Recap

- Two types of synchronization
  - Mutual exclusion → Locks
  - Ordering constraints → Condition variables

- Condition variables: Enable a thread to sleep inside a critical section by
  - Releasing lock
  - Putting thread onto waiting list
  - Going to sleep
  - After being woken, call lock()
Thread-safe queue with condition variables

```java
cv queueCV;

enqueue()
    queueMutex.lock()
    find tail of queue
    add new element to tail of queue
    queueCV.signal()
    queueMutex.unlock()
}
decqueue()
    queueMutex.lock()
    while(queue is empty) {
        queueCV.wait();
    }
    remove item from queue
    queueMutex.unlock()
    return removed item
```
Operations on condition variables

- **wait()**
  - Atomically release lock, add thread to waiting list, go to sleep

- **signal()**
  - Wake up one thread waiting on this condition variable

- **broadcast()**
  - Wake up all threads waiting on this condition variable
  - When is this useful?
Thread-safe queue with condition variables

cv queueCV;

enqueue(set of elements)
    queueMutex.lock()
    find tail of queue
    add new elements to tail of queue
    queueCV.broadcast()
    queueMutex.unlock()
}

decqueue()
    queueMutex.lock()
    while (queue is empty) {
        queueCV.wait();
    }
    remove item from queue
    queueMutex.unlock()
    return removed item
}
Monitors

- Combine two types of synchronization
  - Locks for mutual exclusion
  - Condition variables for ordering constraints

- A monitor = a lock + the condition variables associated with that lock
Producer-consumer (bounded buffer)

- Producers put things into a shared buffer; consumers take them out
- Need to synchronize actions of producers and consumers

Why use a shared buffer?
- Lets producers and consumers operate somewhat independently

Used in many situations
- Unix pipes
- Project 1!
- Coke vending machine
Producer-consumer with monitors

- **Shared variables**
  - State of coke machine slots
    - *numCokes* (assume coke machine can hold at most MAX cokes)
  - One lock (*cokeLock*) to protect this data

- **When must a thread pause?**
  - Mutual exclusion (when acquiring a lock)
  - Consumer must wait if all slots are empty
    - Use condition variable *waitingConsumers*
  - Producer must wait if all slots are full
    - Use condition variable *waitingProducers*
### Producer-consumer with monitors

<table>
<thead>
<tr>
<th>Consumer</th>
<th>Producer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Consumer</strong></td>
<td><strong>Producer</strong></td>
</tr>
<tr>
<td>cokeLock.lock()</td>
<td>cokeLock.lock()</td>
</tr>
<tr>
<td>while (numCokes == 0) {</td>
<td>while (numCokes == MAX) {</td>
</tr>
<tr>
<td>waitingConsumers.wait();</td>
<td>waitingProducers.wait();</td>
</tr>
<tr>
<td>}</td>
<td>}</td>
</tr>
<tr>
<td>take coke out of machine</td>
<td>add coke to machine</td>
</tr>
<tr>
<td>numCokes--</td>
<td>numCokes++</td>
</tr>
<tr>
<td>waitingProducers.signal();</td>
<td>waitingConsumers.signal();</td>
</tr>
<tr>
<td>cokeLock.unlock();</td>
<td>cokeLock.unlock();</td>
</tr>
</tbody>
</table>
Producer-consumer with monitors

**Consumer**

```java
cokeLock.lock()

while (numCokes == 0) {
    waitingConsumers.wait()
}

take coke out of machine
numCokes--

waitingProducers.signal()

cokeLock.unlock()
```

**Producer**

```java
cokeLock.lock()

while (1) {
    sleep(1 hour)
    while (numCokes == MAX) {
        waitingProducers.wait()
    }
    add coke to machine
    numCokes++

    waitingConsumers.signal()
}

cokeLockunlock()
```
Producer-consumer with monitors

**Consumer**

```java
cokeLock.lock()

while (numCokes == 0) {
    waitingConsumers.wait()
}

take coke out of machine
numCokes--

waitingProducers.signal()

cokeLock.unlock()
```

**Producer**

```java
cokeLock.lock()

while (numCokes == MAX) {
    waitingProducers.wait()
}

add coke to machine
numCokes++

if (numCokes == 1) {
    waitingConsumers.signal()
}

cokeLock.unlock()
```
Producer-consumer with monitors

**Consumer**

```java
cokeLock.lock()

while (numCokes == 0) {
    waitingCons&Prod.wait()
}

take coke out of machine
numCokes--

waitingCons&Prod.signal()

cokeLock.unlock()
```

**Producer**

```java
cokeLock.lock()

while (numCokes == MAX) {
    waitingCons&Prod.wait()
}

add coke to machine
numCokes++

waitingCons&Prod.signal()

cokeLock.unlock()
```
Producer-consumer with monitors

**Consumer**

```java
cokeLock.lock()

while (numCokes == 0) {
    waitingCons&Prod.wait()
}

take coke out of machine
numCokes--

waitingCons&Prod.broadcast()

cokeLock.unlock()
```

**Producer**

```java
cokeLock.lock()

while (numCokes == MAX) {
    waitingCons&Prod.wait()
}

add coke to machine
numCokes++

waitingCons&Prod.broadcast()

cokeLock.unlock()
```
Producer-consumer with monitors

**Consumer**

cokeLock.lock()

while (numCokes == 0) {
    waitingConsumers.wait()
}

take coke out of machine
numCokes--

**Producer**

cokeLock.lock()

while (numCokes == MAX) {
    waitingProducers.wait()
}

add coke to machine
numCokes++

**Consumer**

waitingProducers.signal()  
cokeLock.unlock()

**Producer**

waitingConsumers.signal()  
cokeLock.unlock()
Announcements

● Started with Project 1?
  ◆ Due in a week

● Group declaration due on Thursday
  ◆ Project 2 will be posted on Tuesday

● Autograder downtime Tue 8pm-Wed 8am
Reader-writer locks

- Recall: Threads need to acquire lock even to read shared data
  - This prevents other threads from accessing the data
- Can we allow more concurrency without risking reading unstable data?

- Problem definition:
  - Shared data will be read and written by multiple threads
  - Allow multiple readers, if no threads are writing data
  - A thread can write only when no other thread is reading or writing
Need for reader-writer locks

- Use of normal mutex locks limits concurrency

**Reader:**
lock()
print catalog
unlock()

**Writer:**
lock()
change catalog
unlock()
Reader-writer locks

- Implement set of functions that a program can use to follow “multiple-reader, single-writer” constraint
  - readerStart()
  - readerFinish()
  - writerStart()
  - writerFinish()

- Pros and cons compared to normal mutex locks?
Another level of abstraction

Concurrent programs

Even higher-level synchronization primitives
(\texttt{readerStart}, \texttt{readerFinish}, \texttt{writerStart}, \texttt{writerFinish})

Higher-level synchronization primitives
(\texttt{lock}, \texttt{monitor}, \texttt{semaphore})

Atomic operations
(\texttt{load/store}, interrupt enable/disable, \texttt{test\&set})
Implementing reader-writer locks with monitors

- Shared data needed to implement readerStart, readerFinish, writerStart, writerFinish?
  - `numReaders`
  - `numWriters`
- Use one lock (`rwLock`)
- Condition variables?
  - `waitingReaders`: readers must wait if there are writers
  - `waitingWriters`: writers must wait if there are readers or writers