CS4410

Operating Systems

Lecture 11:
Condition variables, and atomic primitives

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Announcements

- **“Missed class” emails**
- Last lecture: max number of “missed class” emails received :)
- Many of those were within the 1-hour limit announced earlier
    - [1] Last minute things come up
    - [2] Defines “are we true friends?” moments
        - We are having a quiz; you don’t seem to be here :)
- No way for me to differentiate between people in [1] and [2]
- If care about fairness, follow the principle of sticking with rules
    - People in [1] may miss out, but assuming this is rare
    - People in [2] do not benefit unfairly
- So, I am going to stick with the rule
    - Sorry if you happen to be in [1]

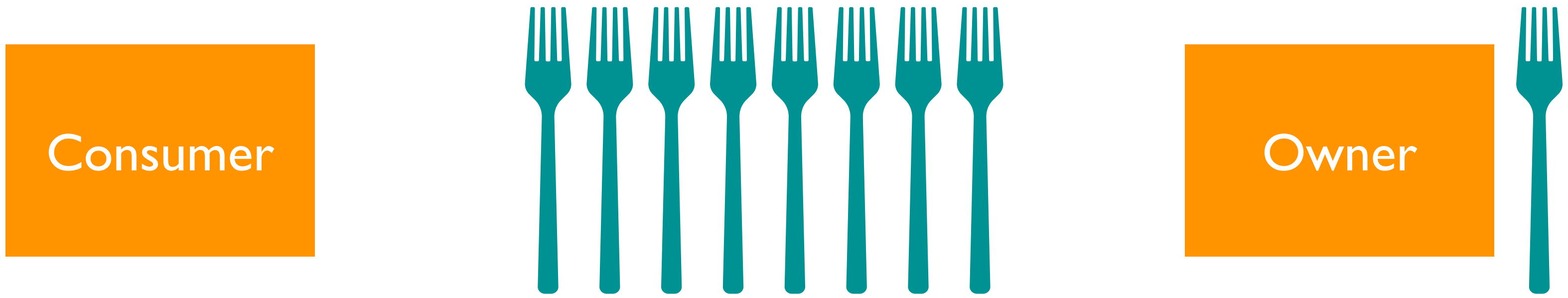
Goal of today's lecture

- Wrap up synchronization and concurrency
- Wrap up Semaphores
- Condition variables, and Monitors
- Atomic instructions, and implementing locks

