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Computer Sciences Department

CS 537
Introduction to Operating Systems

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Semaphores

Questions answered in this lecture:

Why are semaphores necessary?

How are semaphores used for mutual exclusion?

How are semaphores used for scheduling constraints?

Examples: Join and Producer/Consumer

Motivation for Semaphores

Locks only provide mutual exclusion

- Ensure only one thread is in critical section at a time

May want more: Place ordering on scheduling of threads

- Example: Producer/Consumer
  - Producer: Creates a resource (data)
  - Consumer: Uses a resource (data)
- Example
  - ps | grep "gcc" | wc
- Don't want producers and consumers to operate in lock step
  - Place a fixed-size buffer between producers and consumers
  - Synchronize accesses to buffer
  - Producer waits if buffer full; consumer waits if buffer empty

Semaphores

Semaphores: Introduced by Dijkstra in 1960s

Semaphores have two purposes

- Mutex: Ensure threads don't access critical section at same time
- Scheduling constraints: Ensure threads execute in specific order

Semaphore Operations

Allocate and Initialize

- Semaphore contains a non-negative integer value
- User cannot read or write value directly after initialization
  - `Sem_t sem;`
  - `Int sem_init(&sem, is_shared, init_value);`

Wait or Test

- P() for "test" in Dutch (proberen)
- Waits until value of sem is > 0, then decrements sem value
- `Int sem_wait(&sem);`

Signal or Increment or Post

- V() for "increment" in Dutch (verhogen)
- Increments value of semaphore
- `Int sem_post(&sem);`

Semaphore Implementation

```
typedef struct {
   int value;
   queue tlist;
} semaphore;
sem_wait (semaphore *S) {  // Must be executed atomically
   S->value--;
   if (S->value < 0) {
        add this process to S->tlist;
        block();
   }
}
sem_signal (semaphore *S) {// Must be executed atomically
   S->value++;
   if (S->value <= 0) {
        remove thread t from S->tlist;
        wakeup(t);
   }
}
```

Semaphore Example

What happens if sem is initialized to 2?

- Scenario: Three processes call sem_wait(&sem)

Observations

- Sem value is negative --> Number of waiters on queue
- Sem value is positive --> Number of threads that can be in c.s. at same time

Mutual Exclusion with Semaphores

Previous example with locks:

```
Void deposit (int amount) {
  mutex_lock(&mylock);
  balance += amount;
  mutex_unlock(&mylocak);
}
```

Example with semaphores:

```
Void deposit(int amount) {
  sem_wait(&sem);
  balance += amount;
  sem_signal(&sem);
}
```

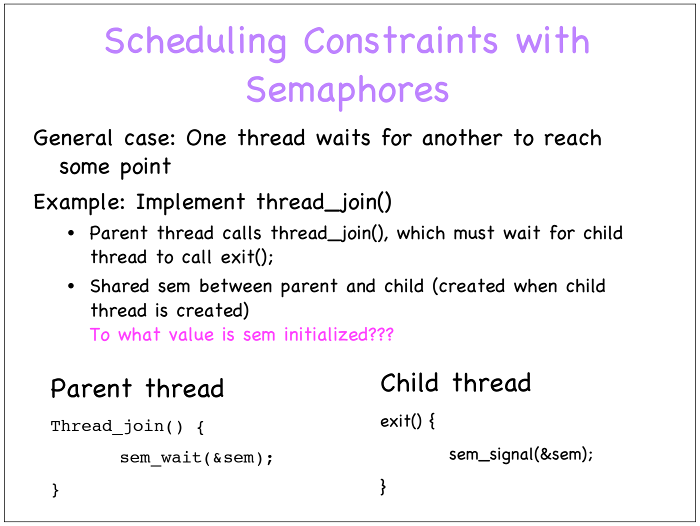
To what value should sem be initialized???

Binary Semaphores

Binary semaphore is sufficient for mutex

- Binary semaphore has boolean value (not integer)
- bsem_wait(): Waits until value is 1, then sets to 0
- bsem_signal(): Sets value to 1, waking one waiting process

General semaphore is also called counting semaphore



Scheduling Constraints with Semaphores

General case: One thread waits for another to reach some point

Example: Implement thread_join()

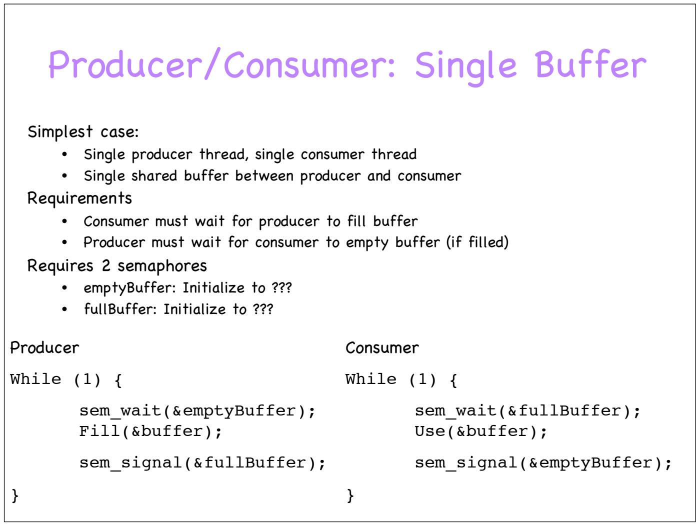
- Parent thread calls thread_join(), which must wait for child thread to call exit();
- Shared sem between parent and child (created when child thread is created)
  To what value is sem initialized???

