Welcome to CS 537

CONCURRENCY: SEMAPHORES

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CS 537, Spring 2020

ADMINISTRIVIA

- Project 3 is due Today 10pm!

- Midterm is next Thursday 3/12, details on Piazza
- Discussion today: Practice, review for the midterm
  ↳ TA review friday & Monday
- AEFIS midsemester feedback → closes on friday

AGENDA / LEARNING OUTCOMES

Concurrency abstractions

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

RECAP

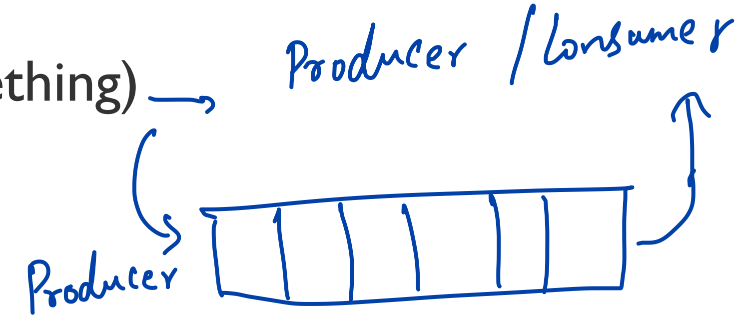
CONCURRENCY OBJECTIVES

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

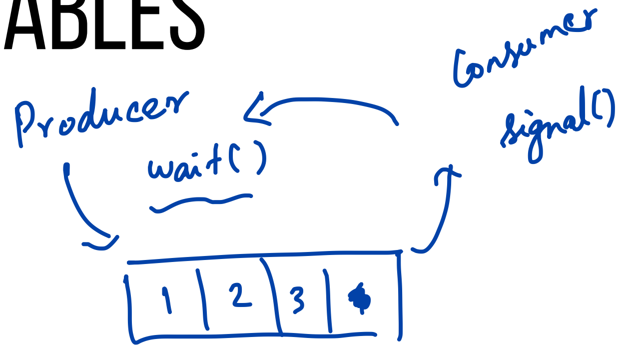
solved with *locks*

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

solved with *condition variables (with state)*



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

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);
    }
}
```

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

1. Keep state in addition to CV's → numfull in producer / consumer thread

2. Always do wait/signal with lock held

3. Whenever thread wakes from waiting, recheck state

while instead of if

QUIZ 17

https://tinyurl.com/cs537-sp20-quiz17

What is the sequence of execution when the producer runs for one iteration followed by the consumer?

P1 P2 P4 P5 P6 C1 C2 C4 C5 C6 C7

What is the sequence of execution if the consumer runs first?

C1 C2 C3 P1 P2 P4 P5 P6 C4 C5 C6 C7

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

False

Prod

lock P1

if (n == m) P2

cond_wait P3

do_fill P4

signal P5

unlock P6

Cons

→ C1 lock

→ C2 if (n == 0)

→ C3 cond_wait

do_get

signal

unlock

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

Initialized

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

init ← 0

T1 sem_wait

V: -1

Wait or Test: sem_wait(sem_t*)

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

↳ sleep

T2 sem_wait

V: -2

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) {
  sem_ int(&sem, 1)
}

void acquire(lock_t *lock) {
  sem_ wait()
}

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

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

initial value

T1 lock
T2 lock

0
-1 T1 sleep
-2 T2 sleep

X
nobody can wake up T1

$\boxed{1}$

0 T1 lock
-1 T2 sleep
-2 T3 sleep

T1 unlock
-1 T2 lock

JOIN WITH CV VS SEMAPHORES

Parent blocks till child exits

```
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
}
```

```
sem_t s;
sem_init(&s, _0_);
```

sem_wait(): Decrement, wait if value < 0

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

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

want parent to block

inc 1 if child runs first

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

PRODUCER/CONSUMER: SEMAPHORES #1

Single producer thread, single consumer thread
Single shared buffer between producer and consumer → Max 1 element

Use 2 semaphores

- emptyBuffer: Initialize to ___1___
- fullBuffer: Initialize to ___0___

Producer

```
while (1) {
    sem_wait(&emptyBuffer); ← 0
    Fill(&buffer);  ← run

    sem_post(&fullBuffer);
}
```

Consumer

```
while (1) {
    sem_wait(&fullBuffer);  -1 , 0 after post
    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 ~~1~~ N
- fullBuffer: Initialize to 0

