Announcements

Project 2a: Graded – see Learn@UW; contact your TA if questions
Part 2b will be longer….

Exam 2: Monday 10/26 7:15 – 9:15 Ingraham B10
- Covers all of Concurrency Piece (lecture and book)
  - Light on chapter 29, nothing from chapter 33
  - Very few questions from Virtualization Piece
- Multiple choice (fewer pure true/false)
- Look at two concurrency homeworks
- **Questions from Project 2**

Project 3: Only xv6 part; watch two videos early
- Due Wed 10/28

Today's Reading: Chapter 31

UNIVERSITY of WISCONSIN-MADISON
Computer Sciences Department

CS 537
Introduction to Operating Systems

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Semaphores

Questions answered in this lecture:

Review: How to implement join with condition variables?

Review: How to implement producer/consumer with condition variables?

What is the difference between **semaphores** and condition variables?

How to implement a **lock** with semaphores?

How to implement semaphores with locks and condition variables?

How to implement **join** and producer/consumer with semaphores?

How to implement **reader/writer locks** with semaphores?

Concurrency Objectives

Mutual exclusion (e.g., A and B don't run at same time)

- solved with *locks*

Ordering (e.g., B runs after A does something)

- solved with *condition variables* and *semaphores*

Condition Variables

wait(cond_t *cv, mutex_t *lock)

- assumes the lock is held when wait() is called
- puts caller to sleep + releases the lock (atomically)
- when awoken, reacquires lock before returning

signal(cond_t *cv)

- wake a single waiting thread (if >= 1 thread is waiting)
- if there is no waiting thread, just return, doing nothing

Join Implementation: Correct

Parent:

```
void thread_join() {
        Mutex_lock(&m);            // w
        if (done == 0)             // x
            Cond_wait(&c, &m); // y
        Mutex_unlock(&m);          // z
}
```

Child:

```
void thread_exit() {
        Mutex_lock(&m);          // a
        done = 1;                // b
        Cond_signal(&c);         // c
        Mutex_unlock(&m);        // d
}
```

Parent:	w	x	y				z
Child:				a	b	c	

Use mutex to ensure no race between interacting with state and wait/signal

Producer/Consumer Problem

Producers generate data (like pipe writers)

Consumers grab data and process it (like pipe readers)

Use condition variables to:
make producers wait when buffers are full
make consumers wait when there is nothing to consume

Broken Implementation of Producer Consumer

```
void *producer(void *arg) {
    for (int i=0; i<loops; i++) {
        Mutex_lock(&m); // p1
        while(numfull == max) //p2
            Cond_wait(&cond, &m); //p3
        do_fill(i); // p4
        Cond_signal(&cond); //p5
        Mutex_unlock(&m); //p6
    }
}
```

```
void *consumer(void *arg) {
    while(1) {
        Mutex_lock(&m); // c1
        while(numfull == 0) // c2
            Cond_wait(&cond, &m); // c3
        int tmp = do_get(); // c4
        Cond_signal(&cond); // c5
        Mutex_unlock(&m); // c6
        printf("%d\n", tmp); // c7
    }
}
```

wait() wait() signal() wait() signal()

Producer: p1 p2 p4 p5 p6 p1 p2 p3
Consumer1: c1 c2 c3
Consumer2: c1 c2 c3 c2 c4 c5

does last signal wake producer or consumer2?

Producer/Consumer: Two CVs

```
void *producer(void *arg) {
    for (int i = 0; i < loops; i++) {
        Mutex_lock(&m); // p1
        if (numfull == max) // p2
            Cond_wait(&empty, &m); // p3
        do_fill(i); // p4
        Cond_signal(&fill); // p5
        Mutex_unlock(&m); //p6
    }
}
```

```
void *consumer(void *arg) {
    while (1) {
        Mutex_lock(&m); // c1
        if (numfull == 0) // c2
            Cond_wait(&fill, &m); // c3
        int tmp = do_get(); // c4
        Cond_signal(&empty); // c5
        Mutex_unlock(&m); // c6
    }
}
```

Is this correct? Can you find a bad schedule?

1. consumer1 waits because numfull == 0
2. producer increments numfull, wakes consumer1
3. before consumer1 runs, consumer2 runs, grabs entry, sets numfull=0.
4. consumer2 then reads bad data.

Producer: p1 p2 p4 p5 p6
Consumer1: c1 c2 c3 c4! ERROR
Consumer2: c1 c2 c4 c5 c6

CV Rule of Thumb 3

Whenever a lock is acquired, recheck assumptions about state!