Parent thread

```
Thread_join() {
        sem_wait(&sem);
}
```

Child thread

```
exit() {
        sem_signal(&sem);
}
```



Producer/Consumer: Single Buffer

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

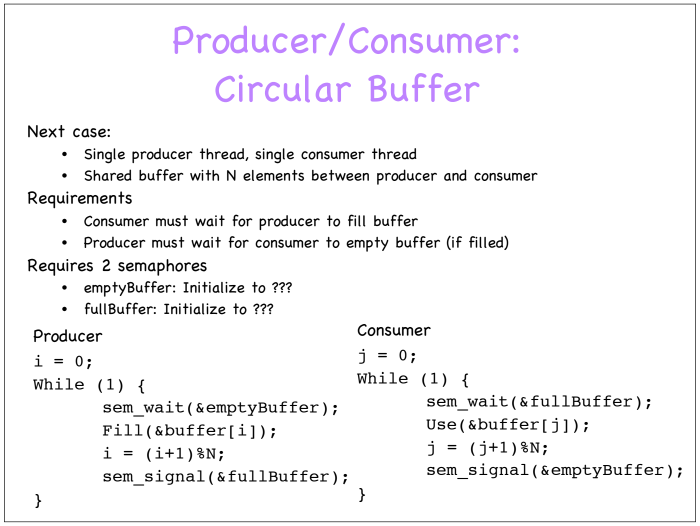
- emptyBuffer: Initialize to ???
- fullBuffer: Initialize to ???

Producer

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

Consumer

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



Producer/Consumer: Circular Buffer

Next case:

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

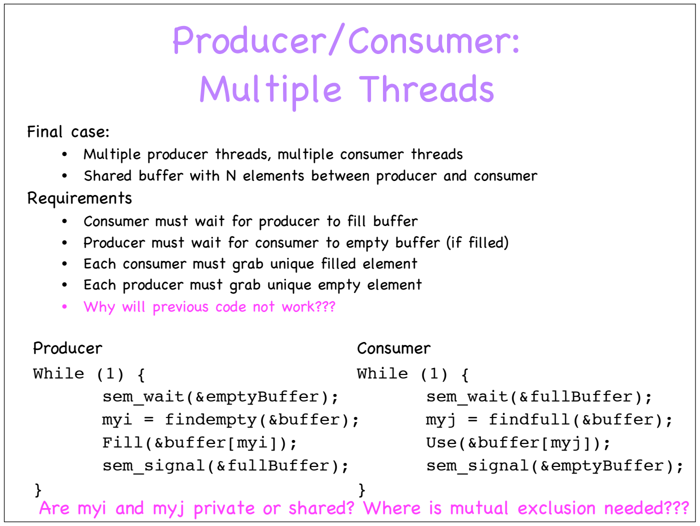
- emptyBuffer: Initialize to ???
- fullBuffer: Initialize to ???

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: Multiple Threads

Final case:

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

Requirements

- Consumer must wait for producer to fill buffer
- Producer must wait for consumer to empty buffer (if filled)
- Each consumer must grab unique filled element
- Each producer must grab unique empty element
- Why will previous code not work???

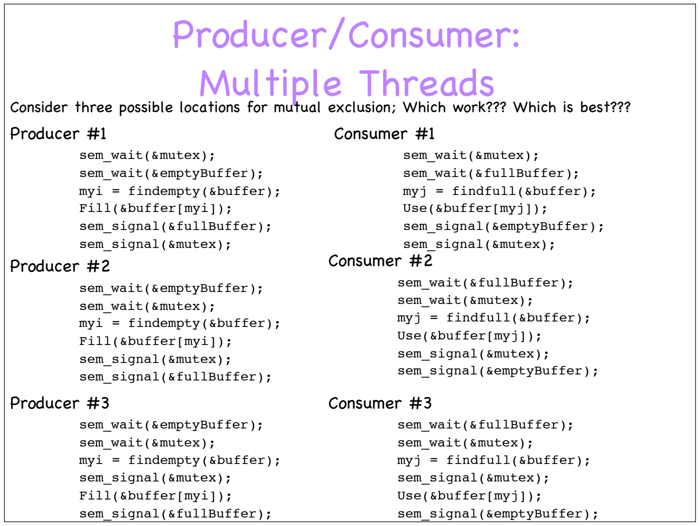
Producer

```
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);
```

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);
```

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);
```