Advanced Concurrent Programming

Presentation Topics

In this presentation we will cover:

- Introduction to Concurrent Libraries
- Working with Synchronizers
- Using the Execution Framework

Introduction to Concurrent Libraries

Who in the world is Doug Lea?

Introduction to Concurrent Libraries

- Java provides built-in basic structures for concurrent programming

- Beyond “basic” concurrent solutions, built-in facilities are limited; foundational but not complete

- As a result, community created own concurrency oriented libraries to address complex situations

Java Thread Model Limitations

Based on block-structured locking

- Locks associated with entire objects
  - Can’t notify specific thread based on condition
  - Have to notify unknown waiting thread
- No way to:
  - “take back” or timeout attempt to acquire lock
  - Modify lock semantics
- No “built-in”:
  - Pooling mechanism
  - Auto-blocking lists
  - Limited atomic operation support

Overview of Concurrent Libraries

- Introduced as part of Java SE 5.0

- Driven by JSR 166
  - Adaptation of Doug Lea's `util.concurrent` package
  - Defined in three packages:
    - `java.util.concurrent`
    - `java.util.concurrent.atomic`
    - `java.util.concurrent.locks`

Motivations for Concurrent Libraries

- Address limitations of Java's thread model
- Standardize and simplify common concurrency mechanisms
  - Lower complexity in development concurrent programs
  - Increase maintainability of concurrent code
  - Lessen common "concurrency" issues
- Provide robust, efficient, and high-performance utilities

java.util.concurrent Package

- Main concurrency package
- Contains classes to aid in concurrency development
- Three main facilities:
  - Concurrent collections
  - Execution framework
  - Synchronizers

Concurrent Collections

Concurrent Collections

- Extend Collections framework into concurrency world
  - More scalable than standard `Collections` classes
  - Compliant with `Collection` framework

- Provide thread safety
  - More "lightweight" than synchronized
  - Typically synchronize on manipulation
  - Typically retrieval is not synchronized

- Contains:
  - List
  - Map
  - Set
  - Queue

Concurrent Collections : Iterators

- Standard `java.util.Iterator`
  - Fail-fast implementation
  - If underlying collection changes, `Iterator` throws `ConcurrentModificationException`

- Concurrency Collections
  - Weakly-consistent implementation
  - Support concurrent modifications
  - May reflect underlying changes while iterating

Concurrent Collections : Lists

- Add concurrency support to lists
  - Alternative to `Collections.synchronizedList`
  - Uses Concurrency APIs for thread-safety

- `CopyOnWriteArrayList`
  - Modifications on the list cause are performed on a copy of an array
  - Efficient because no locking on traversal
  - Not-efficient because of memory copy

Concurrent Collections : Maps

- Two interfaces:
  - `ConcurrentMap`
  - `ConcurrentNavigableMap`
- Provide atomic operations for Map
  - `putIfAbsent`
  - `remove`
  - `replace`
- Implementations include:
  - `ConcurrentHashMap`
  - `ConcurrentSkipListMap`

Concurrent Collections : Set

- Implementations include:
  - `CopyOnWriteArraySet`
  - `ConcurrentSkipListSet`

- More fine grained access control

Collection Framework : Queues

New `Queue` interface added to `java.util`

- Represents some form of waiting list
- Implementations have different ordering algorithms
  - First-in-first-out (FIFO)
  - Last-in-first-out (LIFO)
  - Natural ordering
  - Priority
- Defined in terms of
  - Head (start of queue)
  - Tail (end of queue)

Collection Framework: Qs [cont.]

- Support normal-collection behaviors
  - `java.util.Collection`
  - `java.util.Iterable`

- Support new behaviors
  - Insertion:
    - `offer` - inserts element into queue; if space available
  - Removal:
    - `remove` - removes head of queue or throws `NoSuchElementException`
    - `poll` - removes head of queue or `null`
  - Viewing
    - `element` - retrieves head or throws `NoSuchElementException`
    - `peek` - retrieves head or `null`

Concurrent Queues

- Concurrency libraries provide concurrent implementations of `Queue` interface
  - `BlockingQueue`
    - Adds waiting functionality to queue
    - `put` - adds to queue or waits for space
    - `take` - removes from queue or waits for availability
  - `BlockingDeque`

Concurrent Queues [cont.]

