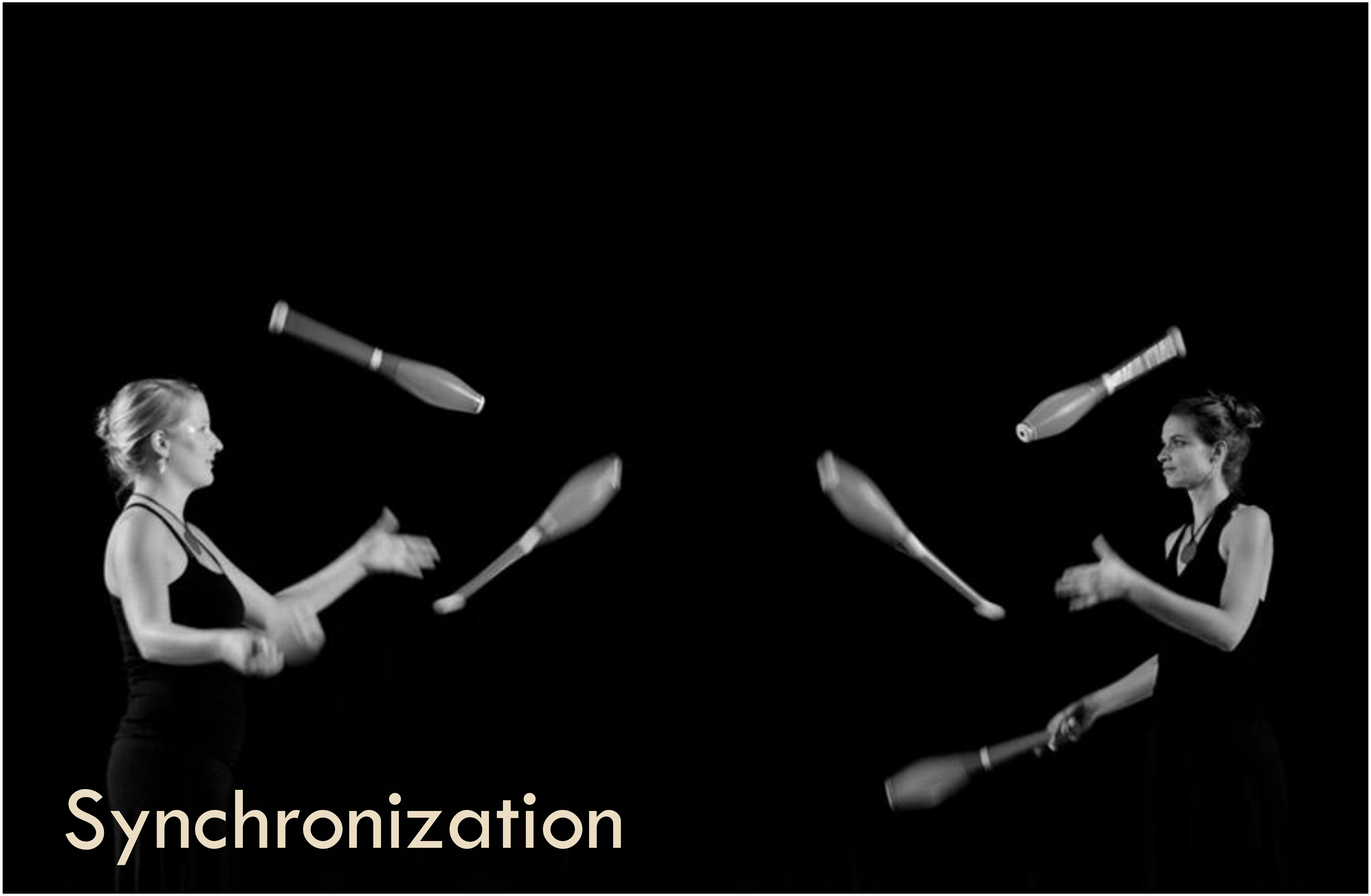


Synchronization

Lecture 24 – Fall 2018

Prelim 2 tonight!

The room assignments are on the course website, page Exams.

Check it carefully!
Come on time!
Bring you Cornell id card!

No lunch with gries this morning. Too much going on. Will reschedule for after Thanksgiving.

Concurrent Programs

A *thread* or *thread of execution* is a sequential stream of computational work.

