COMP 322: Fundamentals of
Parallel Programming

Lecture 26: Introduction to Java Threads & Synchronized Statement

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Is this a linearizable execution for a FIFO queue, q?

<table>
<thead>
<tr>
<th>Time</th>
<th>Task A</th>
<th>Task B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Invoke q.enq(x)</td>
<td>Invoke q.enq(y)</td>
</tr>
<tr>
<td>1</td>
<td>Return from q.enq(x)</td>
<td>Work on q.enq(y)</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Return from q.enq(y)</td>
</tr>
<tr>
<td>3</td>
<td>Invoke q.deq()</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Work on q.deq()</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Return y from q.deq()</td>
<td></td>
</tr>
</tbody>
</table>

No! q.enq(x) must precede q.enq(y) in all linear sequences of method calls invoked on q. It is illegal for the q.deq() operation to return y.
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.

```java
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 thread
        // Case 1: If this thread was executing
        //   then that object’s run method
        // Case 2: If this class is subclassed, the
        //   in the subclass is called
    void start() { ... } // Causes this thread to
    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

1. // Start of main thread
2. sum1 = 0; sum2 = 0; // sum1 & sum2 are static fields
3. Thread t1 = new Thread(() -> {
4.     // Child task computes sum of lower half of array
5.     for(int i=0; i < X.length/2; i++) sum1 += X[i];
6.     });
7. t1.start();
8. // Parent task computes sum of upper half of array
9. for(int i=X.length/2; i < X.length; i++) sum2 += X[i];
10. // Parent task waits for child task to complete (join)
11. t1.join();
12. return sum1 + sum2;
Two-way Parallel Array Sum using HJ-Lib’s finish & async API’s

1. // Start of Task T0 (main program)
2. sum1 = 0; sum2 = 0; // sum1 & sum2 are static fields
3. finish() -> {
4.   async() -> {
5.     // Child task computes sum of lower half of array
6.     for(int i=0; i < X.length/2; i++) sum1 += X[i];
7.   }};
8. // Parent task computes sum of upper half of array
9. for(int i=X.length/2; i < X.length; i++) sum2 += X[i];
10. }};
11. // Parent task waits for child task to complete (join)
12. return sum1 + sum2;
HJlib runtime uses Java threads as workers

- HJlib runtime creates a small number of worker threads, typically one per core
- Workers push async’s/continuations into a logical work queue
  - when an async operation is performed
  - when an end-finish operation is reached
- Workers pull task/continuation work item when they are idle
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
  ```java
  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.
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() { ... }
}

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

```java
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);
              }
          }
      }
  }
  ```
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);
            }
        }
    }
}
```