COMP 322: Fundamentals of Parallel Programming

Lecture 26: Java Threads, Java's synchronized statement

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Worksheet 25 Solution

```
1.   // Assume that no. of enq() operations is < Integer.MAX_VALUE
2.   class Queue1 {
3.     AtomicInteger head = new AtomicInteger(0);
4.     AtomicInteger tail = new AtomicInteger(0);
5.     Object[] items = new Object[Integer.MAX_VALUE];
6.     public void enq(Object x) {
7.       int slot = tail.getAndIncrement(); // isolated(tail) ...
8.      items[slot] = x;
9.    } // enq
10.    public Object deq() throws EmptyException {
11.      int slot = head.getAndIncrement(); // isolated(head) ...
12.      Object value = items[slot];
13.      if (value == null) throw new EmptyException();
14.      return value;
15.    } // deq
16. } // Queue1

17. // Client code
18. finish {
19.   Queue1 q = new Queue1();
20.   async q.enq(new Integer(1));
21.   q.enq(newInteger(2));
22.   Integer x = (Integer) q.deq();
23. }
```

Q: Can you show an execution for which deq() results in an EmptyException in line 22 below?

A: Yes, consider the case when the async on line 20 introduces an arbitrary delay between lines 7 and 8

Introduction to Java threads: java.lang.Thread class

- Execution of a Java program begins with an instance of Thread created by the Java Virtual Machine (JVM) that executes the program's main() method.
- Parallelism can be introduced by creating additional instances of class Thread that execute as parallel threads.

```
public class Thread extends Object implements Runnable {
  Thread() { ... } // Creates a new Thread
  Thread(Runnable r) { ... } // Creates a new Thread with Runnable object r
  void run() { ... } // Code to be executed by thr
   // Case 1: If this thread was cr
   //          then that object's run method
   // Case 2: If this class is subclassed, t
   //          in the subclass is called
  void start() { ... } // Causes this thread to sta
  void join() { ... } // Wait for this thread to die
  void join(long m) // Wait at most m milliseconds for thread to die
  static Thread currentThread() // Returns currently executing thread
  . . .
}
```

A lambda can be passed as a Runnable

start() and join() methods

- A Thread instance starts executing when its start() method is invoked
  - —start() can be invoked at most once per Thread instance
    - – Like actors, except that Java threads don't process messages
  - —As with async, the parent thread can immediately move to the next statement after invoking t.start()
- A t.join() call forces the invoking thread to wait till thread t completes.
  - —Lower-level primitive than finish since it only waits for a single thread rather than a collection of threads
  - —No restriction on which thread performs a join on which thread, so it is possible to create a deadlock cycle using join()
    - – Declaring thread references as final does not help because the new() and start() operations are separated for threads (unlike futures, where they are integrated)

Two-way Parallel Array Sum using Java Threads

```
// Start of main thread
sum1 = 0; sum2 = 0; // sum1 & sum2 are static fields
Thread t1 = new Thread(() -> {
      // Child task computes sum of lower half of array
      for(int i=0; i < X.length/2; i++) sum1 += X[i];
   });
t1.start();
// Parent task computes sum of upper half of array
for(int i=X.length/2; i < X.length; i++) sum2 += X[i];
// Parent task waits for child task to complete (join)
t1.join();
return sum1 + sum2;
```

How to convert a sequential library to a monitor in HJ vs. Java?

<u>HJ approach</u>:

- Use object-based isolation to ensure that each call to a public method is isolated on "this" e.g.,

  ```
  public void add(...) { isolated(this) { .... } }
  ```

- Can also use general isolated statement, but that is overkill e.g.,

  ```
  public void add(...) { isolated { .... } }
  ```

<u>Java approach</u>:

- Use Java's synchronized statement instead of object-based isolation e.g.,

  ```
  public void add(...) { synchronized(this) { .... } }
  ```

  or equivalently

  ```
  public synchronized void add(...) { ....  }
  ```

- Both HJ and Java programs can use specialized implementations of monitors available in java.util.concurrent
  — ConcurrentHashMap, ConcurrentLinkedQueue, CopyOnWriteArraySet

