CONCURRENCY: CONDITION VARIABLES, SEMAPHORES

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ADMINISTRIVIA

- Project 3 is due next Monday 3/11

- Midterm is next Wednesday 3/13 at 5.15pm, details on Piazza
- Includes all material covered till 3/12
- Work out practice midterms before discussion!

AGENDA / LEARNING OUTCOMES

Concurrency abstractions

- How to implement producer-consumer pattern with CV/locks?
- How can semaphores help this implementation?

RECAP

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*

ORDERING EXAMPLE: JOIN

```
pthread_t p1, p2;
Pthread_create(&p1, NULL, mythread, "A");
Pthread_create(&p2, NULL, mythread, "B");
// join waits for the threads to finish
Pthread_join(p1, NULL);
Pthread_join(p2, NULL);
printf("main: done\n [balance: %d]\n [should: %d]\n",
    balance, max*2);
return 0;
```

how to implement join()?

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

RULES OF THUMB

Keep state in addition to CV's!

CV's are used to signal threads when state changes

If state is already as needed, thread doesn't wait for a signal!

Hold mutex lock while calling wait/signal

Ensures no race between interacting with state and wait/signal

PRODUCER/CONSUMER PROBLEM

EXAMPLE: UNIX PIPES

A pipe may have many writers and readers

Internally, there is a finite-sized buffer

Writers add data to the buffer

- Writers have to wait if buffer is full

Readers remove data from the buffer

- Readers have to wait if buffer is empty

EXAMPLE: UNIX PIPES

start

Buf:

end

EXAMPLE: UNIX PIPES

Implementation:

- reads/writes to buffer require locking
- when buffers are full, writers must wait
- when buffers are empty, readers must wait

PRODUCER/CONSUMER PROBLEM

Producers generate data (like pipe writers)

Consumers grab data and process it (like pipe readers)

Producer/consumer problems are frequent in systems (e.g. web servers)

General strategy use condition variables to:
- make producers wait when buffers are full
- make consumers wait when there is nothing to consume

PRODUCE/CONSUMER EXAMPLE

Start with easy case:

- 1 producer thread
- 1 consumer thread
- 1 shared buffer to fill/consume (max = 1)

Numfull = number of buffers currently filled

numfull

Thread 1 state:

```
void *producer(void *arg) {
    for (int i=0; i<loops; i++) {
        Mutex_lock(&m);
        if(numfull == max)
            Cond_wait(&cond, &m);
        do_fill(i);
        Cond_signal(&cond);
        Mutex_unlock(&m);
    }
}
```

Thread 2 state:

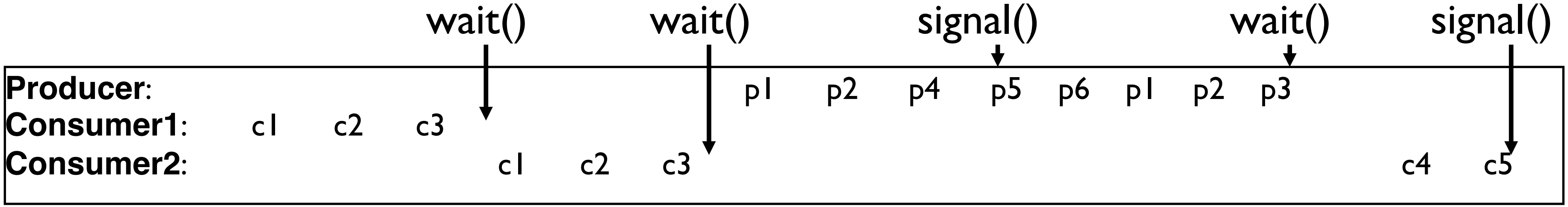
```
void *consumer(void *arg) {
    while(1) {
        Mutex_lock(&m);
        if(numfull == 0)
            Cond_wait(&cond, &m);
        int tmp = do_get();
        Cond_signal(&cond);
        Mutex_unlock(&m);
        printf("%d\n", tmp);
    }
}
```

WHAT ABOUT 2 CONSUMERS?

Can you find a problematic timeline with 2 consumers (still 1 producer)?

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

```c
void *consumer(void *arg) {
    while(1) {
        Mutex_lock(&m);  // c1
        if(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
    }
}
```



HOW TO WAKE THE RIGHT THREAD?

Wake all the threads!?

Better solution (usually): use two condition variables

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);
        if (numfull == 0)
            Cond_wait(&fill, &m);
        int tmp = do_get();
        Cond_signal(&empty);
        Mutex_unlock(&m);
    }
}
```

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
    }
}
```

Producer:
Consumer1:
Consumer2:

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);
    }
}
```

GOOD RULE OF THUMB 3

Whenever a lock is acquired, recheck assumptions about state!

Another thread could grab lock in between signal and wakeup from wait

Note that some libraries also have "spurious wakeups"

(may wake multiple waiting threads at signal or at any time)

SUMMARY: RULES OF THUMB FOR CVS

1. Keep state in addition to CV's

2. Always do wait/signal with lock held

3. Whenever thread wakes from waiting, recheck state

SUMMARY: 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

INTRODUCING 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) sem_wait(sem_t*)

Decrements sem value, Waits until value of sem is >= 0

Signal or Post (sometime V() for Dutch) sem_post(sem_t*)

Increment sem value, then wake a single waiter


BUNNY
https://tinyurl.com/cs537-sp19-bunny7

BUNNY: BUILD LOCK FROM SEMAPHORE

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

void init(lock_t *lock) {

}

void acquire(lock_t *lock) {

}

void release(lock_t *lock) {

}
```

sem_init(sem_t*, int initial)
sem_wait(sem_t*): Decrement, wait until value >= 0
sem_post(sem_t*): Increment value
then wake a single waiter

https://tinyurl.com/cs537-sp19-bunny7

JOIN WITH CV VS SEMAPHORES

```
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
}
```

```
sem_t s;
sem_init(&s, ___-);
```

sem_wait(): Decrement, wait until value >= 0
sem_post(): Increment value, then wake a single waiter

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

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

PRODUCER/CONSUMER: SEMAPHORES #1

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

Use 2 semaphores
- emptyBuffer: Initialize to _________
- fullBuffer: Initialize to ___________

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

Single producer thread, single consumer thread

Shared buffer with **N** elements between producer and consumer

Use 2 semaphores

- emptyBuffer: Initialize to ____________
- fullBuffer: Initialize to ____________

```
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

PRODUCER/CONSUMER: MULTIPLE THREADS

```
Producer
while (1) {
    sem_wait(&emptyBuffer);
    my_i = findempty(&buffer);
    Fill(&buffer[my_i]);
    sem_signal(&fullBuffer);
}
```

```
Consumer
while (1) {
    sem_wait(&fullBuffer);
    my_j = findfull(&buffer);
    Use(&buffer[my_j]);
    sem_signal(&emptyBuffer);
}
```

Are `my_i` and `my_j` 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);
    my_i = findempty(&buffer);
    Fill(&buffer[my_i]);
    sem_signal(&fullBuffer);
    sem_signal(&mutex);
```

```
Consumer #1
    sem_wait(&mutex);
    sem_wait(&fullBuffer);
    my_j = findfull(&buffer);
    Use(&buffer[my_j]);
    sem_signal(&emptyBuffer);
    sem_signal(&mutex);
```

PRODUCER/CONSUMER: MULTIPLE THREADS

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

```
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

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 next?

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 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 and for reader/writer locks

NEXT STEPS

Project 3: Out now!

Midterm details posted

Next class: How to build a semaphore, deadlocks