Lecture 8
Sharing Objects
ThreadLocal

- Another mechanism for localizing objects in threads so that thread-safety is guaranteed
  - A ThreadLocal object can be seen as a container for other objects, e.g.
    - ThreadLocal<List<Long>> idList;
    - idList is a ThreadLocal object containing several List<Long> objects
  - Each thread accessing a ThreadLocal object is given its own copy of a contained object
    - E.g. any thread accessing idList is given its own local List<Long> object by idList
- Since objects in a ThreadLocal container are local to individual threads, no need for synchronization to ensure thread-safety
- ThreadLocal objects often used when single-threaded applications with global variables are made multi-threaded
  - The global variable is made into a ThreadLocal variable
  - Each thread then has its own copy of the formerly global variable
ThreadLocal API

- Key methods for ThreadLocal<T>
  - `public T get ()`
    Get instance of T associated with thread executing get ()
  - `public void set (T e)`
    Change instance of T associated with thread executing set () to e
  - `protected T initialValue ()`
    Define how to compute initial value associated with a thread (called when get() invoked first time, provided set () not called previously)
  - `public void remove ()`
    Remove object associated with thread

- How to define initialValue? Usually via anonymous inner classes
Anonymous Inner Classes

- Used to create subclasses of a given class without using subclass declarations
- Example

```java
ThreadLocal<
  ArrayList<Long>
>> threadIds =
new ThreadLocal<
  ArrayList<Long>
>> () {
  protected ArrayList<Long> initialValue () {
    return new ArrayList<Long> ();
  }
}
```

- The `protected` is an anonymous inner class
- It creates a subclass of `ThreadLocal<
  ArrayList<Long>
>>` in which the default `initialValue()` method is overridden
public class ManagerThread extends Thread {

    private static ThreadLocal<ArrayList<Long>> threadIds
        = new ThreadLocal<ArrayList<Long>>() {
            protected ArrayList<Long> initialValue () { return new ArrayList<Long> (); }
        };
    private int numWorkers;

    ManagerThread (String name, int n) { this.setName (name); numWorkers = n; }

    private void startWorker () {
        WorkerThread t = new WorkerThread ();
        ArrayList<Long> workerIds = threadIds.get ();
        workerIds.add(t.getId());
        t.start ();
    }

    public void run () {
        for (int i = 0; i < numWorkers; i++) startWorker ();
        String output = getName () + " worker ids: ";
        for (Long id : threadIds.get ()) output += (Long.toString (id) + " ");
        System.out.println (output);
    }
}
Immutability

• Synchronization incurs overhead
  – Locking reduces performance
  – Ensuring thread-safety makes code more complex

• How to reduce overhead?
  – Don’t share objects among threads if you don’t have to
  – Use immutable objects whenever you can!
Immutable Objects

• Why do we need synchronization? To cope with changes to object state
  – If fields in a method are modified while a method executes, the invariants in the class spec might be temporarily invalidated
  – Without synchronization these invalid values are visible to threads with access to the object

• If object’s don’t change, then there is no need to synchronize!
  – If invariant holds when object is created, then they are guaranteed to remain true
  – Immutable objects have this property: once they are created, their state never changes
Immutable Objects

• Typically created with fields declared as final
  – e.g.
    ```java
    final int a = 7;
    ```
  – Final fields can never have their values changed outside a constructor, and can only be assigned once inside a constructor

• True immutability requires more, though
  – Final fields may store a reference to a mutable object, e.g.
    ```java
    final MutablePoint p = new ...;
    ```
  – Even though this reference cannot change, the methods of `p` can still be used to change the state of `p`

• So an object is immutable if
  – All its fields are `final`
  – Its state can never change (i.e. no mutable subobjects are published)

• Is this sufficient?
Mutability and Visibility

• Final fields change values once!
  – When a constructor is first called, fields are allocated and given default values
  – As the constructor executes, new values are computed and assigned to fields

• If a constructor publishes this, then another thread might see the value of a final field before it has been assigned to. (In other words: data race)
Immutability and Publishing