Objects and Locks in Java --- synchronized statements and methods

- Every Java object has an associated lock acquired via:
  - synchronized statements
    - ```
      synchronized( foo ) { // acquire foo's lock
        // execute code while holding foo's lock
      } // release foo's lock
      ```
  - synchronized methods
    - ```
      public synchronized void op1() { // acquire 'this' lock
        // execute method while holding 'this' lock
      } // release 'this' lock
      ```
- Java language does not enforce any relationship between object used for locking and objects accessed in isolated code
  - If same object is used for locking and data access, then the object behaves like a monitor
- Locking and unlocking are automatic
  - Locks are released when a synchronized block exits
    - By normal means: end of block reached, return, break
    - When an exception is thrown and not caught

Locking guarantees in Java

- It is desirable to use java.util.concurrent.atomic and other standard monitor classes when possible
- Locks are needed for more general cases. Basic idea is to implement `synchronized(a) <stmt>` as follows:
  1. Acquire lock for object a
  2. Execute <stmt>
  3. Release lock for object a
- The responsibility for ensuring that the choice of locks correctly implements the semantics of monitors/isolated lies with the programmer.
- The main guarantee provided by locks is that only one thread can hold a given lock at a time, and the thread is blocked when acquiring a lock if the lock is unavailable.

Deadlock example with Java synchronized statement

- The code below can deadlock if `leftHand()` and `rightHand()` are called concurrently from different threads
  - Because the locks are not acquired in the same order

```
public class ObviousDeadlock {
   . . .
   public void leftHand() {
       synchronized(lock1) {
           synchronized(lock2) {
               for (int i=0; i<10000; i++)
                   sum += random.nextInt(100);
           }
       }
   }
   public void rightHand() {
       synchronized(lock2) {
           synchronized(lock1) {
               for (int i=0; i<10000; i++)
                   sum += random.nextInt(100);
           }
       }
   }
}
```

Deadlock avoidance in HJ with object-based isolation

- HJ implementation ensures that all locks are acquired in the same order
- ==> no deadlock

```
public class NoDeadlock1 {
   . . .
   public void leftHand() {
       isolated(lock1, lock2) {
               for (int i=0; i<10000; i++)
                   sum += random.nextInt(100);

       }
   }
   public void rightHand() {
       isolated(lock2,lock1) {
               for (int i=0; i<10000; i++)
                   sum += random.nextInt(100);
           }
       }
   }
}
```

Dynamic Order Deadlocks

- There are even more subtle ways for threads to deadlock due to inconsistent lock ordering
  - Consider a method to transfer a balance from one account to another:

```
public class SubtleDeadlock {
       public void transferFunds(Account from,
                                 Account to,
                                 int amount) {
           synchronized (from) {
               synchronized (to) {
                   from.subtractFromBalance(amount);
                   to.addToBalance(amount);
               }
           }
       }
   }
```

  - What if one thread tries to transfer from A to B while another tries to transfer from B to A ?

    Inconsistent lock order again – Deadlock!

Avoiding Dynamic Order Deadlocks

- The solution is to induce a lock ordering
  - Here, uses an existing unique numeric key, acctId, to establish an order

```
public class SafeTransfer {
    public void transferFunds(Account from, Account to, int amount) {
        Account firstLock, secondLock;
        if (fromAccount.acctId == toAccount.acctId)
            throw new Exception("Cannot self-transfer");
        else if (fromAccount.acctId < toAccount.acctId) {
            firstLock = fromAccount;
            secondLock = toAccount;
        }
        else {
            firstLock = toAccount;
            secondLock = fromAccount;
        }
        synchronized (firstLock) {
          synchronized (secondLock) {
            from.subtractFromBalance(amount);
            to.addToBalance(amount);
          }
        }
    }
}
```

