COMP 322: Fundamentals of Parallel Programming

Lecture 26: Java synchronized statement (contd), Advanced Locking

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Solution to Worksheet #25: Java Threads

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

```
1.  // Start of thread t0 (main program)
2.  sum1 = 0; sum2 = 0; // Assume that sum1 & sum2 are fields
3.  // Compute sum1 (lower half) and sum2 (upper half) in parallel
4.  final int len = X.length;
5.  Runnable r1 = new Runnable() {
6.    public void run(){ for(int i=0 ; i < len/2 ; i++) sum1+=X[i];}
7.  };
8.  Thread t1 = new Thread(r1);
9.  t1.start();
10. Runnable r2 = new Runnable() {
11.   public void run(){ for(int i=len/2 ; i < len ; i++) sum2+=X[i];}
12. };
13. Thread t2 = new Thread(r2);
14. t2.start();
15. int sum = sum1 + sum2; // data race between t0 & t1, and t0 & t2
16. t1.join(); t2.join();
```


Acknowledgments for Today's Lecture

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- ECE 3005 course slides from Georgia Tech
  - —http://users.ece.gatech.edu/~copeland/jac/3055-05/ppt/ch07-sync-b.ppt
- A Sophomoric Introduction to Shared-Memory Parallelism and Concurrency, Lecture 6, Dan Grossman, U. Washington
  - —http://www.cs.washington.edu/homes/djg/teachingMaterials/grossmanSPAC_lec6.pptx

Complete Bounded Buffer using Java Synchronization (Recap)

```
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
    }
}
```


insert() with wait/notify Methods

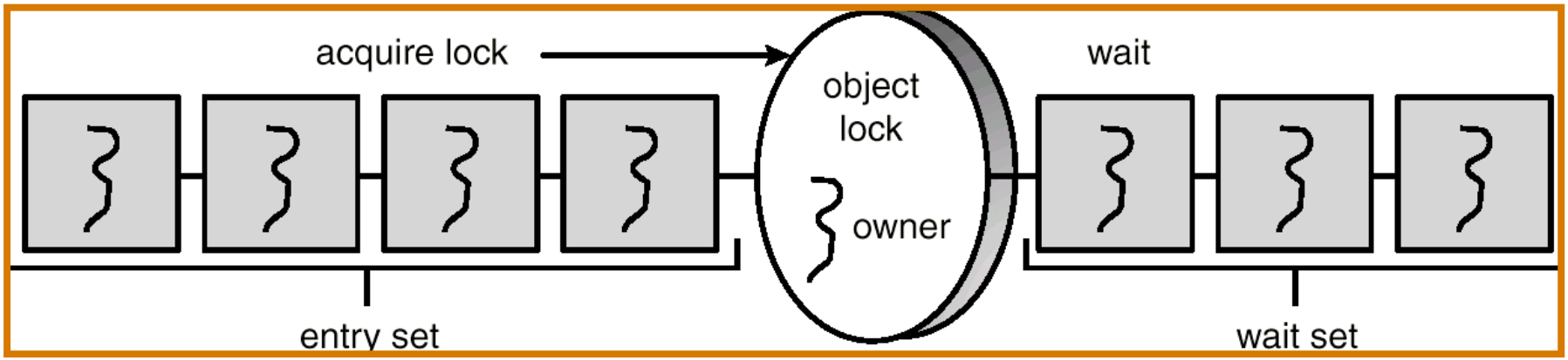
```
1.public synchronized void insert(Object item) {
2. while (count == BUFFER SIZE) {
3.              try {
4.                     wait();
5.              }
6.              catch (InterruptedException e) { }
7. }
8. ++count;
9. buffer[in] = item;
10.     in = (in + 1) % BUFFER SIZE;
11.     notify(); // Should we use notifyall() instead?
12.}
```


remove() with wait/notify Methods

```
1.public synchronized Object remove() {
2. Object item;
3. while (count == 0) {
4.              try {
5.                      wait();
6.              }
7.              catch (InterruptedException e) { }
8. }
9. --count;
10.     item = buffer[out];
11.     out = (out + 1) % BUFFER SIZE;
12.     notify(); // Should we use notifyall() instead?
13.     return item;
14.}
```


Entry and Wait Sets

Scenario for BUFFER_SIZE = 1 with multiple producers (P0, P1, ...) and multiple consumers (C0, C1, ...)