Concurrency is about controlling access by multiple *threads* to shared resources.

Last time: Learned about

1. Race conditions
2. Deadlock
3. How to create a thread in Java.

Purpose of this lecture

Show you Java constructs for eliminating race conditions, allowing threads to access a data structure in a safe way but allowing as much concurrency as possible.

This requires

- (1) The locking of an object so that others cannot access it, called synchronization.
- (2) Use of two new Java methods: wait() and notifyAll()

As an example, throughout, we use a bounded buffer.

Look at JavaHyperText, entry Thread !!!!!!!

An Example: bounded buffer

finite capacity (e.g. 20 loaves)
implemented as a queue

Threads A: produce loaves of bread and put them in the queue

Threads B: consume loaves by taking them off the queue

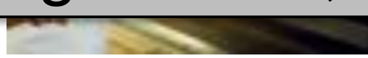
An Example: bounded buffer

finite capacity (e.g. 20 loaves)

implemented as a queue

Separation of concerns:

1. How do you implement a queue in an array?
2. How do you implement a bounded buffer, which allows producers to add to it and consumers to take things from it, all in parallel?



Threads A: produce loaves of bread and put them in the queue

Threads B: consume loaves by taking them off the queue

ArrayQueue

Array b[0..5]

	0	1	2	3	4	5	b.length
b	5	3	6	2	4		

put values 5 3 6 2 4 into queue

ArrayQueue

Array b[0..5]

	0	1	2	3	4	5	b.length
b	5	3	6	2	4		

put values 5 3 6 2 4 into queue

get, get, get

ArrayQueue

Array b[0..5]

	0	1	2	3	4	5	b.length
b	3	5		2	4	1	

Values wrap around!!

put values 5 3 6 2 4 into queue

get, get, get

put values 1 3 5

ArrayQueue

h

	0	1	2	3	4	5	b.length
b	3	5		2	4	1	

Values wrap around!!

```
int[] b; // 0 <= h < b.length. The queue contains the
int h;   // n elements b[h], b[h+1], b[h+2], …
int n;   // b[h+n-1] (all indices mod b.length)
```

```
/** Pre: there is space */
public void put(int v){
    b[(h+n) % b.length]= v;
    n= n+1;
}
```

```
/** Pre: not empty */
public int get(){
    int v= b[h];
    h= (h+1) % b.length;
    n= n-1;
    return v;
}
```

Bounded Buffer


```
/** An instance maintains a bounded buffer of fixed size */
class BoundedBuffer<E> {

     ArrayQueue<E> aq;
```

```
     /**  Put v into the bounded buffer.*/
```

```
     public void produce(E v) {
           if (!aq.isFull()) { aq.put(v) };
     }


     /**  Consume v from the bounded buffer.*/
```

```
     public E consume() {
           return aq.isEmpty() ? null : aq.get();
     }
}
```

Bounded Buffer


```
/** An instance maintains a bounded buffer of fixed size */
class BoundedBuffer<E> {

    ArrayQueue<E> aq;

    /**  Put v into the bounded buffer.*/
    public void produce(E v) {
        if (!aq.isFull()) { aq.put(v) };
    }
}
```

Problems

1. Chef doesn't easily know whether bread was added.
2. Suppose
    (a) First chef finds it not full.
    (b) Another chef butts in and adds a bread
    (c) First chef tries to add and can't because it's full. Need a way to prevent this

Synchronized block

a.k.a. *locks* or *mutual exclusion*

synchronized (object} { … }

Execution of the synchronized block:

1. "Acquire" the object, so that no other thread can acquire it and use it.
2. Execute the block.
3. "Release" the object, so that other threads can acquire it.

1. Might have to wait if other thread has acquired object.

2. While this thread is executing the synchronized block,
The object is *locked*. No other thread can obtain the lock.

Bounded Buffer


```
/** An instance maintains a bounded buffer of fixed size */
class BoundedBuffer<E> {

    ArrayQueue<E> aq;
```

```
    /** Put v into the bounded buffer.*/
    public void produce(E v) {

        if (!aq.isFull()) { aq.put(v) };

    }
}
```

After finding aq not full, but before putting v, another chef might beat you to it and fill up buffer aq!

