Synchronization II

COMS W4118

References: Operating Systems Concepts (9e), Linux Kernel Development, previous W4118s

Semaphore motivation

- Problem with lock: ensures mutual exclusion, but no execution order

- Producer-consumer problem: need to enforce execution order
  – Producer: create resources
  – Consumer: use resources
  – bounded buffer between them
  – Execution order: producer waits if buffer full, consumer waits if buffer empty
  – E.g., $ cat 1.txt | sort | uniq | wc

Semaphore definition

- A synchronization variable that contains an integer value
  - Can't access this integer value directly
  - Must initialize to some value
    - sem_init (sem_t *s, int pshared, unsigned int value)
  - Has two operations to manipulate this integer
    - sem_wait (or down(), P())
    - sem_post (or up(), V())

```
int sem_wait(sem_t *s) {
    wait until value of semaphore s
        is greater than 0
    decrement the value of
        semaphore s by 1
}
```

```
int sem_post(sem_t *s) {
    increment the value of
        semaphore s by 1
    if there are threads waiting, wake
        up one
}
```

Semaphore uses: mutual exclusion

- Mutual exclusion
  - Semaphore as mutex
  - Binary semaphore: X=1

```
// initialize to X
sem_init(s, 0, X)

sem_wait(s);
// critical section
sem_post(s);
```

- Mutual exclusion with more than one resources
  - Counting semaphore: X>1
  - Initialize to be the number of available resources

Semaphore uses: execution order

- Execution order
  - One thread waits for another
  - What should initial value be?

```
//thread 0

... // 1st half of computation

sem_post(s);
```

```
// thread 1

sem_wait(s);

... //2nd half of computation
```

How to implement semaphores?

Pretty much the same as the mutex implementation we saw last time (note the direct transfer of semaphore):

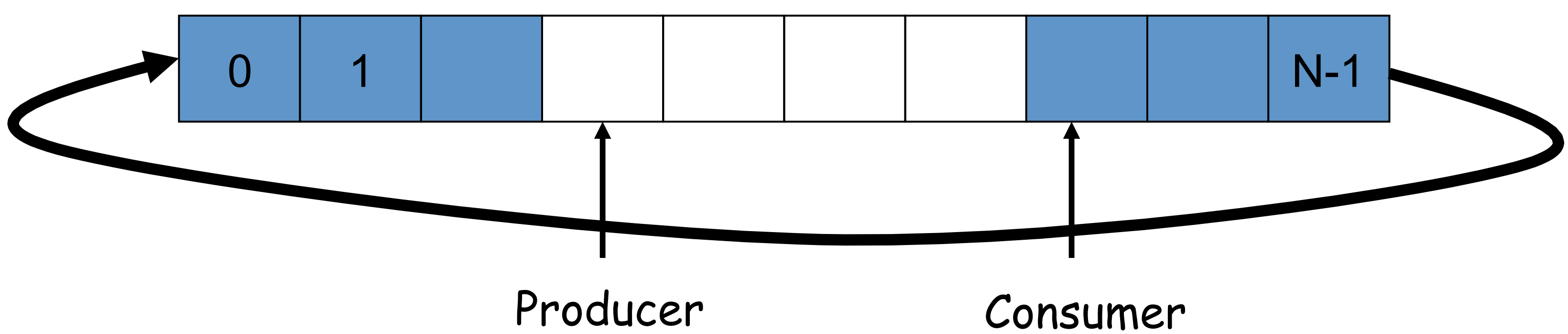
```
Semaphore { int value = 0; int guard = 0; }
```

```
P() {
    while (test_and_set(guard))
        ;
    if (value == 0) {
        Add to wait queue;
        Sleep and set guard to 0;
    } else {
        value--;
        guard = 0;
    }
}
```

```
V() {
    while (test_and_set(guard))
        ;
    if (wait queue not empty) {
        Remove from wait queue;
        Add to ready queue;
    } else {
        value++;
    }
    guard = 0;
}
```