Time-step	Entry set	Buffer state	Wait set
t	P0	EMPTY	C0, C1
t+1	C0, P1	FULL	C1
t+2	C0	FULL	P1, C1

Problem: notify() may select the "wrong" thread each time, leading to livelock ⇒ use notifyAll() instead.

notify() vs. notifyAll() --- Recap

- 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

Two Tips for working with Java Threads

- Any variable from an outer scope that is accessed in an anonymous inner class (e.g., in the run() method) must be declared final.

```
final int len = X.length;
Runnable r = new Runnable() {
  public void run() {
    for(int i=0 ; i < len/2 ; i++) sum1 += X[i];
  }
};
```

- Remember to call the start() method on any thread that you create. Otherwise, the thread's computation does not get executed.

```
Thread t = new Thread(r); t.start();
```


Cancelling Threads: Interruption

- Problem: how do we shut down a thread like a web server?
- Need to communicate that shutdown has been requested
  - —Could set a flag that is polled in the main loop

    But main loop could be blocked in `accept()`
- Interruption provides a means of signalling a request to another thread
- Each `Thread` has an "interrupted status" which is
  - —Set when `interrupt()` method is invoked on it
  - —Queried by `isInterrupted()` method
- Many blocking methods respect interruption requests and return early by throwing checked `InterruptedException`
  - – `Object.wait()`
  - —Throwing IE usually clears interrupted status

Calling methods that may throw InterruptedException

- Many methods in Java thread libraries may throw an InterruptedException e.g., <thread>.join(), <object>.wait(),
- When calling any such method, you will either need to include each call to join() in a try-catch block, or add a "throws InterruptedException" clause to the definition of the method that includes the call to join()

- Try-catch example

```
public class Foo implements Runnable {

   public void run() {
       try {
           t1.join();
       }
       catch (InterruptedException e) {
           Thread.currentThread().interrupt();
       } } }
```


TrafficSignal example (throws clause)

- The `wait` methods will
  - —Atomically release the lock and block the current thread
  - —Reacquire lock before returning
- `notify()` means wake up one waiting thread
- `notifyAll()` means wake up all waiting threads

```
public class TrafficSignal {
    public enum Color { GREEN, YELLOW, RED };
    private Color color;
    public synchronized void setColor(Color color) {
        this.color = color;
        notifyAll();
    }
    public synchronized void awaitGreen() throws InterruptedException
{
      while (color != Color.GREEN) wait(); // waits on "this" object
    }
}
```


Responses to Interruption

- Re-throw IE
  - —So caller can handle interruption request
- Cancel and return early
  - —Clean up and exit without signalling an error
  - —May require rollback or recovery
- Ignore interruption
  - —When it is too dangerous to stop
  - —Should re-assert interrupted status before returning
- Postpone interruption
  - —Remember that interrupt occurred
  - —Finish what you are doing and then throw IE
- Throw a general failure exception
  - —When interruption is one of many reasons method can fail

Example: Shutting Down the Web Server

```
1.  public class WebServerWithShutdown {
2.     private final ServerSocket server;
3.     private Thread serverThread;
4.     public WebServerWithShutdown(int port) throws IOException {
5.        server = new ServerSocket(port);
6.        server.setSoTimeout(5000);  // so we can check for interruption
7.     }
8.     public synchronized void shutdownServer() throws IE..,IOException {
9.        if (serverThread == null) throw new IllegalStateException();
10.       serverThread.interrupt();
11.       serverThread.join(5000);  // wait 5s before closing socket
12.       server.close();           // to give thread a chance to cleanup
13.    }
14.    public synchronized void startServer() {
15.       if (serverThread == null) {
16.          (serverThread = new Thread() {
17.             public void run() {
18.                while (!Thread.interrupted()) {
19.                   try { processRequest(server.accept()); }
20.                   catch (SocketTimeoutException e) { continue; }
21.                   catch (IOException ex) { /* log it */ }
22.                }
23.             }
24.          }).start();
25.       }
26.    }
27. }
```