Use of synchronized

```
synchronized (object) {
   code
}
```

The object is the outhouse.
The code is the person, waiting to get into the object.
If the key is on the door, the code takes it, goes in, locks the door, executes, opens the door, comes out, and hangs the key up.

Key is hanging the outhouse.

Anyone can grab the key, go inside, and lock the door. They have the key.

When they come out, they lock the door and hang the key by the front door. Anyone (only one) person can then grab the key, go inside, lock the door.

That's what synchronized implements!

Synchronized block


```
/** An instance maintains a bounded buffer of fixed size */
class BoundedBuffer<E> {

    ArrayQueue<E> aq;
```

```
    /** Put v into the bounded buffer.*/
```

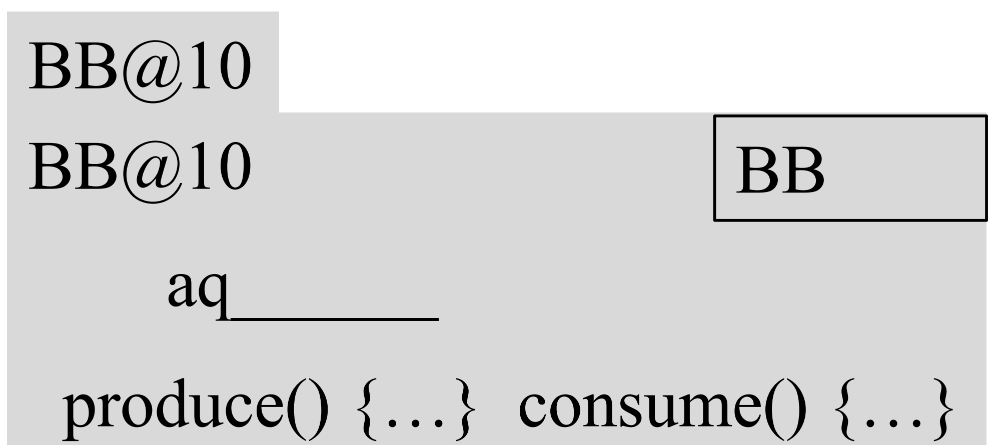
```
    public void produce(E v) {
        synchronized (aq) {
            if (!aq.isFull()) { aq.put(v) };
        }
    }

}
```

Synchronized blocks

```
public void produce(E v) {
    synchronized(this) {
        if (!aq.isFull()) { aq.put(v);
}
    }
}
```

You can synchronize (lock) any object, including **this**.



Synchronized Methods

```
public void produce(E v) {
    synchronized(this) {
        if (!aq.isFull()) { aq.put(v); }
    }
}
```

You can synchronize (lock) any object, including **this**.

```
public synchronized void produce(E v) {
    if (!aq.isFull()) { aq.put(v); }
}
```

Or you can synchronize methods
This is the same as wrapping the entire method implementation in a synchronized(this) block

Bounded buffer


```
/** An instance maintains a bounded buffer of fixed size */
class BoundedBuffer<E> {

    ArrayQueue<E> aq;

    /**  Put v into the bounded buffer.*/
    public synchronized void produce(E v) {
         if (!aq.isFull()) { aq.put(v); }
    }

}
```

What happens of aq is full?

We want to wait until it becomes non-full —until there is a place to put v.

Somebody has to buy a loaf of bread before we can put more bread on the shelf.

Two lists for a synchronized object

For every synchronized object *sobj*, Java maintains:

1. **locklist:** a list of threads that are waiting to obtain the lock on *sobj*
2. **waitlist:** a list of threads that had the lock but executed wait()
   - e.g. because they couldn't proceed

Method wait() is defined in Object

Wait()


```
class BoundedBuffer<E> {

    ArrayQueue<E> aq;

    /**  Put v into the bounded buffer.*/
    public synchronized void produce(E v) {
        while (aq.isFull()) {
            try { wait(); }
            catch(InterruptedException e) {}
        }
        aq.put(v);

    }    notifyAll()

    ...
}
```

need while loop (not if statement) to prevent race conditions

puts thread on the wait list

threads can be interrupted if this happens just continue.

locklist **waitlist**

notify() and notifyAll()

- Methods notify() and notifyAll() are defined in Object
- notify() moves one thread from the waitlist to the locklist
  - Note: which thread is moved is arbitrary
- notifyAll() moves all threads on the waitlist to the locklist

locklist **waitlist**

notify() and notifyAll()


```
/** An instance maintains a bounded buffer of fixed size */
class BoundedBuffer<E> {

     ArrayQueue<E> aq;

     /**  Put v into the bounded buffer.*/
     public synchronized void produce(E v) {
          while (aq.isFull()) {
               try { wait(); }
               catch(InterruptedException e){}
          }
          aq.put(v);
          notifyAll()
     }
     ...
}
```

WHY use of notify() may hang.