Java's Object Locks are Reentrant

- Locks are granted on a per-thread basis
  - Called reentrant or recursive locks
  - Promotes object-oriented concurrent code
- A synchronized block means execution of this code requires the current thread to hold this lock
  - If it does — fine
  - If it doesn't — then acquire the lock
- Reentrancy means that recursive methods, invocation of super methods, or local callbacks, don't deadlock

```
public class Widget {
   public synchronized void doSomething() { ... }
}
public class LoggingWidget extends Widget {
   public synchronized void doSomething() {
        Logger.log(this + ": calling doSomething()");
        super.doSomething();  // Doesn't deadlock!
     }
 }
```

Object-based isolation in HJ does not deadlock

```
public class NoDeadlock2 {
       public void transferFunds(Account from,
                                 Account to,
                                 int amount) {
           isolated (from, to) {
                from.subtractFromBalance(amount);
                to.addToBalance(amount);
           } } } }
```

- HJ's implementation guarantees that object-based isolation is deadlock-free
- However, HJ does not permit an inner isolated statement to add a new object e.g., the following code is not permitted in HJ, but the equivalent synchronized version is permitted in Java

Not permitted in HJ (if from != to)

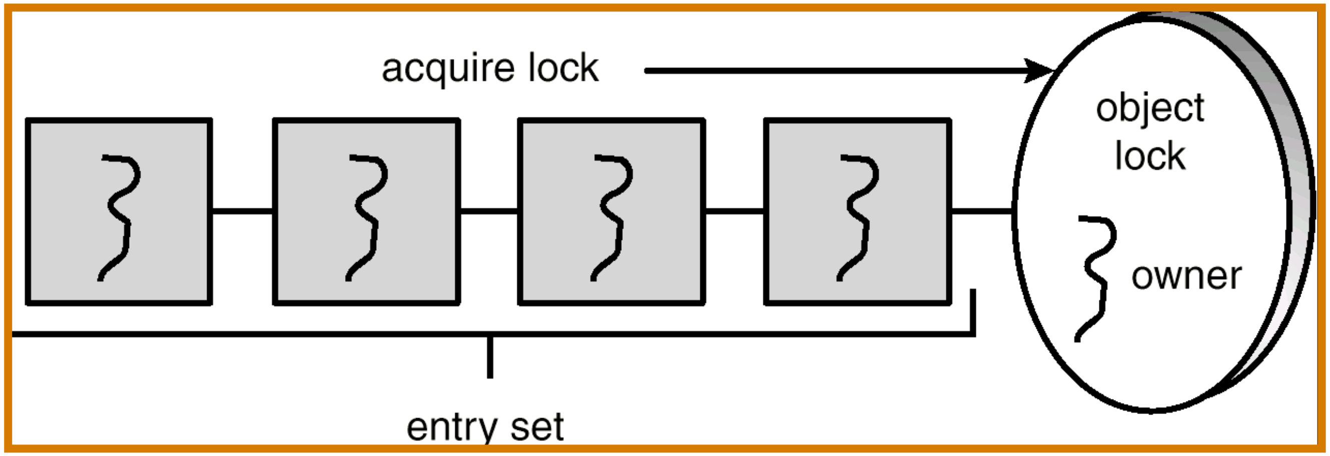
```
isolated (from) {
  ...
  isolated (to) { . . .}
}
```

Permitted in Java

```
synchronized (from) {
  ...
  synchronized(to) { . . .}
}
```

Implementation of Java synchronized statements/methods

- Every object has an associated lock
- "synchronized" is translated to matching monitorenter and monitorexit bytecode instructions for the Java virtual machine
  - monitorenter requests "ownership" of the object's lock
  - monitorexit releases "ownership" of the object's lock
- If a thread performing monitorenter does not own the lock (because another thread already owns it), it is placed in an unordered "entry set" for the object's lock



