COMP 322: Fundamentals of Parallel Programming

Lecture 23: Java Threads, Java synchronized statement

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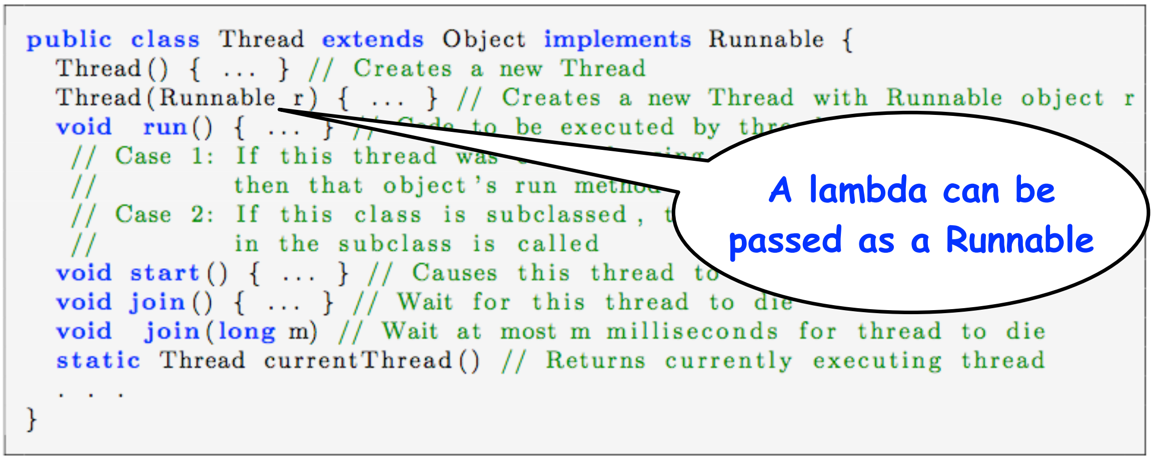
Unit 7.1: Introduction to Java threads and java.lang.Thread class

- **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
   //          then that object's run metho
   // Case 2: If this class is subclassed, t
   //          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
  - 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() even when there are no data races
    - Declaring thread references as final does not help because the new() and start() operations are separated for threads (unlike futures, where they are integrated)

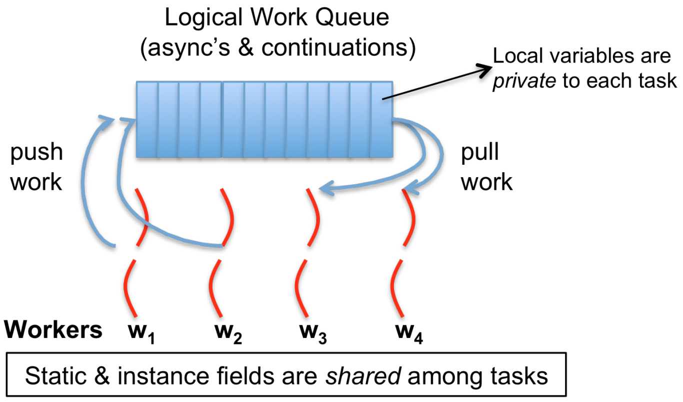
Two-way Parallel Array Sum using Java Threads

```
// 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;
```

Compare with Two-way Parallel Array Sum using HJ-Lib's finish & async API's

```
// Start of Task T0 (main program)
sum1 = 0; sum2 = 0; // sum1 & sum2 are static fields
finish(() -> {
  async(() -> {
    // Child task computes sum of lower half of array
    for(int i=0; i < X.length/2; i++) sum1 += X[i];
  });
  // 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)
return sum1 + sum2;
```

HJlib runtime uses Java threads as workers



- **HJlib runtime creates a small number of worker threads in a *thread pool*, 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**

Unit 7.2: 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 preferable to use java.util.concurrent.atomic or HJlib isolated constructs, since they cannot deadlock
- Locks are needed for more general cases. Basic idea is for JVM 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 isolation 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);
          }
       }
    }
  }
```

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!
    }
 }
```

Monitors

- One definition of monitor is a thread-safe class, object, or module that uses wrapped mutual exclusion in order to safely allow access to a method or variable by more than one thread. The defining characteristic of a monitor is that its methods are executed with mutual exclusion: At each point in time, at most one thread may be executing any of its methods. Using a condition variable(s), it can also provide the ability for threads to wait on a certain condition (thus uhttps://en.wikipedia.org/wiki/Monitor_(synchronization)sing the above definition of a "monitor"). For the rest of this article, this sense of "monitor" will be referred to as a "thread-safe object/class/module".

- Source: https://en.wikipedia.org/wiki/Monitor_(synchronization)

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.,

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

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

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

Java approach:

- 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