CONCURRENCY: SEMAPHORES

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ADMINISTRIVIA

Midterm: Solutions, Grades

Mid-semester grades soon

P4 progress

AGENDA / LEARNING OUTCOMES

Concurrency abstractions

- How can semaphores help with producer-consumer?
- How to implement semaphores?

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 (with state)*

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

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	

Rule of Thumb: Keep state in addition to CV's!

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);
    }
}
```

1. Keep state in addition to CV's
2. Always do wait/signal with lock held
3. Whenever thread wakes from waiting, recheck state

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

SEMAPHORE OPERATIONS

Wait or Test: sem_wait(sem_t*)

Decrements sem value by 1, Waits if value of sem is negative (< 0)

Signal or Post: sem_post(sem_t*)

Increment sem value by 1, then wake a single waiter if exists

Value of the semaphore, when negative = the number of waiting threads

Binary Semaphore (Lock)

```
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 if value < 0

sem_post(sem_t*): Increment value
then wake a single waiter

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 if 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_post(&fullBuffer);
}
```

Consumer

```
while (1) {
    sem_wait(&fullBuffer);
    Use(&buffer);
    sem_post(&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_post(&fullBuffer);
}
```

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

Consumer

```
while (1) {
    sem_wait(&fullBuffer);
    my_j = findfull(&buffer);
    Use(&buffer[my_j]);
    sem_post(&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_post(&fullBuffer);
    sem_post(&mutex);
```

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

PRODUCER/CONSUMER: MULTIPLE THREADS

```
Producer #2
    sem_wait(&emptyBuffer);
    sem_wait(&mutex);
    myi = findempty(&buffer);
    Fill(&buffer[myi]);
    sem_post(&mutex);
    sem_post(&fullBuffer);
```

```
Consumer #2
    sem_wait(&fullBuffer);
    sem_wait(&mutex);
    myj = findfull(&buffer);
    Use(&buffer[myj]);
    sem_post(&mutex);
    sem_post(&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_post(&mutex);
    Fill(&buffer[myi]);
    sem_post(&fullBuffer);
```

```
Consumer #3
    sem_wait(&fullBuffer);
    sem_wait(&mutex);
    myj = findfull(&buffer);
    sem_post(&mutex);
    Use(&buffer[myj]);
    sem_post(&emptyBuffer);
```

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

QUIZ 12

```
int done = 0;
pthread_cond_t c = PTHREAD_COND_INITIALIZER;

void thr_exit() {
   done = 1;                          //e1
   Pthread_cond_signal(&c);           //e2
}

void thr_join() {
   if (done == 0)                     //j1
      Pthread_cond_wait(&c);          //j2
}
```

Execution order

j1, e1, e2, j2

```
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
    }
}
```

```
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
    }
}
```

Producer runs for one iteration followed by the consumer?

Assume you start from i = 0, numfull = 0, max = 5

If the consumer runs first?

The variable 'numfull' cannot be greater than the variable 'loops'.

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()

READER/WRITER LOCKS

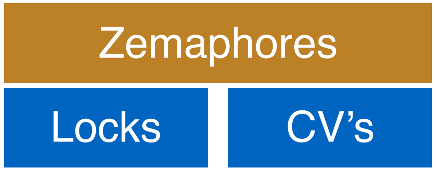
```
void rwlock_acquire_readlock(rwlock_t *rw) {
        sem_wait(&rw->lock);
        rw->readers++;
        if (rw->readers == 1)
            sem_wait(&rw->writelock);
        sem_post(&rw->lock);
}
void rwlock_release_readlock(rwlock_t *rw) {
        sem_wait(&rw->lock);
        rw->readers--;
   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

BUILD ZEMAPHORE!

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

void zem_init(zem_t *s, int value) {
    s->value = value;
    cond_init(&s->cond);
    lock_init(&s->lock);
}
```



zem_wait(): Waits while value <= 0, Decrement

zem_post(): Increment value, then wake a single waiter

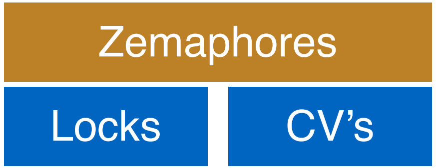
BUILD ZEMAPHORE FROM LOCKS AND CV

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

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

zem_wait(): Waits while value <= 0, Decrement

zem_post(): Increment value, then wake a single waiter



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(): Decrement and then wait if < 0 (atomic)

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

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

NEXT STEPS

Concurrency Bugs!