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; // Otherwise do not change memory
  } else {
    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!

interface:

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 wakup!
  } 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 wailing 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&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);
}

Recall: 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, ....

Recall: Circular Buffer Data Structure (sequential case)

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

- Insert: write & bump write ptr (enqueue)
- Remove: read & bump read ptr (dequeue)
- How to tell if Full (on insert) Empty (on remove)?
- And what do you do if it is?
- What needs to be atomic?

mutex buf_lock = <initially unlocked>
Producer(item) {
  acquire(&buf_lock);
  while (buffer full) {};
  enqueue(item);
  release(&buf_lock);
}
Consumer() {
  acquire(&buf_lock);
  while (buffer empty) {};
  item = dequeue();
  release(&buf_lock);
  return item
}

Recall: Circular Buffer – first cut

Will we ever come out of the wait loop?
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.

Semaphore 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:
  ```c
  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:
  ```c
  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

Full Solution to Bounded Buffer (coke machine)

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

Discussion about Solution

• Why asymmetry?
  – Producer does: semaP(&emptyBuffer), semaV(&fullBuffer)
  – Consumer does: semaP(&fullBuffer), semaV(&emptyBuffer)
• Is order of P's important?
  – Yes! Can cause deadlock
• Is order of V's important?
  – No, except that it might affect scheduling efficiency
• What if we have 2 producers or 2 consumers?
  – Do we need to change anything?
    Decrease # of empty slots
    Increase # of occupied slots
  ```c
  Producer(item) {
    semaP(&mutex);
    semaP(&emptySlots);
    Enqueue(item);
    semaV(&mutex);
  }
  Consumer() {
    semaP(&fullSlots);
    item = Dequeue();
    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

Administrivia

- Midterm Thursday (February 17)!
  - No class on day of midterm
  - 7-9PM
  - All materials up to today’s lecture!
- Head TA will be posting where you are supposed to go
  - We have 3 primary rooms, and others
- If you are sick, let us know.
  - Do not come to the midterm!
- No class on Thursday
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 nothing, 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);
  if (isEmpty(&queue)) {
    cond_wait(&buf_CV,&buf_lock);
  }
  item = dequeue(&queue);
  release(&buf_lock);
  return(item);
  ```

Mesa monitors

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

  ```
  acquire(&buf_lock);
  while (isEmpty(&queue)) {
    cond_wait(&buf_CV,&buf_lock);
  }
  item = dequeue(&queue);
  release(&buf_lock);
  ```
Circular Buffer – 3rd 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
}

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
  do something so no need to wait

  lock
  condvar.signal();
  unlock

  Check and/or update state variables
  Wait if necessary
  Check and/or update state variables
Basic Readers/Writers Solution

- Correctness Constraints:
  - Readers can access database when no writers
  - Writers can access database when no readers or writers
  - Only one thread manipulates state variables at a time

- Basic structure of a solution:
  - Reader()
    - Wait until no writers
    - Access database
    - Check out - wake up a waiting writer
  - Writer()
    - Wait until no active readers or writers
    - Access database
    - Check out - wake up waiting readers or writer

- 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

```c
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);
    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

```c
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);
    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()

```c
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);
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()

```c
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);
if (AR == 0 & WW > 0)
    cond_signal(&okToWrite);
release(&lock);
```
Simulation of Readers/Writers Solution

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

  ```c
  Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;
      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)**
  - $AR = 1$, $WR = 0$, $AW = 0$, $WW = 0$

  ```c
  Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;
      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)**
  - $AR = 2$, $WR = 0$, $AW = 0$, $WW = 0$

  ```c
  Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;
      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) {
        WR++;
        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 + WR) > 0) {
        WR++;
        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 comes along (R1 and R2 are still accessing dbase)
- AR = 2, WR = 0, AW = 0, WW = 0

Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {
        WW++;
        cond_wait(&okToWrite,&lock); // Sleep on cond var
        WW--;  // No longer waiting
    }
    AW++;  // Now we are active!
    release(&lock);
}

