
COMP 322: Fundamentals of Parallel Programming

Lecture 26: Introduction to Java Threads & Synchronized Statement

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Solution to Worksheet #24: Linearizability of method calls on a concurrent object

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

Time	Task A	Task B
0	Invoke $q.enq(x)$	
1	Return from $q.enq(x)$	
2		Invoke $q.enq(y)$
3	Invoke $q.deq()$	Work on $q.enq(y)$
4	Work on $q.deq()$	Return from $q.enq(y)$
5	Return y from $q.deq()$	

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.

```
1 public class Thread extends Object implements Runnable {
2     Thread() { ... } // Creates a new Thread
3     Thread(Runnable r) { ... } // Creates a new Thread with Runnable object r
4     void run() { ... } // Code to be executed by thread
5     // Case 1: If this thread was created with a Runnable object r,
6     //           then that object's run method is called.
7     // Case 2: If this class is subclassed, the run method
8     //           in the subclass is called.
9     void start() { ... } // Causes this thread to start
10    void join() { ... } // Wait for this thread to die
11    void join(long m) // Wait at most m milliseconds for thread to die
12    static Thread currentThread() // Returns currently executing thread
13    . . .
14 }
```

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;
```

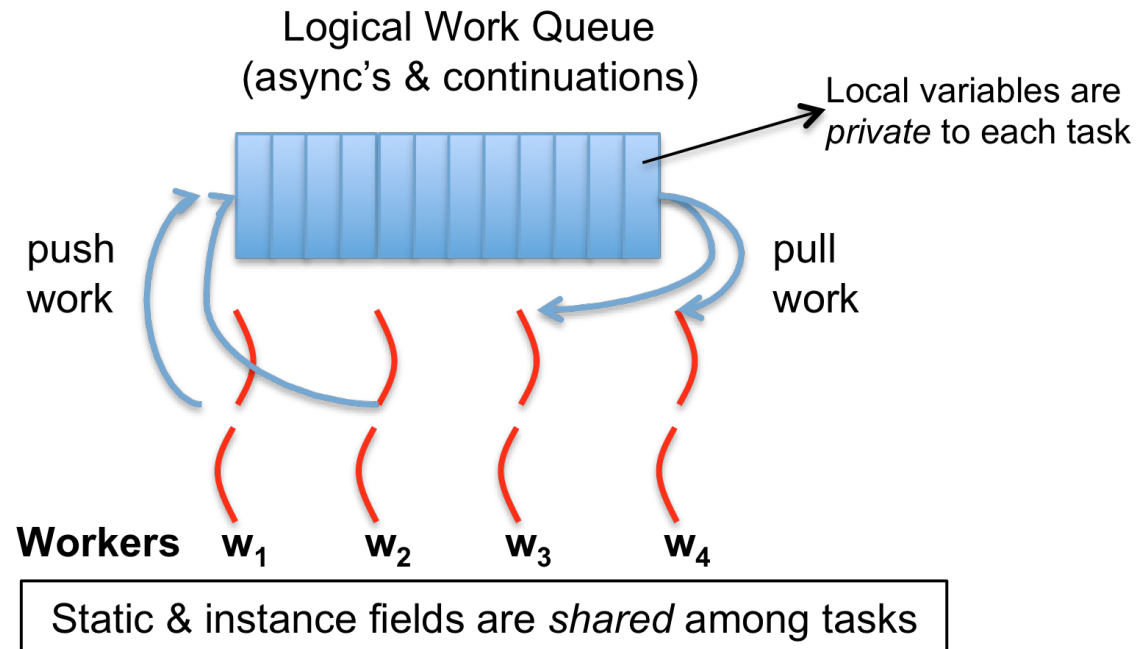


Two-way Parallel Array Sum using HJ-Lib's finish & async API's

```
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.,

```
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`



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

```
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!
    }
}
```



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 (from.acctId == to.acctId)  
            throw new Exception("Cannot self-transfer");  
        else if (from.acctId < to.acctId) {  
            firstLock = from;  
            secondLock = to;  
        }  
        else {  
            firstLock = to;  
            secondLock = from;  
        }  
        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 (from.acctId == to.acctId)  
            throw new Exception("Cannot self-transfer");  
        else if (from.acctId < to.acctId) {  
            firstLock = from;  
            secondLock = to;  
        }  
        else {  
            firstLock = to;  
            secondLock = from;  
        }  
        synchronized (firstLock) {  
            synchronized (secondLock) {  
                from.subtractFromBalance(amount);  
                to.addToBalance(amount);  
            }  
        }  
    }  
}
```