Use "while" intead of "if"

Possible for another thread to grab lock between signal and wakeup from wait

- Difference between Mesa (practical implementation) and Hoare (theoretical) semantics
- Signal() simply makes a thread runnable, does not guarantee thread run next

Note that some libraries also have "spurious wakeups"

- May wake multiple waiting threads at signal or at any time

Producer/Consumer: Two CVs and While

```
void *producer(void *arg) {
    for (int i = 0; i < loops; i++) {
        Mutex_lock(&m); // p1
        while (numfull == max) // p2
            Cond_wait(&empty, &m); // p3
        do_fill(i); // p4
        Cond_signal(&fill); // p5
        Mutex_unlock(&m); //p6
    }
}
```

```
void *consumer(void *arg) {
    while (1) {
        Mutex_lock(&m);
        while (numfull == 0)
            Cond_wait(&fill, &m);
        int tmp = do_get();
        Cond_signal(&empty);
        Mutex_unlock(&m);
    }
}
```

Is this correct? Can you find a bad schedule?

Correct!

- no concurrent access to shared state
- every time lock is acquired, assumptions are reevaluated
- a consumer will get to run after every `do_fill()`
- a producer will get to run after every `do_get()`

Summary: Rules of Thumb for CVs

Keep state in addition to CV's

Always do wait/signal with lock held

Whenever thread wakes from waiting, recheck state

Condition Variables vs Semaphores

Condition variables have no state (other than waiting queue)

- Programmer must track additional state

Semaphores have state: track integer value

- State cannot be directly accessed by user program, but state determines behavior of semaphore operations

Semaphore Operations

Allocate and Initialize

```
sem_t sem;
sem_init(sem_t *s, int initval) {
  s->value = initval;
}
```

User cannot read or write value directly after initialization

Wait or Test (sometime P() for Dutch word)

Waits until value of sem is > 0, then decrements sem value

Signal or Increment or Post (sometime V() for Dutch)

Increment sem value, then wake a single waiter

wait and post are atomic

Join with CV vs Semaphores

CVs:

```
void thread_join() {
        Mutex_lock(&m);            // w
        if (done == 0)             // x
            Cond_wait(&c, &m);     // y
        Mutex_unlock(&m);          // z
}
```

```
void thread_exit() {
        Mutex_lock(&m);            // a
        done = 1;                  // b
        Cond_signal(&c);           // c
        Mutex_unlock(&m);          // d
}
```

Semaphores:

Sem_wait(): Waits until value > 0, then decrement
Sem_post(): Increment value, then wake a single waiter

```
sem_t s;
sem_init(&s, ???);
```

Initialize to 0 (so sem_wait() must wait…)

```
void thread_join() {
        sem_wait(&s);
}
```

```
void thread_exit() {
        sem_post(&s)
}
```

Equivalence Claim

Semaphores are equally powerful to Locks+CVs

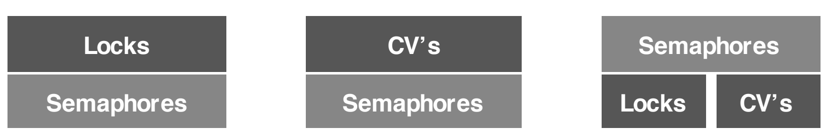
- what does this mean?

One might be more convenient, but that's not relevant

Equivalence means each can be built from the other

Proof Steps

Want to show we can do these three things:



Build Lock from Semaphore

```
typedef struct __lock_t {
// whatever data structs you need go here
} lock_t;

void init(lock_t *lock) {
}

void acquire(lock_t *lock) {
}

void release(lock_t *lock) {
}
```

Sem_wait(): Waits until value > 0, then decrement
Sem_post(): Increment value, then wake a single waiter

Locks
Semaphores

Build Lock from Semaphore

```
typedef struct __lock_t {
  sem_t sem;
} lock_t;

void init(lock_t *lock) {
  sem_init(&lock->sem, ??);
}
void acquire(lock_t *lock) {
  sem_wait(&lock->sem);
}
void release(lock_t *lock) {
  sem_post(&lock->sem);
}
```

1 → 1 thread can grab lock

Sem_wait(): Waits until value > 0, then decrement
Sem_post(): Increment value, then wake a single waiter

Locks
Semaphores

Building CV's over Semaphores

Possible, but really hard to do right

Read about Microsoft Research's attempts:

http://research.microsoft.com/pubs/64242/ImplementingCVs.pdf

Build Semaphore from Lock and CV

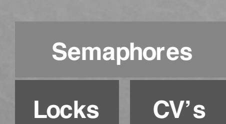
```
Typedef struct {
    // what goes here?


} sem_t;

Void sem_init(sem_t *s, int value) {
    // what goes here?


}
```

Sem_wait(): Waits until value > 0, then decrement
Sem_post(): Increment value, then wake a single waiter