Monitors – a Diagrammatic summary

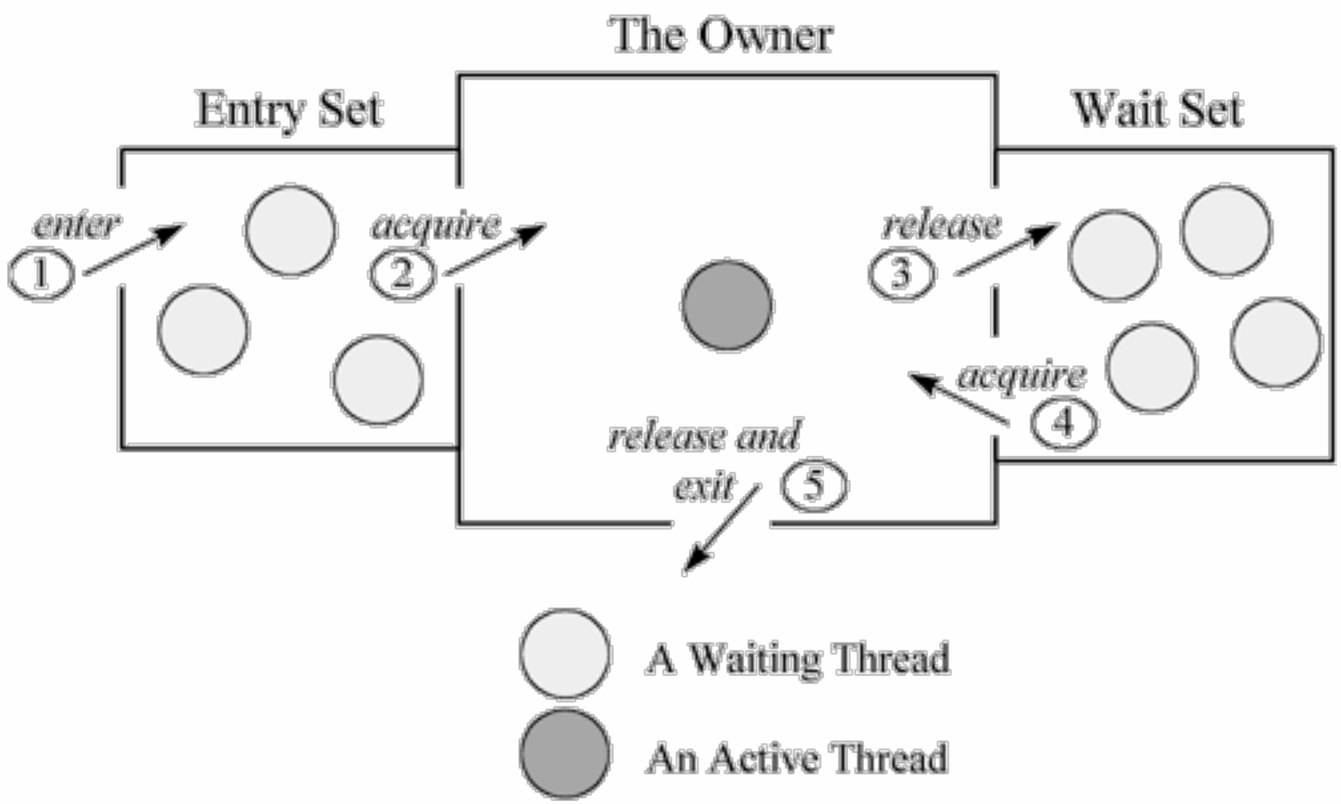


Figure 20-1. A Java monitor.

Figure source: http://www.artima.com/insidejvm/ed2/images/fig20-1.gif

What if you want to wait for shared state to satisfy a desired property?

```
public synchronized void insert(Object item) { // producer
    // TODO: wait till count < BUFFER SIZE
    ++count;
    buffer[in] = item;
    in = (in + 1) % BUFFER SIZE;
    // TODO: notify consumers that an insert has been performed
}

public synchronized Object remove() { // consumer
    Object item;
    // TODO: wait till count > 0
    --count;
    item = buffer[out];
    out = (out + 1) % BUFFER SIZE;
    // TODO: notify producers that a remove() has been performed
    return item;
}
```

