CMSC 433 – Programming Language Technologies and Paradigms

Java Concurrency Utilities

Overview

- Synchronized Collections
- Concurrent Collections
  - ConcurrentHashMap
  - CopyOnWriteArrayList
  - BlockingQueues
- Synchronizers
  - Latches
  - FutureTask
  - Semaphores
  - Barriers & Exchangers

Why Concurrency Utilities

- Java's built-in concurrency primitives – wait(), notify(), and synchronized are limited
  - Hard to use correctly; Easy to use incorrectly
  - Too low level for many applications
  - Can perform poorly if used incorrectly
    - Less of an issue now than it used to be
  - Leave out useful concurrency constructs

java.util.concurrent Goals

- Provide efficient, correct & reusable concurrency building blocks
- Enhance scalability, performance, readability, maintainability, and thread-safety of concurrent Java applications

Synchronized Collections

- Many of the Collection classes are not thread-safe
- Can use methods in the Collections class to add some thread safety to these classes, e.g.,

```
List list = Collections.synchronizedList(new ArrayList());
```

Wrapper Implementation

…

```
public int size() {
  synchronized(mutex) {return c.size();}
}
public boolean isEmpty() {
  synchronized(mutex) {return c.isEmpty();}
}
public boolean contains(Object o) {
  synchronized(mutex) {return c.contains(o);}
}
```

…

Synchronized Collections

- Must handle compound actions manually
- For example,

```
public static void deleteLast(List list) {
    synchronized (list) {
        int lastIndex = list.size() - 1;
        list.remove(lastIndex);
    }
}
```

Synchronized Collections

- Iterators must be manually synchronized

```
Collection<Type> c =
        Collections.synchronizedCollection(myCollection);
synchronized(c) {
  for (Type e : c)
     foo(e);
}
```

Synchronized Collections

```
List list = Collections.synchronizedList(new ArrayList());
 ...
  synchronized(list) {
      Iterator i = list.iterator(); // Must be in synchronized block
      while (i.hasNext())
          foo(i.next());
  }
```

Non-Obvious Use of Iterators

```
public class HiddenIterator {
  private final Set<Integer> set = new HashSet<Integer>();
  public void foo() {
     System.out.println(set);
  }
}
```

ConcurrentModificationException

- Can’t modify a synchronized Collection while iterating over it
  - Iterator may throw ConcurrentModificationException
- Need to manually lock collection
  - Or copy the collection and iterate over the copy

Concurrent Collections

- java.util.concurrent includes concurrent collection classes
- Allows multiple operations to overlap
  - Some differences in semantics
- Some examples
  - ConcurrentHashMap
  - CopyOnWriteArrayList
  - ArrayBlockingQueue

ConcurrentHashMap

- Concurrent Hash-based Map
  - Uses lock striping, rather than a single lock
  - Allows concurrent readers
  - Readers operate concurrently with writers
  - Limited number of writers can modify the map concurrently

ConcurrentHashMap Iterators

- Iterate over the elements that existed when the iterator was created
- Tolerate updates while iterating
  - No ConcurrentModificationException
- May or may not reflect updates that occur while iterating

ConcurrentHashMap Tradeoffs

- size() and isEmpty() are only approximations
- No built-in way to lock the entire map

- Supports several compound operations

```
public interface ConcurrentMap<K,V> extends Map<K,V> {
    // Insert into map only if no value is mapped from K
      V putIfAbsent(K key, V value);
    // Remove only if K is mapped to V
      boolean remove(K key, V value);
    // Replace value only if K is mapped to oldValue
      boolean replace(K key, V oldValue, V newValue);
    // Replace value only if K is mapped to some value
      V replace(K key, V newValue);}
```

Performance Comparison

- ConcurrentHashMap vs. Collections.synchronizedMap
- See HashMapPerfTest.java
- **Note:** incrementCount() is not safe

CopyOnWriteArrayList

- Concurrent List
- Effectively immutable
  - Creates and republishes a new copy of the collection every time it is modified

