CS4410

Operating Systems

Lecture 10:
Semaphores and Monitors

Rachit Agarwal

Announcements

- **Office hours**
  - Priority to students who signed up (Calendly link on webpage)
  - You are welcome to walk in, but strict prioritization
- **Homework submission**
  - You are required to “mark” pages for individual answers
  - We will deduct 10% if you do not mark pages
- **Prelims**
  - **Prelim1:** 14th October; **Prelim2:** 23rd November
  - **In-class:** there should be no conflicts; no make up
  - Open notes, open book, open everything except:
    - The Internet
    - Other students
  - Infinite time: we want to test you on your knowledge, not speed

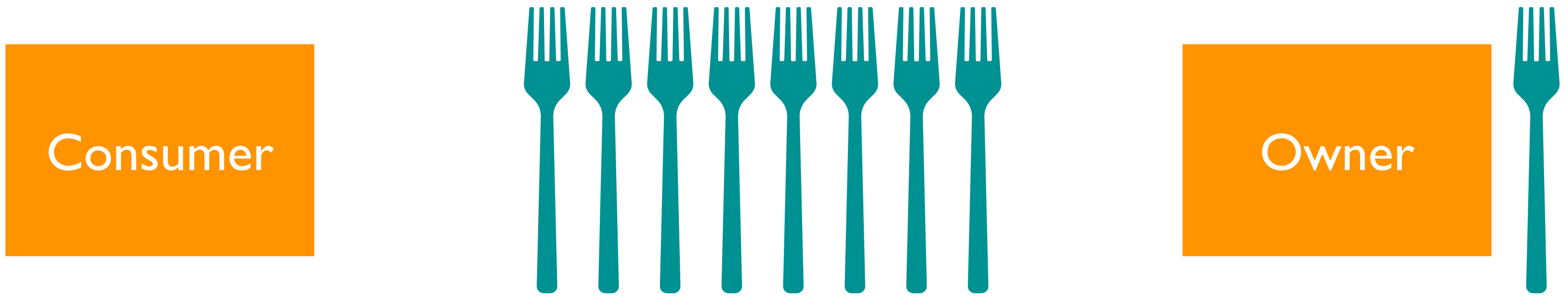
Goal of today's lecture

- Wrap up synchronization and concurrent programming
- Semaphores, Condition variables, and Monitors

Examples that we have seen so far

- The racing threads
- The complicated racing threads
- The ATM banking
- Too-much-milk
- Producer-consumer

Example 5: The producer-consumer problem



- Suppose we want to build a **fork dispenser** for a cafe
- The dispenser (shared resource) has limited capacity
- Consumers pull out forks on one end of the dispenser
  - removeFromDispenser()
  - Error if tries to pull out a fork from an empty dispenser
  - Error if cannot pull out a fork when there is one
- Owner adds forks on the other end of the dispenser
  - addToDispenser()
  - Error if tries to add a fork to a full dispenser

Example 5: The producer consumer problem

Suppose we implement producer and consumer in the following manner:

```
Consumer() {
  while(true)
  {
    if(forkCount > 0)
    {
      Fork = removeFromDispenser();
      forkCount = forkCount - 1;
      use(Fork);
    }
  }
}
```

```
Owner(fork) {
  while(true)
  {
    if(forkCount < dispenserSize)
    {
      Fork = newFork();
      addToDispenser(Fork);
      forkCount = forkCount + 1;
    }
  }
}
```

Is this correct?

Example 5: The producer consumer problem

- t=0, dispenserSize = 5, forkCount = 5

```
if(forkCount > 0)
{
  Fork = removeFromDispenser();
  forkCount = forkCount - 1 ;
  use(Fork);
}
```

```
if(forkCount < dispenserSize)
{
  Fork = newFork();
  addToDispenser(Fork);
```

```
if(forkCount > 0)
{
  Fork = removeFromDispenser();
  forkCount = forkCount - 1 ;
  use(Fork);
}
```

```
  forkCount = forkCount + 1;
}
```

Time

Inconsistent forkCount!!