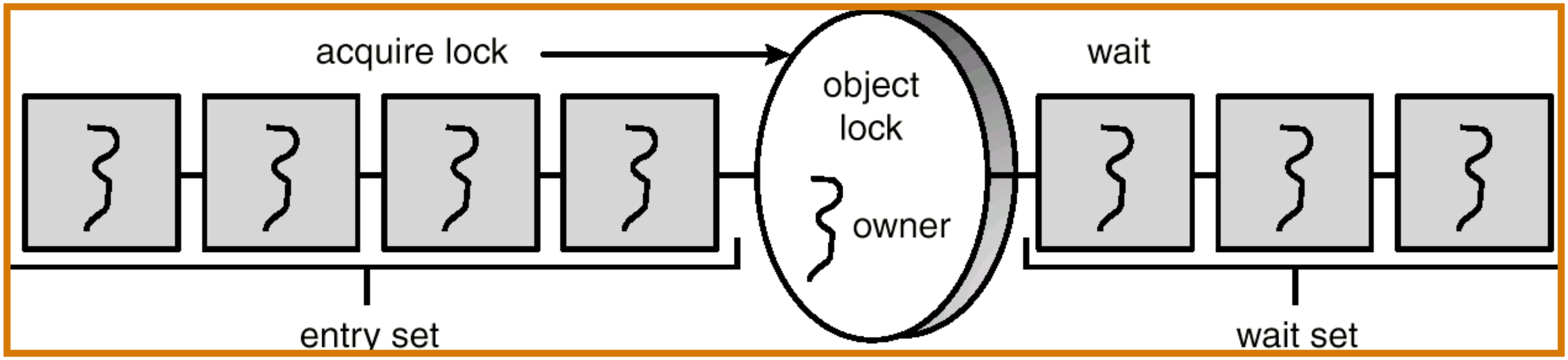
The Java wait() Method

- A thread can perform a wait() method on an object that it owns:
  1. the thread releases the object lock
  2. thread state is set to blocked
  3. thread is placed in the wait set
- Causes thread to wait until another thread invokes the notify() method or the notifyAll() method for this object.
- Since interrupts and spurious wake-ups are possible, this method should always be used in a loop e.g.,

```
synchronized (obj) {
    while (<condition does not hold>)
        obj.wait();
    ... // Perform action appropriate to condition
}
```

- Java's wait-notify is related to "condition variables" in POSIX threads

Entry and Wait Sets



The notify() Method

When a thread calls notify(), the following occurs:

1. selects an arbitrary thread T from the wait set
2. moves T to the entry set
3. sets T to Runnable

T can now compete for the object's lock again

Multiple Notifications

- notify() selects an arbitrary thread from the wait set.
  - This may not be the thread that you want to be selected.
  - Java does not allow you to specify the thread to be selected
- notifyAll() removes ALL threads from the wait set and places them in the entry set. This allows the threads to decide among themselves who should proceed next.
- notifyAll() is a conservative strategy that works best when multiple threads may be in the wait set

insert() with wait/notify Methods

```
public synchronized void insert(Object item) {
   while (count == BUFFER SIZE) {
                try {
                        wait();
                }
                catch (InterruptedException e) { }
   }
   ++count;
   buffer[in] = item;
   in = (in + 1) % BUFFER SIZE;
   notify();
}
```

remove() with wait/notify Methods

```
public synchronized Object remove() {
    Object item;
    while (count == 0) {
                try {
                        wait();
                }
                catch (InterruptedException e) { }
    }
    --count;
    item = buffer[out];
    out = (out + 1) % BUFFER SIZE;
    notify();
    return item;
}
```

Complete Bounded Buffer using Java Synchronization

```
public class BoundedBuffer implements Buffer
{
   private static final int BUFFER SIZE = 5;
   private int count, in, out;
   private Object[] buffer;
   public BoundedBuffer() { // buffer is initially empty
               count = 0;
               in = 0;
               out = 0;
               buffer = new Object[BUFFER SIZE];
   }
   public synchronized void insert(Object item) { // See previous slides
   }
   public synchronized Object remove() { // See previous slides
   }
}
```

Worksheet #26: Java Threads and Data Races

Name: ______________________ Netid: ______________________

1) Write a sketch of the pseudocode for a Java threads program that exhibits a data race using start() and join() operations.

2) Write a sketch of the pseudocode for a Java threads program that exhibits a data race using synchronized statements