CopyOnWriteArrayList Iterators

- Iterates over elements that were contained in the CopyOnWriteArray at the start of iteration
- Tolerate updates while iterating
  - No ConcurrentModificationException

CopyOnWriteArrayList Tradeoffs

- Copying the backing array can be expensive
- Most effective when iteration is far more common than modification

Queues

- Queue interface added to java.util

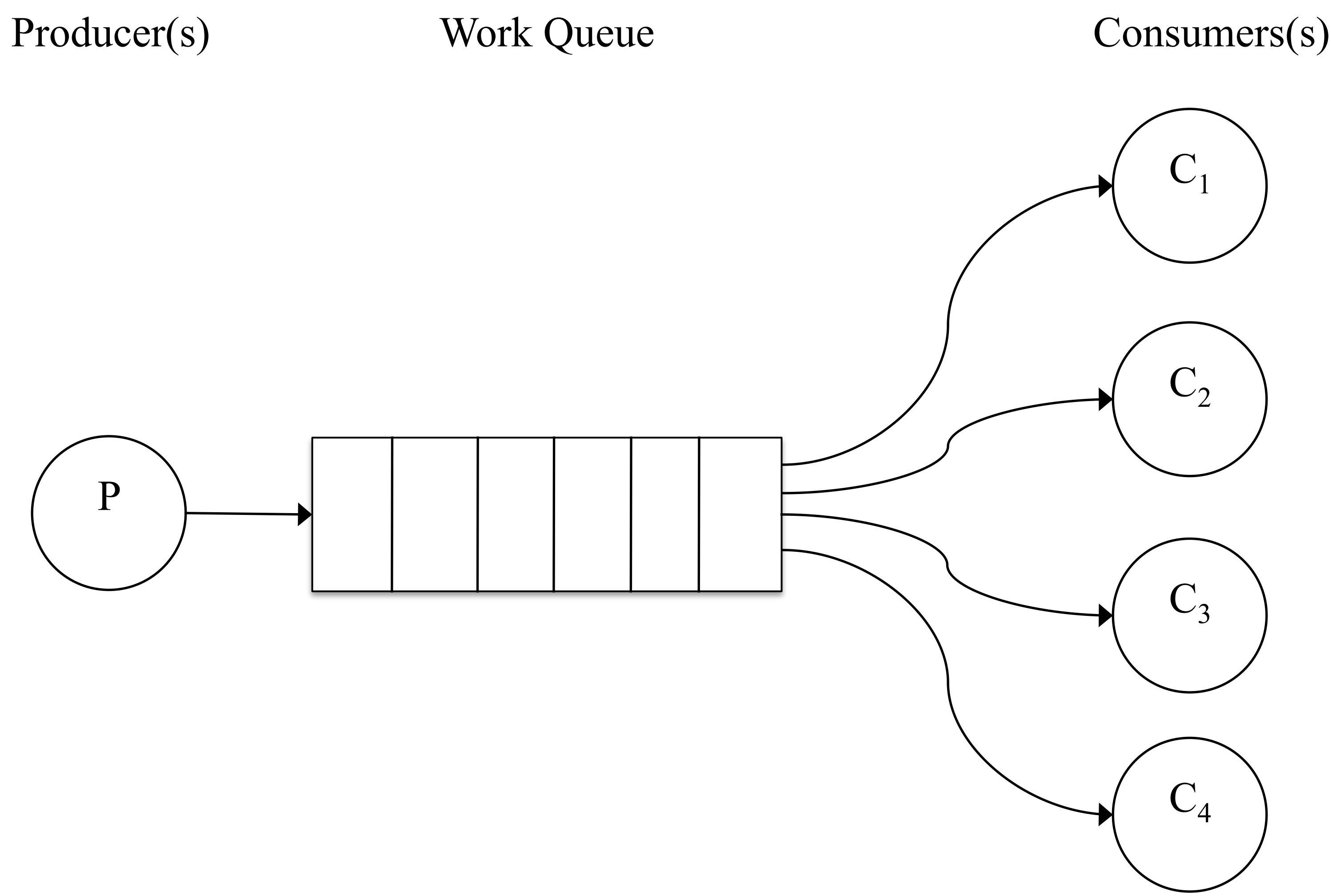
```
interface Queue<E> extends Collection<E> {
   boolean offer(E x); // try to insert, return true if insert succeeded
   E poll();  //retrieve and remove. Return null if empty
   E remove() throws NoSuchElementException; //retrieve and remove
   E peek(); // retrieve, don’t remove. Return null if empty
   E element() throws NoSuchElementException; //retrieve, don’t remove
}
```

