COMP 322: Fundamentals of Parallel Programming

Lecture 29: Java's synchronized statement

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Acknowledgments for Today’s Lecture

- “Introduction to Concurrent Programming in Java”, Joe Bowbeer, David Holmes, OOPSLA 2007 tutorial slides
  - Contributing authors: Doug Lea, Brian Goetz
Thread.start() and Thread.join() provide rudimentary support for async and finish. What about monitors, critical sections, isolated?

```
// Start of Task T1 (main program)
sum1 = 0; sum2 = 0; // Assume that sum1 & sum2 are fields (not local vars)
// Compute sum1 (lower half) and sum2 (upper half) in parallel
final int len = X.length;
Runnable r1 = new Runnable() {
    public void run(){ for(int i=0 ; i < len/2 ; i++) sum1 += X[i];}
};
Thread t1 = new Thread(r1);
t1.start();
Runnable r2 = new Runnable() {
    public void run(){ for(int i=len/2 ; i < len ; i++) sum2 += X[i];}
};
Thread t2 = new Thread(r2);
t2.start();
// Wait for threads t1 and t2 to complete
t1.join(); t2.join();
int sum = sum1 + sum2;
```
Monitors --- an object-oriented approach to isolation (Recap from Lecture 21)

• A monitor is an object containing
  • some local variables (private data)
  • some methods that operate on local data (monitor regions)
• Only one task can be active in a monitor at a time, executing some monitor region
  • Analogous to a critical section for a single object
• Monitors can also be used for
  • Mutual exclusion
  • Cooperation among parallel method invocations
How to convert a sequential library to a monitor in HJ vs. Java?

**HJ approach:**
- Use object-based isolation to ensure that each call to a public method is isolated on “this” e.g.,
  ```java
  public void add(...) { isolated(this) { .... } }
  ```
- Can also use general isolated statement, but that is overkill e.g.,
  ```java
  public void add(...) { isolated { .... } }
  ```

**Java approach:**
- Use Java’s synchronized statement instead of object-based isolation e.g.,
  ```java
  public void add(...) { synchronized(this) { .... } }, or equivalently
  public synchronized void add(...) { .... } // Like synchronized(this)
  ```
- 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

- Java’s synchronized is related to “mutex” locks in POSIX thread library
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 that synchronized(a) <stmt> is implemented 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 lock at a time, and the thread is blocked when acquiring a lock if the lock is unavailable.
Monitors – a Diagrammatic summary

![Diagram of a Java monitor]

Figure 20-1. A Java monitor.

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

```java
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
• \( \Rightarrow \) 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:
  
  ```java
  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

```java
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

```java
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

```java
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)               Permitted in Java
isolated (from) {                                    synchronized (from) {
    ...                                               ...                   
    isolated (to) { . . . }                            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
What if you want to wait for shared state to satisfy a desired property?

```java
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.,

  ```java
  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 diagram illustrates the interaction between the entry set, wait set, and the object lock. The entry set contains processes that are waiting to acquire the lock, while the wait set contains processes that are waiting for a signal. The object lock is owned by a specific process, and processes acquire it using the acquire lock operation.
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.
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;
}
```
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
    }
}