Example 5: Producer consumer problem with Locks

- Let's try locks

```
Consumer() {
  while(true)
  {
    lock.acquire();
    if(forkCount > 0)
    {
      Fork = removeFromDispenser();
      forkCount = forkCount - 1 ;
      use(Fork);
    }
    lock.release();
  }
}
```

```
Owner(fork) {
  while(true)
  {
    lock.acquire();
    if(forkCount < dispenserSize)
    {
      Fork = newFork();
      addToDispenser(Fork);
      forkCount = forkCount + 1;
    }
    lock.release();
  }
}
```

CPU cycles may be wasted:
Consumer/producer may repeatedly acquire and release locks!!!

Semaphores

- Semaphores are a kind of generalized lock

- A semaphore is "stateful"
  - Has a non-negative value associated with it
  - Value is incremented and decremented atomically

- Semaphore has a positive value initially, and offers two atomic operations
  - **Down()** or **P()—stands for "proberen" (to test) in Dutch**:
    - Thread "waits" for the semaphore value to become positive
    - When so, atomically decrement it by 1
  - **Up()** or **V()—stands for "verhogen" (to increment) in Dutch**:
    - Thread "waits" for the semaphore value to become less than "max"
    - When so, atomically increment the semaphore value by 1
    - Wake up a thread waiting on P, if any

- Binary Semaphore: Semaphore with initial value 1
  - Mutual exclusion like locks

Example 5: Producer consumer problem with semaphores

Split binary semaphore: at most one of the semaphore is released

```
enoughRoom = semaphore(1);
count = semaphore(0);
```

```
Consumers() {
  while(true)
  {
    count.down();
    Fork = removeFromDispenser();
    forkCount = forkCount - 1;
    enoughRoom.up();
    use(Fork);
  }
}
```

```
Owner(fork) {
  while(true)
  {
    Fork = newFork();
    enoughRoom.down();
    addToDispenser(Fork);
    forkCount = forkCount + 1;
    count.up();
  }
}
```

- Problem?
- Only works for dispenser size = 1

Example 5: Producer consumer problem with semaphores

Count semaphore: at most one of the semaphore is released

```
enoughRoom = semaphore(dispenser_capacity);
count = semaphore(0);
```

```
Consumers() {
  while(true)
  {
    count.down();
    Fork = removeFromDispenser();
    forkCount = forkCount - 1;
    enoughRoom.up();
    use(Fork);
  }
}
```

```
Owner(fork) {
  while(true)
  {
    Fork = newFork();
    enoughRoom.down();
    addToDispenser(Fork);
    forkCount = forkCount + 1;
    count.up();
  }
}
```

Problem?

Does not work: number of consumers/producers > 1

forkCount can become inconsistent with multiple threads in critical section

Example 5: Producer consumer problem with semaphores

```
enoughRoom = semaphore(dispenser_capacity);
count = semaphore(0);
```

```
Consumers() {
  while(true)
  {
        lock.acquire();
        count.down();
        Fork = removeFromDispenser();
        forkCount = forkCount - 1;
        enoughRoom.up();
        lock.release();
        use(Fork);
  }
}
```

```
Owner(fork) {
  while(true)
  {
        lock.acquire();
        Fork = newFork();
        enoughRoom.down();
        addToDispenser(Fork);
        forkCount = forkCount + 1;
        count.up();
        lock.release();
  }
}
```

Problem?