Build Semaphore from Lock and CV

```
Typedef struct {
    int value;
    cond_t cond;
    lock_t lock;
} sem_t;

Void sem_init(sem_t *s, int value) {
    s->value = value;
    cond_init(&s->cond);
    lock_init(&s->lock);
}
```

Sem_wait(): Waits until value > 0, then decrement
Sem_post(): Increment value, then wake a single waiter

Semaphores
Locks | CV's

Build Semaphore from Lock and CV

```
Sem_wait{sem_t *s) {
    // what goes here?
}
```

```
Sem_post{sem_t *s) {
    // what goes here?
}
```

Sem_wait(): Waits until value > 0, then decrement
Sem_post(): Increment value, then wake a single waiter

Semaphores
Locks | CV's

Build Semaphore from Lock and CV

```
Sem_wait{sem_t *s) {
    lock_acquire(&s->lock);
    // this stuff is atomic


    lock_release(&s->lock);
}
```

```
Sem_post{sem_t *s) {
    lock_acquire(&s->lock);
    // this stuff is atomic

    lock_release(&s->lock);
}
```

Semaphores

Locks | CV's

Sem_wait(): Waits until value > 0, then decrement
Sem_post(): Increment value, then wake a single waiter

Build Semaphore from Lock and CV

```
Sem_wait{sem_t *s) {
    lock_acquire(&s->lock);
    while (s->value <= 0)
        cond_wait(&s->cond);
    s->value--;
    lock_release(&s->lock);
}
```

```
Sem_post{sem_t *s) {
    lock_acquire(&s->lock);
    // this stuff is atomic

    lock_release(&s->lock);
}
```

Semaphores

Locks | CV's

Sem_wait(): Waits until value > 0, then decrement
Sem_post(): Increment value, then wake a single waiter

Build Semaphore from Lock and CV

```
Sem_wait{sem_t *s) {
    lock_acquire(&s->lock);
    while (s->value <= 0)
        cond_wait(&s->cond);
    s->value--;
    lock_release(&s->lock);
}
```

```
Sem_post{sem_t *s) {
    lock_acquire(&s->lock);
    s->value++;
    cond_signal(&s->cond);
    lock_release(&s->lock);
}
```

Semaphores	
Locks	CV's

Sem_wait(): Waits until value > 0, then decrement
Sem_post(): Increment value, then wake a single waiter

Producer/Consumer: Semaphores #1

Simplest case:

- Single producer thread, single consumer thread
- Single shared buffer between producer and consumer

Requirements

- Consumer must wait for producer to fill buffer
- Producer must wait for consumer to empty buffer (if filled)

Requires 2 semaphores

- emptyBuffer: Initialize to ??? 1 → 1 empty buffer; producer can run 1 time first
- fullBuffer: Initialize to ??? 0 → 0 full buffers; consumer can run 0 times first

Producer

```
While (1) {
    sem_wait(&emptyBuffer);
    Fill(&buffer);
    sem_signal(&fullBuffer);
}
```

Consumer

```
While (1) {
    sem_wait(&fullBuffer);
    Use(&buffer);
    sem_signal(&emptyBuffer);
}
```

Producer/Consumer: Semaphores #2

Next case: **Circular Buffer**

- Single producer thread, single consumer thread
- Shared buffer with **N** elements between producer and consumer

Requires 2 semaphores

- emptyBuffer: Initialize to ??? N → N empty buffers; producer can run N times first
- fullBuffer: Initialize to ??? 0 → 0 full buffers; consumer can run 0 times first

Producer

```
i = 0;
While (1) {
    sem_wait(&emptyBuffer);
    Fill(&buffer[i]);
    i = (i+1)%N;
    sem_signal(&fullBuffer);
}
```

Consumer

```
j = 0;
While (1) {
    sem_wait(&fullBuffer);
    Use(&buffer[j]);
    j = (j+1)%N;
    sem_signal(&emptyBuffer);
}
```

Producer/Consumer: Semaphore #3

Final case:

- **Multiple producer threads, multiple consumer threads**
- Shared buffer with N elements between producer and consumer

Requirements

- Each consumer must grab unique filled element
- Each producer must grab unique empty element
- **Why will previous code (shown below) not work???**

Producer

```
i = 0;
While (1) {
    sem_wait(&emptyBuffer);
    Fill(&buffer[i]);
    i = (i+1)%N;
    sem_signal(&fullBuffer);
}
```

Consumer

```
j = 0;
While (1) {
    sem_wait(&fullBuffer);
    Use(&buffer[j]);
    j = (j+1)%N;
    sem_signal(&emptyBuffer);
}
```

Are i and j private or shared? Need each producer to grab unique buffer

Producer/Consumer: Multiple Threads

Final case:

- Multiple producer threads, multiple consumer threads
- Shared buffer with N elements between producer and consumer

Requirements

- Each consumer must grab unique filled element
- Each producer must grab unique empty element

Producer

```
While (1) {
    sem_wait(&emptyBuffer);
    myi = findempty(&buffer);
    Fill(&buffer[myi]);
    sem_signal(&fullBuffer);
}
```

Consumer

```
While (1) {
    sem_wait(&fullBuffer);
    myj = findfull(&buffer);
    Use(&buffer[myj]);
    sem_signal(&emptyBuffer);
}
```

Are myi and myj private or shared? Where is mutual exclusion needed???

