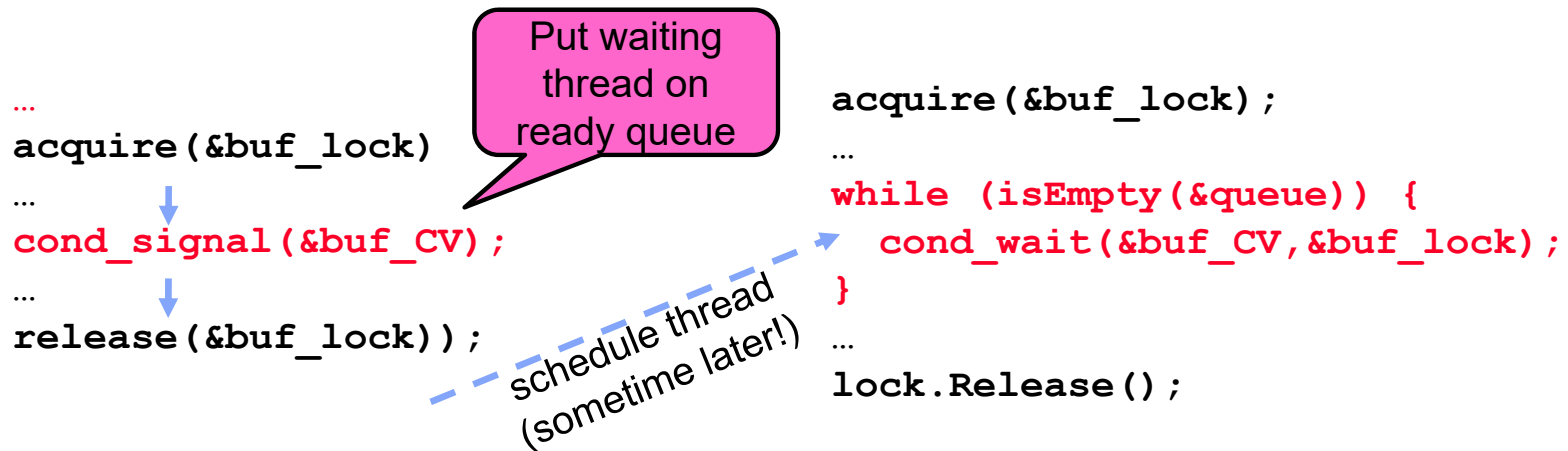
- Signaler gives up lock, CPU to waiter; waiter runs immediately
- Then, Waiter gives up lock, processor back to signaler when it exits critical section or if it waits again



- 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)

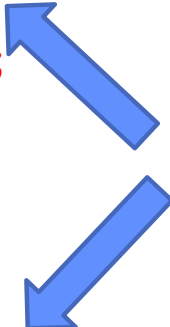
```
lock buf_lock = <initially unlocked>
```

```
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  
}
```

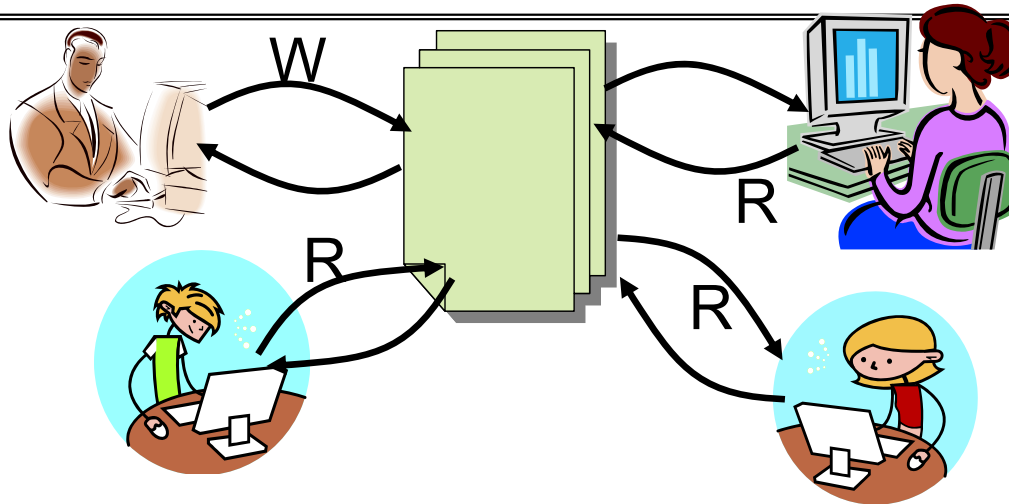


**What does thread do
when it is waiting?
- Sleep, not busywait!**

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?

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
```




Check and/or update
state variables
Wait if necessary

do something so no need to wait

```
lock

condvar.signal();

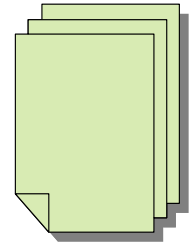
unlock
```



Check and/or update
state variables

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?

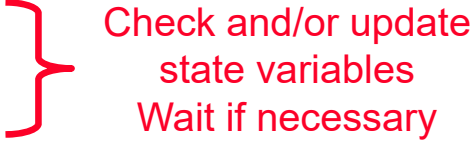
```
Wait(Lock *thelock, Semaphore *thesema) {  
    release(thelock);  
    semaP(thesema);  
    acquire(thelock);  
}  
Signal(Semaphore *thesema) {  
    if semaphore queue is not empty  
        semaV(thesema);  
}
```

 - 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
```



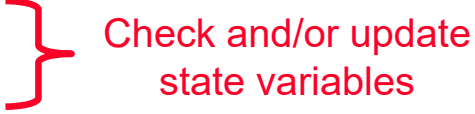
Check and/or update
state variables
Wait if necessary

do something so no need to wait

```
lock

condvar.signal();

unlock
```



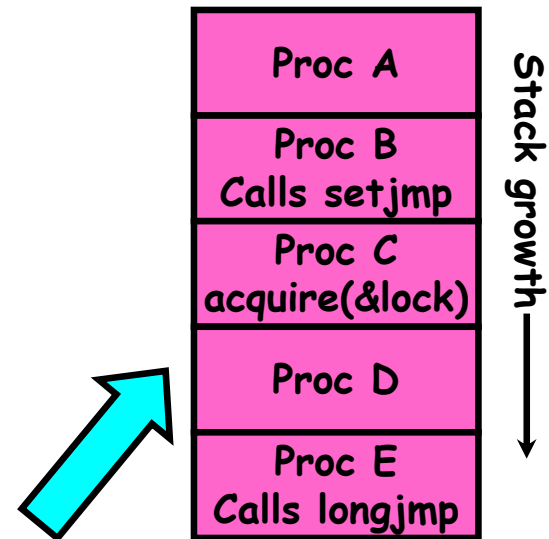
Check and/or update
state variables

C-Language Support for Synchronization

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

```
int Rtn() {  
    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`, popping 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