Max buffer size = N

```
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);
}
```

block here if buffer is empty

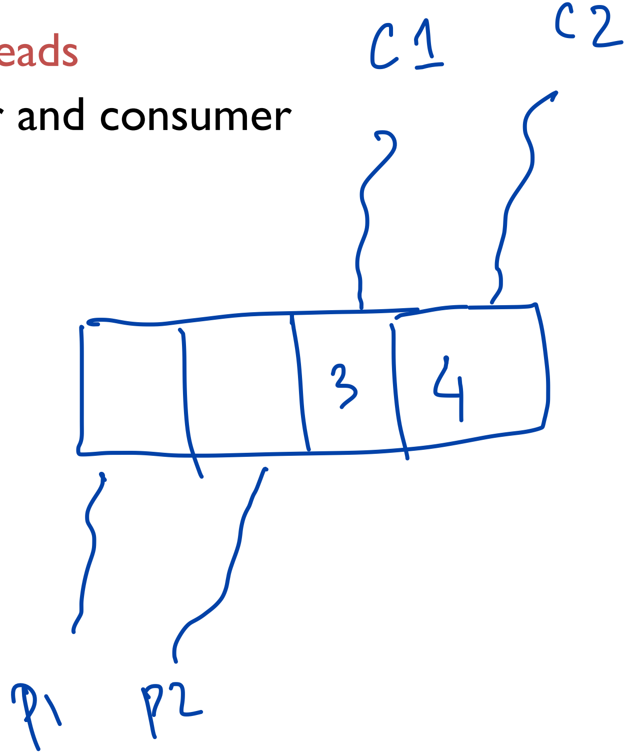
PRODUCER/CONSUMER: SEMAPHORE #3

Final case:

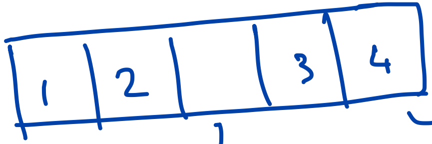
- Multiple producer threads, multiple consumer threads
- Shared buffer with N elements between producer and consumer

Requirements

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



PRODUCER/CONSUMER: MULTIPLE THREADS



my_j

5

my_i

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);
}
```

Two producer threads could write to same location

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);
```

← P1 wait

Consumer #1

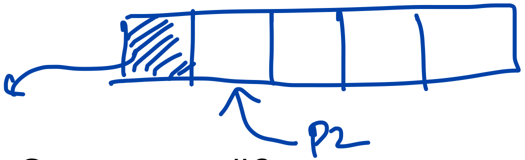
```
    sem_wait(&mutex);
    sem_wait(&fullBuffer);
    my_j = findfull(&buffer);
    Use(&buffer[my_j]);
    sem_post(&emptyBuffer);
    sem_post(&mutex);
```

C1 locks

← waits

Dead lock

Producer/Consumer: Multiple Threads



P1, P2

Producer #2

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

5

P2 wait

P1 lock

P1 unlock

Computation / disk access

Consumer #2

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

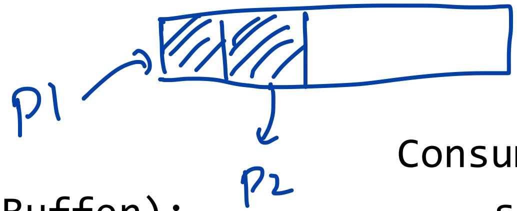
Works, but limits concurrency:

Only 1 thread at a time can be using or filling different buffers

PRODUCER/CONSUMER: MULTIPLE THREADS

in-use

1 | 0 | 0 | 0 | 0



Producer #3

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

P1, P2 do this at the same time

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

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);
}
```

Two semaphores

Num of readers

Lock init

READER/WRITER LOCKS

R2

R1

```
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); }
```

inc readers

wait if writer threads

Mutual exclusion

both read lock

T	n Readers	w2
	0	1
T1: acquire_readlock()	1	0
T2: acquire_readlock()	2	0
T3: acquire_writelock()	2	-1
T2: release_readlock()	1	-1
T1: release_readlock()	0	0
T4: acquire_readlock()		
T5: acquire_readlock()		
T3: release_writelock()		

// what happens next?

Exclusive

QUIZ 18

https://tinyurl.com/cs537-sp20-quiz18

T1: acquire_readlock() → T1 gets read lock RUN

T2: acquire_readlock() → T2 gets read lock $\boxed{\text{RUN}}$

T3: acquire_writelock() → T3 blocked

T4: acquire_writelock() → T4 gets write lock RUN

T5: acquire_writelock() → T5 blocked → waiting for write lock

T6: acquire_readlock() → T6 blocked

T8: acquire_writelock() → T8 gets write lock RUN

T7: acquire_readlock() → T7 wait for read lock

T9: acquire_readlock() → T9 wait for read lock

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

Project 3: Due Today!

Midterm details posted on Piazza

Discussion today: Practice for midterm

Next class: Deadlocks