Deadlock:

consumer takes lock, executes down(), producer cannot update if forkcount=0;

or, forkcount=dispenser-size and producer gets the lock;

Example 5: Producer consumer problem with semaphores

- Let's use binary semaphores which are similar to locks

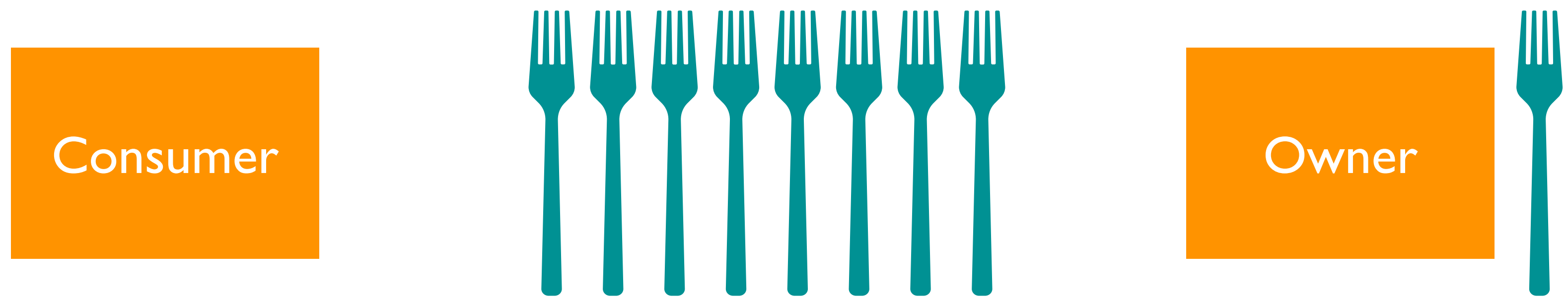
```
enoughRoom = semaphore(dispenser_capacity);
count = semaphore(0);
```

```
Consumers() {
  while(true)
  {
    count.down();
    lock.acquire();
    Fork = removeFromDispenser();
    forkCount = forkCount - 1;
    lock.release();
    enoughRoom.up();
    use(Fork);
  }
}
```

```
Owner(fork) {
  while(true)
  {
    Fork = newFork();
    enoughRoom.down();
    lock.acquire();
    addToDispenser(Fork);
    forkCount = forkCount + 1;
    lock.release();
    count.up();
  }
}
```

Complicated sequence of semaphore locks, easy to make mistakes!!

Example 5: The producer-consumer problem



- Suppose we want to build a **fork dispenser** for a cafe
- The dispenser (shared resource) has limited capacity
- Consumers pull out forks on one end of the dispenser
    - removeFromDispenser()
    - **sleep()—consumer blocks until the producer wakes it up**
    - Error if tries to pull out a fork from an empty dispenser
    - Error if cannot pull out a fork when there is one
- Owner adds forks on the other end of the dispenser
    - addToDispenser()
    - **wakeup()—a routine for producer to wake up a consumer**
    - Error if tries to add a fork to a full dispenser

Example 5: The producer-consumer problem: Attempt 2

- Suppose we implement producer and consumer this way

```
Consumers() {
    while(true) {
      if(forkCount == 0)
      {
        sleep();
      }
      Fork = removeFromDispenser();
      forkCount = forkCount - 1;
      if(forkCount == dispenserCapacity - 1)
      {
        wakeup(owner);
      }
      use(Fork);
    }
}
```

```
Owner(fork) {
  while(true) {
    Fork = newFork();
    if(forkCount == dispenserCapacity)
    {
      sleep();
    }
    addToDispenser(Fork);
    forkCount = forkCount + 1;
    if(forkCount == 1)
    {
      wakeup(consumer);
    }
  }
}
```

Wrong: inconsistent forkcount

Example 5: The producer-consumer problem: Attempt 2

- Suppose we implement producer and consumer this way

```
Consumers() {
    while(true) {
        lock.acquire()
        if(forkCount == 0) {
            lock.release();
            sleep();
            lock.acquire();
        }
        Fork = removeFromDispenser();
        forkCount = forkCount - 1;
        if(forkCount == dispenserCapacity - 1) {
            wakeup(owner);
        }
        use(Fork);
        lock.release();
    }
}
```

```
Owner(fork) {
  while(true) {
        Fork = newFork();
        lock.acquire();
        if(forkCount ==
        dispenserCapacity) {
            lock.release();
            sleep();
            lock.acquire();
        }
        addToDispenser(Fork);
        forkCount = forkCount + 1;
        if(forkCount == 1) {
            wakeup(consumer);
        }
        lock.release();
  }
}
```

Deadlocks!