Note: shutdownServer can be harmlessly called more than once

Use of class objects in synchronized statements/methods

- A `class` object exists for every class
- `static synchronized` methods lock the `class` object
- `class` object can be locked explicitly:
  - `synchronized(Foo.class) { /* ... */ }`
- No connection between locking the `Class` object and locking an instance of the class
  - —Locking the `Class` object does not lock any instance
  - —Instance methods that use static variables must synchronize access to them explicitly by locking the `Class` object
    - Always use the class literal to get reference to `Class` object—not `this.getClass()` as you may access a subclass object

java.util.concurrent

- General purpose toolkit for developing concurrent applications
  - —import java.util.concurrent.*
- Goals: "Something for Everyone!"
  - —Make some problems trivial to solve by everyone
    - Develop thread-safe classes, such as servlets, built on concurrent building blocks like `ConcurrentHashMap`
  - —Make some problems easier to solve by concurrent programmers
    - Develop concurrent applications using thread pools, barriers, latches, and blocking queues
  - —Make some problems possible to solve by concurrency experts
    - Develop custom locking classes, lock-free algorithms
- HJ approach
  - —Build HJ runtime on top of java.util.concurrent library

Key Functional Groups in j.u.c.

- Atomic variables
  - —The key to writing lock-free algorithms
- Concurrent Collections:
  - —Queues, blocking queues, concurrent hash map, …
  - —Data structures designed for concurrent environments
- Locks and Conditions
  - —More flexible synchronization control
  - —Read/write locks
- Executors, Thread pools and Futures
  - —Execution frameworks for asynchronous tasking
- Synchronizers: Semaphore, Latch, Barrier, Exchanger
  - —Ready made tools for thread coordination

Locks

- Use of monitor synchronization is just fine for most applications, but it has some shortcomings
  - Single wait-set per lock
  - No way to interrupt or time-out when waiting for a lock
  - Locking must be block-structured
    - Inconvenient to acquire a variable number of locks at once
    - Advanced techniques, such as hand-over-hand locking, are not possible
- Lock objects address these limitations
  - But harder to use: Need **`finally`** block to ensure release
  - So if you don't need them, stick with **`synchronized`**

Example of hand-over-hand locking:

- L1.lock() … L2.lock() … L1.unlock() … L3.lock() … L2.unlock() ….

java.util.concurrent.locks.Lock interface

```
interface Lock {
   void lock();
   void lockInterruptibly() throws InterruptedException;
   boolean tryLock(); // return false if lock is not obtained
   boolean tryLock(long timeout, TimeUnit unit)
                                throws InterruptedException;
   void unlock();
   Condition newCondition();
   // can associate multiple condition vars with lock
 }
```

- **java.util.concurrent.locks.Lock interface is implemented by java.util.concurrent.locks.ReentrantLock class**

Simple ReentrantLock() example

- Used extensively within `java.util.concurrent`

```
final Lock lock = new ReentrantLock();
...
lock.lock();
try {
  // perform operations protected by lock
}
catch(Exception ex) {
  // restore invariants & rethrow
}
finally {
  lock.unlock();
}
```

- **Must manually ensure lock is released**

java.util.concurrent.locks.condition interface

- Can be allocated by calling ReentrantLock.newCondition()
- Supports multiple condition variables per lock
- Methods supported by an instance of condition
  - —void await() // NOTE: not wait
    - Causes current thread to wait until it is signaled or interrupted
    - Variants available with support for interruption and timeout
  - —void signal() // NOTE: not notify
    - Wakes up one thread waiting on this condition
  - —void signalAll() // NOTE: not notifyAll()
    - Wakes up all threads waiting on this condition
- For additional details see
  - —http://download.oracle.com/javase/1.5.0/docs/api/java/util/concurrent/locks/Condition.html