Producer-Consumer (Bounded-Buffer) Problem

- Bounded buffer: size N, Access entry 0… N-1, then “wrap around” to 0 again
- Producer process writes data to buffer
- Consumer process reads data from buffer
- Execution order constraints
  - Producer shouldn’t try to produce if buffer is full
  - Consumer shouldn’t try to consume if buffer is empty



Solving Producer-Consumer problem

- Two semaphores
  - sem_t full; // # of filled slots
  - sem_t empty; // # of empty slots
- What should initial values be?
- Problem: mutual exclusion?

```
sem_init(&full, 0, X);
sem_init(&empty, 0, Y);
```

```
producer() {
    sem_wait(empty);
    … // fill a slot
    sem_post(full);
}
```

```
consumer() {
    sem_wait(full);
    … // empty a slot
    sem_post(empty);
}
```

Solving Producer-Consumer problem: final

- Three semaphores
  - sem_t full; // # of filled slots
  - sem_t empty; // # of empty slots
  - sem_t mutex; // mutual exclusion

```
sem_init(&full, 0, 0);
sem_init(&empty, 0, N);
sem_init(&mutex, 0, 1);
```

```
producer() {
    sem_wait(empty);
    sem_wait(&mutex);
    … // fill a slot
    sem_post(&mutex);
    sem_post(full);
}
```

```
consumer() {
    sem_wait(full);
    sem_wait(&mutex);
    … // empty a slot
    sem_post(&mutex);
    sem_post(empty);
}
```

Outline

- Semaphores
- Monitors and condition variables

Monitors

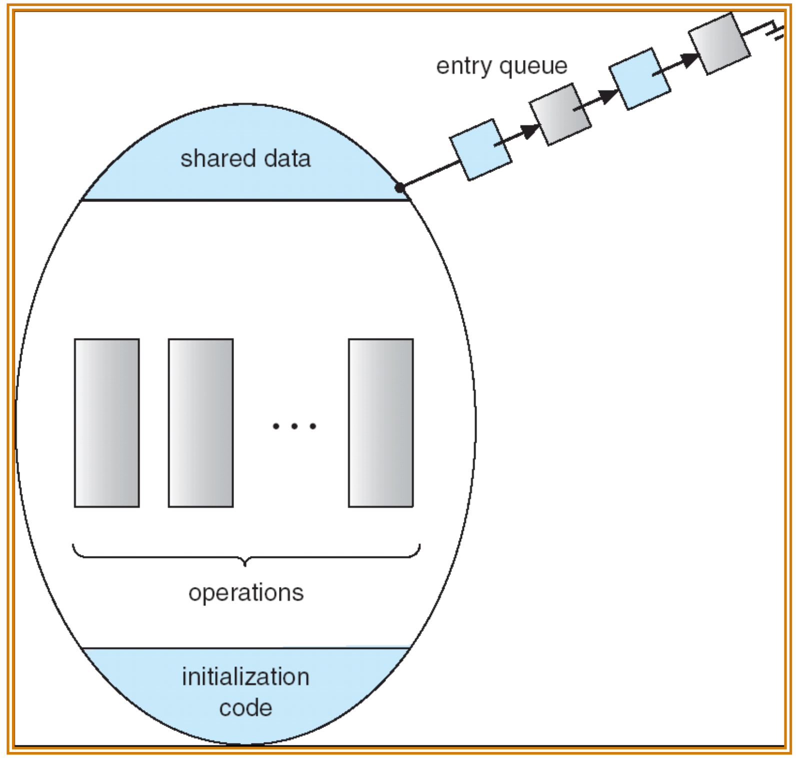
- Background: concurrent programming meets object-oriented programming
  - When concurrent programming became a big deal, object-oriented programming too
  - People started to think about ways to make concurrent programming more structured

- Monitor: object with a set of monitor procedures and only one thread may be active (i.e. running one of the monitor procedures) at a time

Schematic view of a monitor

- Can think of a monitor as one big lock for a set of operations/ methods

- In other words, a language implementation of mutexes



How to implement monitor?