Example 5: The producer-consumer problem: Attempt 2

- **Can lead to "deadlocks"**
  - Step 1: The consumer reads forkCount (=0); about to enter **if**
  - Step 2: Just before calling sleep()
    - Consumer interrupted
    - Producer adds a fork, puts it into dispenser, forkCount=1
    - Since forkCount=1, tries to wake up the consumer
    - But the consumer isn't sleeping yet—wakeup call lost
  - Step 3: The consumer calls sleep()
    - Goes to sleep;
    - Never wakes up, since wakeup call only when forkCount=1
  - Step 4: Producer fills up the dispenser
    - Goes to sleep
    - Never wakes up, since wakeup call only from consumer

Example 5: The producer-consumer problem: Attempt 2

- Suppose we implement producer and consumer this way

```
Consumers() {
    while(true) {
        lock.acquire()
        if(forkCount == 0) {
            lock.release();
            sleep();
            lock.acquire();
        }
        Fork = removeFromDispenser();
        forkCount = forkCount - 1;
        if(forkCount == dispenserCapacity - 1) {
            wakeup(owner);
        }
        use(Fork);
        lock.release();
    }
}
```

```
Owner(fork) {
  while(true) {
        Fork = newFork();
        lock.acquire();
        if(forkCount ==
        dispenserCapacity) {
            lock.release();
            sleep();
            lock.acquire();
        }
        addToDispenser(Fork);
        forkCount = forkCount + 1;
        if(forkCount == 1) {
            wakeup(consumer);
        }
        lock.release();
  }
}
```

Deadlocks!

What we really need for synchronization

- We need higher-level synchronization mechanism that provides

- **Mutual exclusion**
  - Easy to create critical sections

- **Scheduling**
  - Block threads until some desired event occurs

Condition variables

- Synchronization mechanisms need more than just mutual exclusion
    - Also need a way to wait for another thread to do something
    - e.g., wait for a fork to be added to the dispenser

- Condition variable: **A mechanisms to wait for** a condition to become true

- **Three operations on condition variables (condition x;)**
    - **wait(condition, lock):**
        - Release lock; put thread to sleep until condition is signaled
        - When thread wakes up again, re-acquire lock before returning
    - **signal(condition, lock):**
        - If any threads waiting on condition, wake up one of them
        - Caller must hold lock: must be the same as the lock used in the wait call
    - **broadcast(condition, lock):**
        - Same as signal, except wake up all waiting threads

Monitors

- When locks and condition variables are used together like the above
    - The result is called a monitor

- Monitor
    - A collection of procedures manipulating a shared data structure
    - One lock that must be held whenever accessing the shared data
        - Typically each procedure acquires the lock at the very beginning
        - And releases the lock before returning
    - One or more condition variables used for waiting

Example 5: Producer-consumer with condition variables

```
enoughRoom = condition();
count = condition();
```

```
Consumers() {
  while(true)
  {
    lock.acquire();
    while(forkCount == 0)
    {
      count.wait(lock);
    }
    Fork = removeFromDispenser();
    forkCount = forkCount - 1;
    if (forkCount == dispenserCapacity-1) {
          enoughRoom.signal();
    }
    lock.release();
    use(Fork);
  }
}
```

```
Owner(fork) {
  while(true)
  {
    lock.acquire();
    Fork = newFork();
    while(forkCount == dispenserCapacity)
    {
      enoughRoom.wait(lock);
    }
    addToDispenser(Fork);
    forkCount = forkCount + 1;
    if (forkCount == 1) {
          count.signal();
    }
    lock.release();
  }
}
```

Can sleep within critical section and simpler code!