BoundedBuffer implementation using two conditions, notFull and notEmpty

```
class BoundedBuffer {
  final Lock lock = new ReentrantLock();
  final Condition notFull  = lock.newCondition();
  final Condition notEmpty = lock.newCondition();

  final Object[] items = new Object[100];
  int putptr, takeptr, count;

  . . .
```


BoundedBuffer implementation using two conditions, notFull and notEmpty (contd)

```
public void put(Object x) throws InterruptedException {
  lock.lock();
  try {
    while (count == items.length) notFull.await();
    items[putptr] = x;
    if (++putptr == items.length) putptr = 0;
    ++count;
    notEmpty.signal();
  } finally {
    lock.unlock();
  }
}
```


BoundedBuffer implementation using two conditions, notFull and notEmpty (contd)

```
public Object take() throws InterruptedException {
  lock.lock();
  try {
    while (count == 0) notEmpty.await();
    Object x = items[takeptr];
    if (++takeptr == items.length) takeptr = 0;
    --count;
    notFull.signal();
    return x;
  } finally {
    lock.unlock();
  }
}
```


Reading vs. writing

- Recall that the use of synchronization is to protect interfering accesses
  - —Multiple concurrent reads of same memory: Not a problem
  - —Multiple concurrent writes of same memory: Problem
  - —Multiple concurrent read & write of same memory: Problem

So far:

- —If concurrent write/write or read/write might occur, use synchronization to ensure one-thread-at-a-time

But:

- —This is unnecessarily conservative: we could still allow multiple simultaneous readers

Consider a hashtable with one coarse-grained lock

- —So only one thread can perform operations at a time

But suppose:

- —There are many simultaneous `lookup` operations
- – `insert` operations are very rare

java.util.concurrent.locks.ReadWriteLock interface

```
interface ReadWriteLock {
  Lock readLock();
  Lock writeLock();
}
```

- Even though the interface appears to just define a pair of locks, the semantics of the pair of locks is coupled as follows
  - —Case 1: a thread has successfully acquired writeLock().lock()
    - No other thread can acquire readLock() or writeLock()
  - —Case 2: no thread has acquired writeLock().lock()
    - Multiple threads can acquire readLock()
    - No other thread can acquire writeLock()
- java.util.concurrent.locks.ReadWriteLock interface is implemented by java.util.concurrent.locks.ReadWriteReentrantLock class

Example code

```
class Hashtable<K,V> {
  …
  // coarse-grained, one lock for table
  ReadWriteLock lk = new ReentrantReadWriteLock();
  V lookup(K key) {
    int bucket = hasher(key);
    lk.readLock().lock(); // only blocks writers
    … read array[bucket] …
    lk.readLock().unlock();
  }
  void insert(K key, V val) {
    int bucket = hasher(key);
    lk.writeLock().lock(); // blocks readers and writers
    … write array[bucket] …
    lk.writeLock().unlock();
  }
}
```


Announcements

- Homework 4 due on Friday, March 22nd
- Week 8 Lecture Quiz due on Friday, March 22nd
- Week 9 lab work due via turn-in as usual, but there is no Week 9 Lab Quiz
- Guest lecture on Friday (March 22nd) by Prof. Swarat Chaudhuri on "Speculative parallelization of isolated blocks"

Worksheet #26: use of tryLock()

Name 1: _____ Name 2: _____

Extend the transferFunds() method from Lecture 25 to use library locks with tryLock() instead of synchronized, and to return a boolean value --- true if it succeeds in obtaining in obtaining both locks and performing the transfer, and false otherwise. Sketch your answer below using pseudocode. Can you create a deadlock with multiple calls to transferFunds() in parallel?

```
1. public void transferFunds(Account from, Account to, int amount) {
2.             synchronized (from) {
3.                 synchronized (to) {
4.                     from.subtractFromBalance(amount);
5.                     to.addToBalance(amount);
6.                 }
7.             }
8.         }
```