Compiler automatically inserts lock and unlock operations upon entry and exit of monitor procedures

```
class account {
    int balance;
    public synchronized void deposit() {
        ++balance;
    }
    public synchronized void withdraw() {
        --balance;
    }
};
```

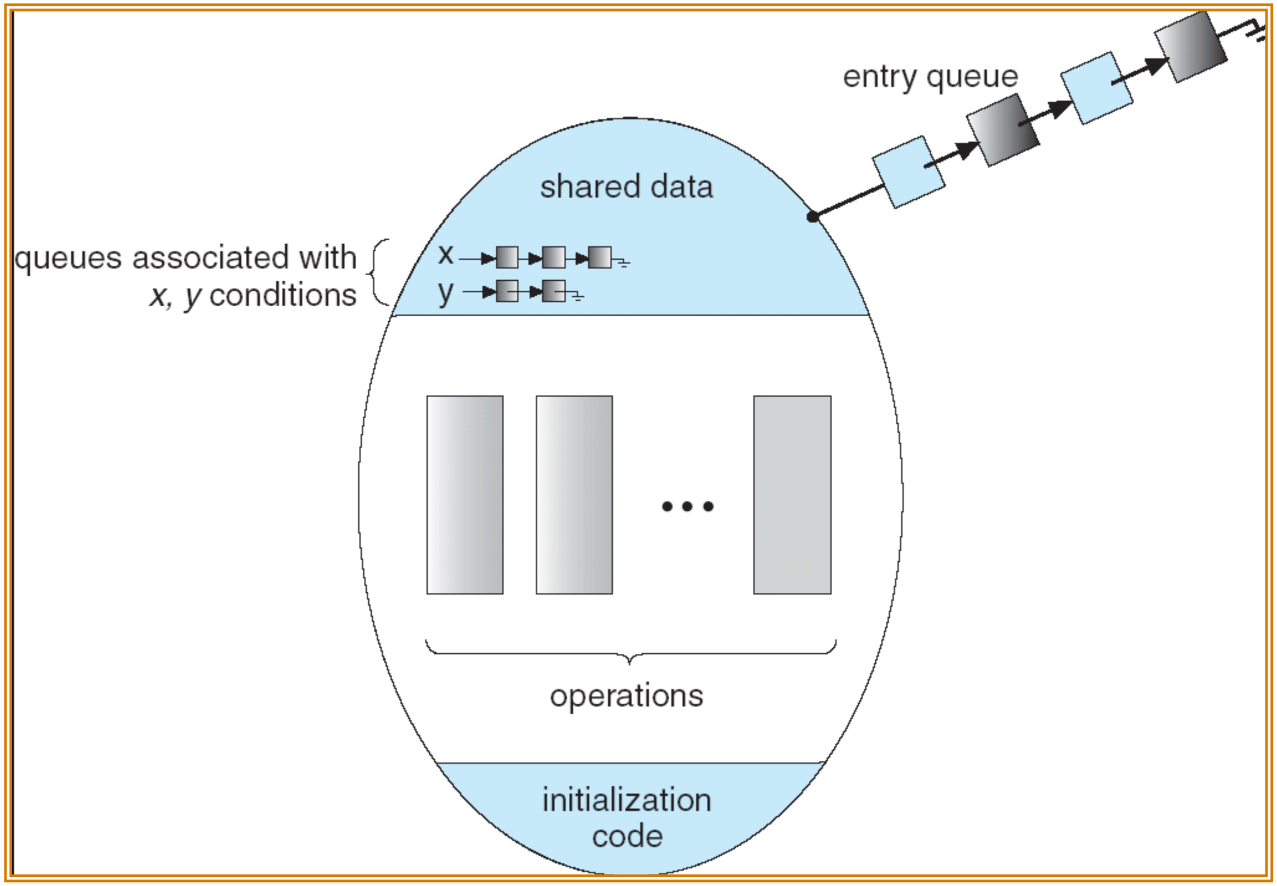
```
lock(this.m);
++balance;
unlock(this.m);
```

```
lock(this.m);
--balance;
unlock(this.m);
```