- One thread-safe, non-blocking implementation
  - ConcurrentLinkedQueue

Blocking Queues

- Extends Queue to provide blocking operations
  - Retrieval: wait for queue to become nonempty
  - Insertion: wait for capacity to be available
- Can be bounded or unbounded
- Implementations provided:
  - LinkedBlockingQueue (FIFO, may be bounded)
  - PriorityBlockingQueue (priority, unbounded)
  - ArrayBlockingQueue (FIFO, bounded)
  - SynchronousQueue (rendezvous channel)

Producer/Consumer Pattern



Producer/Consumer Tips

- Bound queue size
- Make put() and take() operations block
  - BlockingQueue provides this
  - Makes programs more robust to overload by throttling activities that can produce more work than consumers can handle

Producer-Consumer Examples

- See:
  - ProducerConsumerPrimitive.java (wait/notify)
  - ProducerConsumerConcUtil.java (BlockingQueue)

Synchronizers

- Utilities for coordinating access and control
- CountDownLatch
  - Allows threads to wait for a set of threads to complete an action
- Future & FutureTask
  - Represents an asynchronous computation
- Semaphore
  - Dijkstra counting semaphore, managing some number of permits
- CyclicBarrier
  - Allows a set of threads to wait until they all reach a specified barrier point
- Exchanger
  - Allows two threads to rendezvous and exchange data, such as exchanging an empty buffer for a full one

CountDownLatch

- Latching variables are conditions that once set never change
- Often used to start several threads, but have them wait for a signal before continuing
- See: CountDownLatchTest.java

Future Use Case

- Client initiates asynchronous computation
- Client receives a “handle” to the result
  - The Future
- Client does other work while waiting for result
- Client requests result from Future, blocking or polling until result is available
- Client uses result

FutureTask

- A cancellable asynchronous computation
- A base implementation of Future
- Can wrap a Callable or Runnable

Future and Callable

- Callable is functional analog of Runnable

```
interface Callable<V> {
  V call() throws Exception;
}
```

- Future represents result of asynchronous computation

```
interface Future<V> {
  V get() throws InterruptedException, ExecutionException;
  V get(long timeout, TimeUnit unit);
  boolean cancel(boolean mayInterrupt);
  boolean isCancelled();
  boolean isDone();
}
```

Future Example

- See: FutureTaskStringReverser.java

Another Future Example

- Implementing a cache with Future

```
public class Cache<K, V>
  Map<K, Future<V>> map = new ConcurrentHashMap();
  public V get (final K key) {
    Future<V> f = map.get(key);  // null if key not found
    if (f == null) { Callable<V> c = new Callable<V>() {
                          public V call() {// compute value associated with key}
    };
    f = new FutureTask<V>(c);
    Future old = map.putIfAbsent(key, f); // if key not found put(key,f) & return null
    if (old == null)  {                              //  otherwise return get(key)
            new Thread(f).start();
    } else { f = old;}
    return f.get();
   }
}
```

Semaphore

- Semaphore maintain a logical set of permits
- Two operations
  - acquire() blocks until a permit is free, then takes it
  - release() adds a permit & releases one blocking acquirer
- Can implement many synchronization protocols
- See:
  - SemaphoreTunnel.java
  - SemaphoreBuffer.java

CyclicBarrier

- Allows threads to wait at a common barrier point
- Useful when a fixed-sized party of threads must occasionally wait for each other
- Cyclic Barriers can be re-used after threads released
- Can execute a Runnable once per barrier point
  - After the last thread arrives, but before any are released
  - Useful for updating shared-state before threads continue
- See:
  - CyclicBarrierEx1.java
  - CyclicBarrierEx2.java