AccessDBase(ReadWrite);
acquire(&lock);
AW--; if (WW > 0)
cond_broadcast(&okToWrite);
else if (WR > 0)
    cond_signal(&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) {
        WW++;
        cond_wait(&okToWrite,&lock); // Sleep on cond var
        WW--;  // No longer waiting
    }
    AW++;  // Now we are active!
    release(&lock);
}

AccessDBase(ReadWrite);
acquire(&lock);
AW--; if (WW > 0)
cond_broadcast(&okToWrite);
else if (WR > 0)
    cond_signal(&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

```c
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) { // Is it safe to write?
        AW++;
        cond_wait(&okToWrite, &lock); // Sleep on cond var
        AR++;
    }
    release(&lock);
    AccessDBase(ReadWrite);
}
```

Simulation of Readers/Writers Solution

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

```c
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--; // Now we are active!
    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

```c
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);
    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

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

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

Simulation of Readers/Writers Solution

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

```c
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
        WR++;
        // No. Writers exist
        cond_wait(&okToRead,&lock);// Sleep on cond var
        // No longer waiting
    }
    AR++; // Now we are active!
    release(&lock);
    AccessDBase(ReadOnly);
    acquire(&lock);
    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 = 2, WR = 1, AW = 0, WW = 1

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

```c
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
        WR++;
        // No. Writers exist
        cond_wait(&okToRead,&lock);// Sleep on cond var
        // No longer waiting
    }
    AR++; // Now we are active!
    release(&lock);
    AccessDBase(ReadOnly);
    acquire(&lock);
    if (AR == 0 && WW > 0)
        cond_signal(&okToWrite);
    release(&lock);
}
Simulation of Readers/Writers Solution

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Simulation of Readers/Writers Solution

- R1 finishes (W1 and R3 waiting)
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Reader() {
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    release(&lock);

    AccessDBase(ReadOnly);
    acquire(&lock);
    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

```c
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
        WR++; // No. Writers exist
        cond_wait(&okToRead,&lock);// Sleep on cond var
    } // 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

```c
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
    } // No longer waiting
    AW++;release(&lock);
    AccessDBase(ReadWrite);
    acquire(&lock);
    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

```c
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
    } // No longer waiting
    AW++;release(&lock);
    AccessDBase(ReadWrite);
    acquire(&lock);
    if (WW > 0){
        cond_signal(&okToWrite);
    } else-if (WR > 0){
        cond_broadcast(&okToRead);
    } 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

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

Simulation of Readers/Writers Solution

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

```c
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);
    if (WW > 0){
        cond_signal(&okToWrite);
    } else-if (WR > 0){
        cond_broadcast(&okToRead);
    } else {release(&lock);
}
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Simulation of Readers/Writers Solution

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

```c
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);
    if (WW > 0){
        cond_signal(&okToWrite);
    } else-if (WR > 0){
        cond_broadcast(&okToRead);
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Simulation of Readers/Writers Solution

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

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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);
    if (WW > 0){
        cond_signal(&okToWrite);
    } else-if (WR > 0){
        cond_broadcast(&okToRead);
    } else {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);
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);
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);
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);
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);
    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()
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)

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); }

Need to change to broadcast():

Must broadcast() to sort things out!
**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?
  
  ```c
  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:

  ```c
  lock while (need to wait) {
    condvar.wait();
  }
  unlock
  do something so no need to wait
  lock
  condvar.signal();
  unlock
  ```

**C-Language Support for Synchronization**

- C language: Pretty straightforward synchronization
  - Just make sure you know all the code paths out of a critical section
  
  ```c
  int Rtn() {
    acquire(&lock);
    if (exception) {
      release(&lock); return errReturnCode;
    } ...
    if Procedure C had lock.acquire, problem!
  }
  ```

**Concurrency and Synchronization in C**

- Harder with more locks
  ```c
  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???
  ```c
  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();
        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 (…)
        {
            lock.release(); // 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.)

```python
import threading
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)

```java
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();`

Recall: User/Kernel Threading Models

- Simple One-to-One Threading Model
- Many-to-One
- Many-to-Many

```
Almost all current implementations
```