Producer/Consumer: Multiple Threads

Consider three possible locations for mutual exclusion

Which work??? Which is best???

Producer #1

```
sem_wait(&mutex);
sem_wait(&emptyBuffer);
myi = findempty(&buffer);
Fill(&buffer[myi]);
sem_signal(&fullBuffer);
sem_signal(&mutex);
```

Consumer #1

```
sem_wait(&mutex);
sem_wait(&fullBuffer);
myj = findfull(&buffer);
Use(&buffer[myj]);
sem_signal(&emptyBuffer);
sem_signal(&mutex);
```

Problem: Deadlock at mutex (e.g., consumer runs first; won't release mutex)

Producer/Consumer: Multiple Threads

Consider three possible locations for mutual exclusion

Which work??? Which is best???

Producer #2

```
sem_wait(&emptyBuffer);
sem_wait(&mutex);
myi = findempty(&buffer);
Fill(&buffer[myi]);
sem_signal(&mutex);
sem_signal(&fullBuffer);
```

Consumer #2

```
sem_wait(&fullBuffer);
sem_wait(&mutex);
myj = findfull(&buffer);
Use(&buffer[myj]);
sem_signal(&mutex);
sem_signal(&emptyBuffer);
```

Works, but limits concurrency:
Only 1 thread at a time can be using or filling different buffers

Producer/Consumer: Multiple Threads

Consider three possible locations for mutual exclusion

Which work??? Which is best???

Producer #3

```
sem_wait(&emptyBuffer);
sem_wait(&mutex);
myi = findempty(&buffer);
sem_signal(&mutex);
Fill(&buffer[myi]);
sem_signal(&fullBuffer);
```

Consumer #3

```
sem_wait(&fullBuffer);
sem_wait(&mutex);
myj = findfull(&buffer);
sem_signal(&mutex);
Use(&buffer[myj]);
sem_signal(&emptyBuffer);
```

Works and increases concurrency; only finding a buffer is protected by mutex;
Filling or Using different buffers can proceed concurrently

Reader/Writer Locks

Goal:

Let multiple reader threads grab lock (shared)

Only one writer thread can grab lock (exclusive)

- No reader threads
- No other writer threads

Let us see if we can understand code…

Reader/Writer Locks

```
typedef struct _rwlock_t {
    sem_t lock;
    sem_t writelock;
    int readers;
} rwlock_t;

void rwlock_init(rwlock_t *rw) {
    rw->readers = 0;
    sem_init(&rw->lock, 1);
    sem_init(&rw->writelock, 1);
}

```

Reader/Writer Locks

```
void rwlock_acquire_readlock(rwlock_t *rw) {
    sem_wait(&rw->lock);
    rw->readers++;
    if (rw->readers == 1)
        sem_wait(&rw->writelock);
    sem_post(&rw->lock);
}
void rwlock_release_readlock(rwlock_t *rw) {
    sem_wait(&rw->lock);
    rw->readers--;
    if (rw->readers == 0)
        sem_post(&rw->writelock); ]
    sem_post(&rw->lock);
}
rwlock_acquire_writelock(rwlock_t *rw) { sem_wait(&rw->writelock);
rwlock_release_writelock(rwlock_t *rw) { sem_post(&rw->writelock); }
```

```
T1: acquire_readlock()
T2: acquire_readlock()
T3: acquire_writelock()
T2: release_readlock()
T1: release_readlock()
T4: acquire_readlock()
T5: acquire_readlock()  // ???
T3: release_writelock()
// what happens???
```

Semaphores

Semaphores are equivalent to locks + condition variables

- Can be used for both mutual exclusion and ordering

Semaphores contain **state**

- How they are initialized depends on how they will be used
- Init to 1: Mutex
- Init to 0: Join (1 thread must arrive first, then other)
- Init to N: Number of available resources

Sem_wait(): Waits until value > 0, then decrement (atomic)

Sem_post(): Increment value, then wake a single waiter (atomic)

Can use semaphores in producer/consumer relationships and for reader/writer locks