Examples that we have seen so far

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

Recall: 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

Recall: 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

Recall: Producer consumer problem with semaphores

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

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

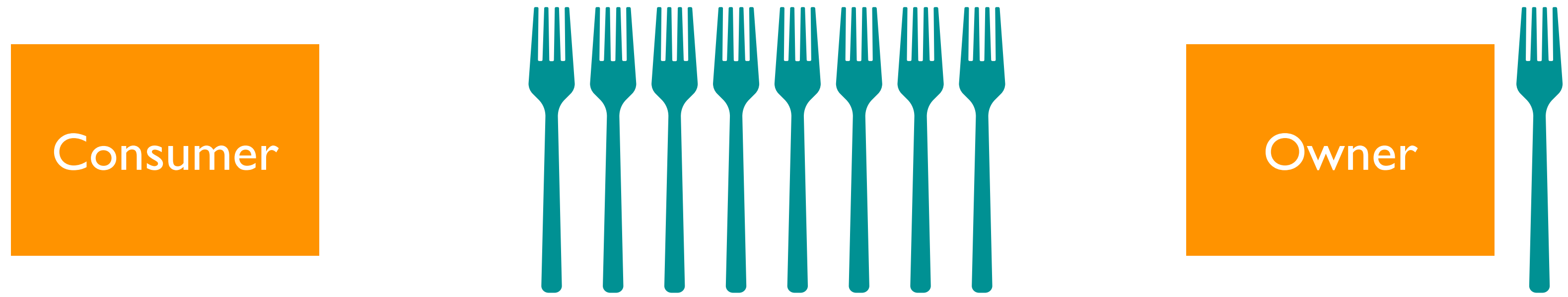
```
Consumers() {
  while(true)
  {
    count.down();
    lock.acquire();
    Fork = removeFromDispenser();
    forkCount = forkCount - 1;
    lock.release();
    enoughRoom.up();
    use(Fork);
  }
}
```

```
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

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 mechanism to enable threads to wait inside a critical section**
  - Achieved by releasing a lock

- **Three operations on condition variables (condition x;)**
  - **wait(condition, lock):**
    - **Atomically:** Release lock; put thread to sleep until condition is signaled
    - When thread wakes up again, re-acquire lock before returning
  - **signal/notify(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/notifyall(condition, lock):**
    - Same as signal/notify, except wake up all waiting threads

Condition variables

- **Three operations on condition variables (condition x;)**
    - x.wait()
    - x.signal() or x.notify()
    - x.broadcast() or x.notifyall()

- **Only call the above operations when holding a lock**

- Condition variables (unlike semaphores) are stateless

Condition variables—notify semantics

- **When a thread calls x.notify(), it is signaling "waiting" threads**
  - There is some task that can be done by the waiting threads
  - The thread calling notify() can continue doing its tasks
  - Which threads executed once notify() is called?
- If no thread waiting on condition variable, notifier continues
- If one or more threads waiting on condition variable
  - At least two "ready" threads: those waiting, and the notifier; which one runs?
- **Mesa (or Brinch Hansen semantics)**
  - Waiting thread moved to ready queue; but not guaranteed to run right away
- **Hoare semantics:**
  - Thread calling notify() suspended, and
  - atomically: ownership of the lock passed to one of the waiting threads
    - The thread getting the ownership resumes execution immediately
  - Thread calling notify() is resumed if the above thread exits critical section
    - Or if the above thread goes to wait again

notify() versus notifyall()

- **Signal versus broadcast**
  - Signals wakes up one of the waiting threads
  - Broadcast wakes up all of the waiting threads
- It is always safe to use notifyall() instead of notify()
  - But performance may be affected
- **notify() is preferable when**
  - At most one waiting thread can make progress (e.g., with mutual exclusion)
  - Any of the threads waiting on condition variable can make progress
- **notifyall() is preferable when**
  - Multiple waiting threads may be able to make progress
  - Some of the waiting threads can make progress, others cannot

Condition variables versus Semaphores

- **wait() versus down()**
    - down() blocks threads only if value=0
    - wait() always blocks, and gives up lock
- **notify() versus up()**
    - up() is stateful
        - if no waiting thread, up() ensures future thread does not wait on down()
    - notify() is stateless
        - If no waiting thread, notify() is a no op
- **Condition variables are stateless, making code easier to read**
    - Conditions for which threads are waiting are **explicit**

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!

One last remaining bit

What is atomic, and what is not?

Recall: Atomic Operations

- “Indivisible operations” supported by hardware
  - Indivisible: An operation that **always runs to completion or not at all**
  - No interruptions
    - It cannot be stopped in the middle
    - And state cannot be modified by someone else in the middle
- Fundamental building block
  - If no atomic operations, then have no way for threads to work together
- What atomic operations should the hardware support?
  - We have studied five examples, each with different complexity
    - And with different set of operations
  - We have also studied three different higher-layer primitives
    - Locks, Semaphores, condition variables
    - Are these atomic? What else is atomic?

Atomic Operations

- Most modern processors support a basic set of atomic operations
  - Atomic read-write
  - Atomic swap
  - test-and-set
  - fetch-and-add
  - compare-and-swap
  - store-conditional

- Can be used to implement higher-level primitives
  - E.g., locks, semaphores, condition variables

Atomic test and set

- Hardware offers an instruction which
  - Sets the value of a memory location to 1
  - Returns the previous value
- **Hardware executes both operations atomically**
- Caller uses return value to see if the instruction changed the state

```
int test_and_set(int* x)
{
  old = *x;
  *x = 1;
  return old;
}
```

Locks using test and set

- Suppose we implement locks this way

```
acquire(lock)
{
  while(test_and_set(lock)) {};
}
```

```
release(lock)
{
  lock = 0;
}
```

```
int x = 0;

while(test_and_set(x)) {}; // acquire lock

// critical section

x = 0; // release lock
```

1. While loop wastes CPU cycles if wait is long !!
2. Efficient only when wait is short?

Atomic compare and swap

- Hardware offers an instruction which
  - Compares a given value with a given expected value
  - If equal, changes it to given new value
    - Return true
  - Else, return false

- All operations are executed atomically

```
int compare_and_swap(int* p, int expected, int new)
 {
   if(*p != expected)
   {
     return false;
   }
   *p = new
   return true;
 }
```

Atomic add using compare and swap

- Suppose we implement atomic add this way

```
atomic_add(int* p, int x)
{
   done = false;
   while(not done)
   {
     value = *p;
     done = compare_and_swap(p, value, value + x)
   }
   return value + x;
}
```

Atomically adds x to the value present at p

Some final thoughts on synchronization

- **One of the hardest topics in operating systems**
  - It is okay if you had hard time grasping some of the ideas
  - All of us have struggled with synchronization (for a very long time!)
- **It is important to understand the problem**
  - We have done many examples
  - Many more examples in books/Internet
- **Synchronization primitives require practice**
  - Many problems in HW2
  - Some more problems in HW3
  - More problems in the book
    - Try to solve them
    - Come to office hours to ask questions
  - Practice, practice, practice