Recall: Thread State in the Kernel

- For every thread in a process, the kernel maintains:
  - The thread’s TCB
  - A kernel stack used for syscalls/interrupts/traps
    - This kernel-state is sometimes called the "kernel thread"
    - The "kernel thread" is suspended (but ready to go) when thread is running in user-space
- Additionally, some threads just do work in the kernel
  - Still has TCB
  - Still has kernel stack
  - But not part of any process, and never executes in user mode
In Pintos, Processes are Single-Threaded

- Pintos processes have only one thread
- TCB: Single page (4 KiB)
  - Stack growing from the top (high addresses)
  - struct thread at the bottom (low addresses)
- struct thread defines the TCB structure and PCB structure in Pintos

Pintos: thread.c

Multithreaded Processes (not in Pintos)

- Traditional implementation strategy:
  - One PCB (process struct) per process
  - Each PCB contains (or stores pointers to) each thread’s TCB

- Linux’s strategy:
  - One task_struct per thread
  - Threads belonging to the same process happen to share some resources
    - Like address space, file descriptor table, etc.

- To what extent does this actually matter?

(Aside): Linux “Task”

- Linux “Kernel Thread”: 2 pages (8 KiB)
  - Stack and thread information on opposite sides
  - Containing stack and thread information + process descriptor
- One task_struct per thread

Multithreaded Processes (not in Pintos)

- Traditional implementation strategy:
  - One PCB (process struct) per process
  - Each PCB contains (or stores pointers to) each thread’s TCB

- Linux’s strategy:
  - One task_struct per thread
  - Threads belonging to the same process happen to share some resources
    - Like address space, file descriptor table, etc.

- To what extent does this actually matter?

Aside: Polymorphic Linked Lists in C

- Many places in the kernel need to maintain a “list of X”
  - This is tricky in C, which has no polymorphism
  - Essentially adding an interface to a package
- In Linux and Pintos this is done by embedding a list_elem in the struct
  - Macros allow shift of view between object and list
  - You saw this in Homework 1

Pintos: list.c
These two threads:
- Are used internally by the kernel
- Don’t correspond to any particular user thread or process

Recall: Scheduling
• Question: How is the OS to decide which of several tasks to take off a queue?
• Scheduling: deciding which threads are given access to resources from moment to moment
  – Often, we think in terms of CPU time, but could also think about access to resources like network BW or disk access
• Next time: we dive into scheduling!
Recall: Address Space

- Program operates in an address space that is distinct from the physical memory space of the machine.

Understanding "Address Space"

- Page table is the primary mechanism.
- Privilege Level determines which regions can be accessed:
  - Which entries can be used.
- System (PL=0) can access all, User (PL=3) only part.
- Each process has its own address space.
- The "System" part of all of them is the same.

All system threads share the same system address space and same memory.

Page Table Mapping (Rough Idea)

User Process View of Memory
Processor Mode (Privilege Level)

Processor registers:
- sp
- ip

Page Table:
- CPL: 3 - user
- 0x00000000
- 0x08048000
- 0xffffffff
- 0xc0000000 argv

Physical Memory:
- User code
- User data
- Heap
- Stack

Aside: x86 (32-bit) Page Table Entry

- Controls many aspects of access
- Later — discuss page table organization
  - For 32 (64?) bit VAS, how large? vs size of memory?
  - Used sparsely

Pintos: page_dir.c

User → Kernel

User code
User data
Heap
Stack

CPL: 3 - user

Kernel code
Kernel data

Process Virtual Address Space
Physical Memory

User → Kernel

Kernel code
Kernel data

CPL: 0 - sys

Page Table

Processor registers
- sp
- ip

Page Table

Physical Memory
Page Table Resides in Memory*

* In the simplest case. Actually more complex. More later.

Kernel Portion of Address Space

- Kernel memory is mapped into address space of every process
- Contains the kernel code
  - Loaded when the machine booted
- Explicitly mapped to physical memory
  - OS creates the page table
- Used to contain all kernel data structures
  - Lists of processes/threads
  - Page tables
  - Open file descriptions, sockets, ttys, ...
- Kernel stack for each thread

1 Kernel Code, Many Kernel Stacks

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
- Readers/Writers Monitor example
  - Shows how monitors allow sophisticated controlled entry to protected code