Condition Variables

- Need wait and wakeup as in semaphores
- Monitor uses Condition Variables
  - Conceptually associated with some conditions
- Operations on condition variables:
  - wait(): suspends the calling thread and releases the monitor lock. When it resumes, reacquire the lock. Called when condition is not true
  - signal(): resumes one thread waiting in wait() if any. Called when condition becomes true and wants to wake up one waiting thread
  - broadcast(): resumes all threads waiting in wait(). Called when condition becomes true and wants to wake up all waiting threads

Monitor with condition variables



So, a good way to think about a monitor: 1 mutex + N cond var in a class object (In Java, it's 1 mutex + 1 condition variable)

Condition variables vs. semaphores

- Semaphores are sticky: they have memory, sem_post() will increment the semaphore counter, even if no one has called sem_wait()
- Condition variables are not: if no one is waiting for a signal(), this signal() is not saved
- Despite the difference, they are as powerful
  - Exercise: implement one using the other

Producer-consumer with monitors

```
monitor ProducerConsumer {
    int nfull = 0;
    cond has_empty, has_full;

    producer() {
       if (nfull == N)
           wait (has_empty);
       … // fill a slot
       ++ nfull;
       signal (has_full);
    }

    consumer() {
       if (nfull == 0)
            wait (has_full);
       … // empty a slot
       -- nfull;
       signal (has_empty);
    }
};
```

- Two condition variables
  - has_empty: buffer has at least one empty slot
  - has_full: buffer has at least one full slot
- nfull: number of filled slots
  - Need to do our own counting for condition variables

Condition variable semantics

- Design question: when signal() wakes up a waiting thread, which thread to run inside the monitor, the signaling thread, or the waiting thread?

- Hoare semantics: suspends the signaling thread, and immediately transfers control to the woken thread
  - Difficult to implement in practice

- Mesa semantics: signal() moves a single waiting thread from the blocked state to a runnable state, then the signaling thread continues until it exits the monitor
  - Easy to implement
  - Problem: race! Before a woken consumer continues, another consumer comes in and grabs the buffer

Fixing the race in mesa monitors

```
monitor ProducerConsumer {
    int nfull = 0;
    cond has_empty, has_full;

    producer() {
       while (nfull == N)
           wait (has_empty);
       … // fill slot
       ++ nfull;
       signal (has_full);
    }

    consumer() {
       while (nfull == 0)
            wait (has_full);
       … // empty slot
       -- nfull
       signal (has_empty);
    }
};
```

- The fix: when woken up, a thread must recheck the condition it was waiting on
- Most systems use mesa semantics
  - E.g., pthread
- You should use while!

Monitor and condition variable in pthread

```
class ProducerConsumer {
    int nfull = 0;
    pthread_mutex_t m;
    pthread_cond_t has_empty, has_full;

public:
    producer() {
      pthread_mutex_lock(&m);
       while (nfull == N)
           pthread_cond_wait (&has_empty, &m);
       … // fill slot
       ++ nfull;
       pthread_cond_signal (has_full);
       pthread_mutex_unlock(&m);
    }
    …
};
```

- C/C++ don't provide monitors; but we can implement monitors using pthread mutex and condition variable
- For producer-consumer problem, need 1 pthread mutex and 2 pthread condition variables (pthread_cond_t)
- Manually lock and unlock mutex for monitor procedures
- pthread_cond_wait (cv, m): atomically waits on cv and releases m