- **ThreadABPrinter.java**
  
  ```java
  public class ThreadABPrinter extends Thread {
    private ImmutableAB ab;
    ThreadABPrinter (ImmutableAB ab) { ... }
    public void run () {
      System.out.println("b = " + ab.getB());
      try { Thread.sleep (100); } catch ... {} 
      System.out.println("b = " + ab.getB());
    }
  }
  ```

- **ImproperImmutableAB.java**
  
  ```java
  public class ImproperImmutableAB implements ...{
    public final int a;
    public final int b;
    ImproperImmutableAB (int a, int b) {
      this.a = a;
      new ThreadABPrinter (this).start();
      try { Thread.sleep(20); } catch ... {}
      this.b = b;
    }
    public int getA () { return a; }
    public int getB () { return b; }
  }
  ```

- **What happens if an ImproperImmutableAB is created?**
  - Thread is launched in constructor
  - this is published
  - Thread sees two different values of final field b!
Immutability Redefined

• An object is *immutable* if
  – All its fields are *final*
  – Its state never changes after construction
  – It is *properly constructed*: this does not escape during construction

• If an object is immutable, then:
  – it is thread-safe
  – it may be safely accessed / published without synchronization!
Immutability and Visibility

• What guarantees visibility of assignments to final fields in immutable objects?
• Answer: the Java Memory Model
  – If an object’s fields are all \texttt{final} ...
  – ... then the JMM says that all writes to these fields are immediately visible, as are all memory writes that happen-before
  – This is like behavior of volatile variables!
• This property is called \textit{initialization safety}
Safe Publication

• Thread-safe classes define objects whose methods behave correctly in the presence of threads

• What about publication of (thread-safe) objects?
  – During construction an object can be in an inconsistent state
  – Even if the methods behave correctly, there may still be program errors if a thread can access a partially constructed object

• Safe publication strategies are designed to ensure this cannot happen
Unsafe Publication (JCIP pp. 50 – 51)

• A simple class (thread safe!) (Holder.java)

```java
public class Holder {
    private int n;
    public Holder (int n) { this.n = n;  }

    public void assertSanity () {
        if (n != n) throw new AssertionError ("n != n !!");
    }
}
```

• What can happen in following scenario?
  – Main creates global variable h of type Holder
  – Main starts a thread t that invokes h.assertSanity()
  – Main executes h = new Holder(42);
Answer: An Assertion Error Can Be Thrown!

• A (partial) event sequence highlighting the issue
  \[ \langle \text{main, write, h.n, 0} \rangle \]
  \[ \langle \text{t1, read, h.n. 0} \rangle \]
  \[ \langle \text{main, write, h.n, 42} \rangle \]
  \[ \langle \text{t1, read, h.n, 42} \rangle \]
  
  ASSERTION THROWN

• What is the real problem?
  – t1 can see the state of the new object for h before its construction is complete
  – There is a data race involving h.n between main and t1
Safe Publication Practices

• To avoid publication problems for mutable objects:
  – Make sure objects are properly constructed (i.e. do not let `this` escape during construction)
  – Make sure state is fully constructed when reference to object is published
• How can we ensure state is fully constructed? By relying on Java Memory Model!
  – Store reference in volatile variable
    This ensures that all writes pending in constructor get performed before reference is published
  – Store reference in final field of a properly constructed object
    JMM again guarantees that all writes pending in the constructor become visible when this happens
  – Store reference in a variable that is properly locked (i.e. any reads to the variable must be in a “happens-after” relationship with the write of the reference to the variable)
    This also ensures visibility of writes in constructor before object state can be queried
• Another approach: initialize objects in a static initializer
  – Works for static objects
  – Static initializers are invoked when classes are loaded, before threads are launched, etc.
Effectively Immutable Objects

• Classes whose fields are not final, but whose state cannot change after construction
  Example: Holder.java!

• Such objects are not guaranteed safe initialization by the Java Memory Model
  To publish such objects, safe-publication practices must be followed as just described

• Once safely published, such objects are thread-safe, however