Exchanger

- Synchronization point where two threads exchange object(s)
  - i.e., a bidirectional SynchronizedQueue
- Each thread presents some object on entry to the exchange() method, and receives the object presented by the other thread on return
- See ExchangerTest.java

Locks and Lock Support

- High-level locking interface
- Adds non-blocking lock acquisition

```
interface Lock {
  void lock();
  void lockInterruptibly() throws IE;
  boolean tryLock();
  boolean tryLock(long time,TimeUnit unit) throws IE;
  void unlock();
  Condition newCondition() throws UnsupportedOperationException;
}
```

ReentrantLock

- Flexible, high-performance lock implementation
- Implements a reentrant mutual exclusion lock (like Java intrinsic locks) but with extra features
  - Can interrupt a thread waiting to acquire a lock
  - Can specify a timeout while waiting for a lock
  - Can poll for lock availability
  - Can have multiple wait-sets per lock via the **Condition** interface
- Outperforms built-in monitor locks in most cases, but slightly less convenient to use (requires finally block to release lock)

Lock Example

- Locks not automatically released
  - Must release lock in **finally** block

```
Lock lock = new ReentrantLock();
...
lock.lock();
try {
  // perform operations protected by lock
} catch (Exception ex) {
 // restore invariants
} finally {
    lock.unlock();
}
```

ReadWrite Locks

- **ReadWriteLock** interface defines a pair of locks;
  - one for readers; one for writers

```
interface ReadWriteLock {
  Lock readLock();
  Lock writeLock();
}
```

- **ReentrantReadWriteLock** class
  - Multiple readers, single writer
  - Allows writer to acquire read lock
  - Allows writer to downgrade to read lock
  - Supports “fair” and “non-fair” (default) acquisition

Read/Write Lock Example

```
class RWDictionaryRWL {
    private final Map<String, Data> m = new TreeMap<String, Data>();
    private final ReentrantReadWriteLock rwl = new ReentrantReadWriteLock();
    private final Lock r = rwl.readLock();
    private final Lock w = rwl.writeLock();
    public Data get(String key) {
        r.lock();
        try { return m.get(key); }
        finally { r.unlock(); }
    }
    public Data put(String key, Data value)
        w.lock();
        try { return m.put(key, value); }
        finally { w.unlock(); }
    }
}
```

Read/Write Lock Example

- See
  - **RWDictionaryIntrinsicLock .java**
  - **RWDictionaryRentrantLock .java**
  - **RWDictionaryRWL.java**

Condition

- Condition lets you wait for a condition to hold (like wait), but adds several features

```
interface Condition {
  void await() throws IE;
  boolean await( long time, TimeUnit unit ) throws IE;
  long awaitNanos( long nanosTimeout) throws IE;
  void awaitUninterruptibly()
  boolean awaitUntil( Date deadline) throws IE;
  void signal();
  void signalAll();
}
```

Condition (cont.)

- Many improvements over wait()/notify()
  - Multiple conditions per lock
  - Absolute and relative time-outs
  - Timed waits tell you why you returned
  - Convenient uninterruptible wait

Condition Example

```
class BoundedBufferCond {
    Lock lock = new ReentrantLock ();
    Condition notFull = lock.newCondition();
    Condition notEmpty = lock.newCondition();
    Object[] items = new Object[100];
    int putptr, takeptr, count;

   public void put( Object x) throws IE {
      lock.lock();
      try {
        while (count == items.length) notFull.await();
        items[putptr] = x;
        if (++putptr == items.length) putptr = 0;
        ++count;
        notEmpty.signal();
      }  finally { lock.unlock(); }
   }
```

Condition Example (cont.)

```
  public Object take() throws IE {
    lock.lock();
    try {
      while (count == 0) notEmpty.await();
      Object x = items[takeptr];
      if  (++takeptr == items.length)  takeptr = 0;
      --count;
      notFull.signal();
      return x;
    } finally { lock.unlock(); }
  }
}
```

Condition Example (cont.)