Two sets:

1. lock: threads waiting to get lock.

2. wait: threads waiting to be notified

Work with a bounded buffer of length 1.

1. Consumer W gets lock, wants White bread, finds buffer empty, and wait()s: is put in set 2.
2. Consumer R gets lock, wants Rye bread, finds buffer empty, wait()s: is put in set 2.
3. Producer gets lock, puts Rye in the buffer, does notify(), gives up lock.
4. The notify() causes one waiting thread to be moved from set 2 to set 1. Choose W.
5. No one has lock, so one Runnable thread, W, is given lock. W wants white, not rye, so wait()s: is put in set 2.
6. Producer gets lock, finds buffer full, wait()s: is put in set 2.

All 3 threads are waiting in set 2. **Nothing more happens.**

Should one use notify() or notifyAll()

But suppose there are two kinds of bread on the shelf —and one still picks the head of the queue, if it's the right kind of bread.

Using notify() can lead to a situation in which no one can make progress.

notifyAll() always works; you need to write documentation if you optimize by using notify()

Eclipse Example

Producer: produce random ints

Consumer 1: even ints

Consumer 2: odd ints

Dropbox: 1-element bounded buffer

Locklist
Threads wanting the Dropbox

Waitlist
Threads who had Dropbox and waited

Word of warning with synchronized

Key is hanging by front door.

Anyone can grab the key, go inside, and lock the door. They have the key.

When they come out, they lock the door and hang the key by the front door. Anyone (only one) person can then grab the key, go inside, lock the door.

That's what synchronized implements!

BUT: You leave the back door open and tell your friends to go in whenever they want

Threads that don't synchronize can get in. Dangerous but useful to increase efficiency.

Using Concurrent Collections...

Java has a bunch of classes to make synchronization easier.

It has synchronized versions of some of the Collections classes

It has an Atomic counter.

From spec for HashSet

… this implementation is not synchronized. If multiple threads access a hash set concurrently, and at least one of the threads modifies the set, it must be synchronized externally. This is typically accomplished by synchronizing on some object that naturally encapsulates the set. If no such object exists, the set should be "wrapped" using method Collections.synchronizedSet This is best done at creation time, to prevent accidental unsynchronized access to the set:

```
Set s = Collections.synchronizedSet(new HashSet(...));
```

Race Conditions

Thread 1 | Thread 2

time ↓

Initially, i = 0

```
tmp = load i;
```
Load 0 from memory

Load 0 from memory
```
tmp = load i;
```

```
tmp = tmp + 1;
store tmp to i;
```
Store 1 to memory

Store 1 to memory
```
tmp = tmp + 1;
store tmp to i;
```

Finally, i = 1

Using Concurrent Collections...


```
import java.util.concurrent.atomic.*;

public class Counter {
  private static AtomicInteger counter;

  public Counter() {
    counter= new AtomicInteger(0);
  }

  public static int getCount() {
    return counter.getAndIncrement();
  }
}
```

Fancier forms of locking

Java. **synchronized** is the core mechanism

But. Java has a class Semaphore. It can be used to allow a limited number of threads (or kinds of threads) to work at the same time. Acquire the semaphore, release the semaphore

Semaphore: a kind of synchronized counter (invented by Dijkstra in 1962-63, THE multiprogramming system)

The Windows and Linux and Apple O/S have kernel locking features, like file locking

Python: acquire a **lock**, release the **lock**. Has semaphores

Summary

Use of multiple processes and multiple threads within each process can exploit concurrency

- may be real (multicore) or virtual (an illusion)

Be careful when using threads:

- synchronize shared memory to avoid race conditions
- avoid deadlock

Even with proper locking concurrent programs can have other problems such as "livelock"

Serious treatment of concurrency is a complex topic (covered in more detail in cs3410 and cs4410)

Nice tutorial at http://docs.oracle.com/javase/tutorial/essential/concurrency/index.html