- Previous example in BoundedBufferCond.java
- See also: BoundedBufferPrim.java

Atomic Variables

- Holder classes for scalars, references and fields
- Supports atomic operations
  - Compare-and-set (CAS)
  - Get and set and arithmetic (where applicable)
- Some main classes: {int, long, ref} X {value, field, array}
  - E.g. AtomicInteger useful for counters, sequences, statistics
- Essential for writing efficient code on MPs
  - Nonblocking data structures & optimistic algorithms
  - Reduce overhead/contention updating “hot” fields
- JVM uses best construct available on platform
  - CAS, load-linked/store-conditional, locks

Atomic Variables

- See: CounterTest.java

Executor

- Standardizes asynchronous invocation
- Separates job submission from execution policy
  - **anExecutor.execute(aRunnable)**
- Rather than
  - **new Thread(aRunnable).start()**
- Two code styles supported:
  - Actions: **Runnables**
  - Functions: **Callables**
- Also has lifecycle mgmt: e.g., cancellation, shutdown
- Executor usually created via **Executors** factory class
  - Configures **ThreadPoolExecutor**
  - Customizes shutdown methods, before/after hooks, saturation policies, queuing

Executor & ExecutorService

- ExecutorService adds lifecycle management to Executor

```
public interface Executor {
  void execute(Runnable command);
}
public interface ExecutorService extends Executor {
  void shutdown();
  List<Runnable> shutdownNow();
  boolean isShutdown();
  boolean isTerminated();
  boolean awaitTermination( long timeout, TimeUnit unit);
  // other convenience methods for submitting tasks
}
```

Creating Executors

- Executors factory methods

```
public class Executors {
  static ExecutorService newSingleThreadedExecutor();
  static ExecutorService newFixedThreadPool(int n);
  static ExecutorService newCachedThreadPool(int n);
  static ScheduledExecutorService newScheduledThreadPool(int n);
  // additional versions & utility methods
}
```

(Not) Executor Example

- Thread per message Web Server

```
class WebServer {
  public static void main( String [] args) {
    ServerSocket socket = new ServerSocket ( 80 );
    while  ( true ) {
      final Socket connection = socket.accept();
      Runnable r = new Runnable () {
        public void run () {handleRequest(connection);}
      };
      new Thread (r).start();
    }
  }
}
```

Executor Example

- Thread pool web server - better resource management

```
class WebServer {
Executor pool = Executors.newFixedThreadPool(7);
public static void main(String[] args) {
    ServerSocket socket = new ServerSocket(80);
     while (true) {
         final Socket connection = socket.accept();
          Runnable r = new Runnable() {
              public void run() {handleRequest(connection);}
          };
         pool.execute(r);
    }
  }
}
```

ScheduledExecutorService

- For deferred and recurring tasks, can schedule
  - **Callable or Runnable to run once** with a fixed delay after submission
  - Schedule a **Runnable to run periodically at a fixed** rate
  - Schedule a **Runnable to run periodically with a** fixed delay between executions
- Submission returns a **ScheduledFutureTask** handle which can be used to cancel the task
- Like **Timer**, but supports pooling and is more robust

Summary Cheat Sheet

- It's the mutable state, stupid
  - All concurrency issues boil down to coordinating access to mutable state. The less mutable state, the easier it is to ensure thread safety
- Make fields final unless they need to be mutable
- Immutable objects are automatically thread safe
  - Immutable objects simplify concurrent programming tremendously
  - They are simpler and safer, and can be shared freely without locking or defensive copying
- Encapsulation makes it practical to manage complexity.
  - Encapsulating data within objects makes it easier to preserve their invariants
  - encapsulating synchronization within objects makes it easier to comply with their synchronization policy

Summary Cheat Sheet (cont.)

- Guard each mutable variable with a lock
- Guard all variables in an invariant with the same lock
- Hold locks for the duration of compound actions
- A program that accesses a mutable variable from multiple threads without synchronization is broken
- Don't rely on clever reasoning about why you don't need to synchronize
- Include thread safety in the design process
- Explicitly document that your class is/isn’t not thread safe
- Document your synchronization policy