Sample implementations:

- Bounded Implementations
  - `ArrayBlockingQueue`
  - `LinkedBlockingQueue`
  - `LinkedBlockingDeque`

- Unbounded Implementations
  - `PriorityBlockingQueue`
  - `DelayQueue`

- Synchronous Implementation
  - `SynchronousQueue`
  - Take waits for put / put waits for take
  - No “internal” capacity

Using LinkedBlockingQueue

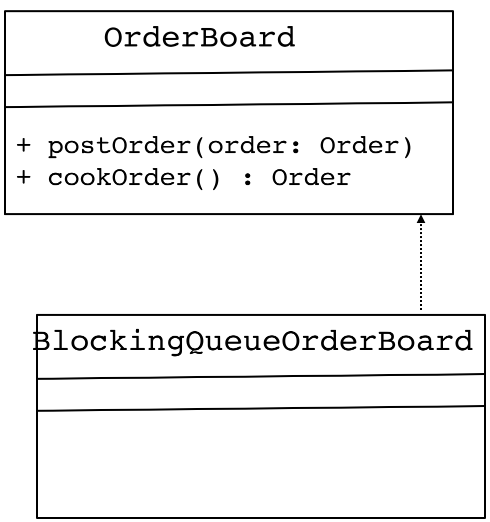
- Can be used to simplify producer - consumer problem

- Current solution uses `OrderBoard`
  - `OrderBoard` manages synchronization
    - Obtains list object lock before modifying list
    - Release list object lock after modifying list
  - `OrderBoard` manages availability
    - Determines whether insert operation is valid
    - Determines whether remove operation is valid
    - Synchronizes threads appropriately

- `LinkedBlockingQueue` alternative
  - Manages synchronization of access
  - Manages availability of access

OrderBoard Redesign

- `OrderBoard` has been redesigned
  - Extracted interface
  - Enables us to create different implementations
  - Don’t need to modify cook or waiter



- `BlockingQueueOrderBoard`
  - Implementation of `OrderBoard`
  - Uses a bounded `BlockingQueue`
  - No synchronization
  - No queue empty / full management
  - Simplifies original `OrderBoard`

BlockingQueue Example

```java
package examples.concurrent.advanced;

import java.util.concurrent.BlockingQueue;
import java.util.concurrent.LinkedBlockingQueue;

/**...*/
public class BlockingQueueOrderBoard implements OrderBoard {

  BlockingQueue<Order> orders;

  public BlockingQueueOrderBoard() {
    orders = new LinkedBlockingQueue<Order>(5);
  }

  public void postOrder(Order toBeProcessed) {
    try {
      orders.put(toBeProcessed);
    } catch (InterruptedException e) {
      e.printStackTrace();
    }
  }

```

BlockingQueue Example [cont.]

```java
    public Order cookOrder() {
        Order returnValue = null;
        try {
            returnValue = orders.take();
        } catch (InterruptedException e) {
            e.printStackTrace();
        }

        return returnValue;
    }
}

```

Lab: Rewrite Order Board

- **GOAL:** Refactor the order board to use a blocking queue from the concurrency library. The resulting code should be less complex, less lines of code. Yet the functionality will be exactly the same.

- **NOTE:** Keep an old copy of the order board around. It will be used in other upcoming labs.

- **DURATION:** 45 minutes
  - 30 minutes - development
  - 15 minutes - group code review.

Execution Framework

Delegate, delegate, delegate

Task Execution

Two task execution frameworks built into Java

1. `Thread` as an execution framework
   - `Runnable` becomes task
   - Thread governs when `run` is executed
   - No support for canceling, scheduled execution, etc.

2. `java.util.Timer` as execution framework
   - Introduced in 1.3
   - Task represented as `TimerTask`
   - Supports canceling, fixed rate scheduling, date-based scheduling
   1. No real-time timing guarantees - relies on wait mechanism

Task Execution [cont.]

- Both task execution frameworks are “functional”, but somewhat incomplete

- Generally you need a more robust execution framework that provides:
  - Thread reuse and pooling
  - Task scheduling
  - Task canceling
  - Decoupling of task registration from execution

Concurrency Execution Framework

- Part of `java.util.concurrent` package
  - Decouples task execution from `Thread` dependency
  - Supports more robust task handling
  - Implemented using Factory and command-pattern

- Built around three key concepts:
  - Tasks
  - Executors
  - Execution services

Execution Framework Tasks

Two “tasks” in concurrency execution framework

1. `java.lang.Runnable`
   - Standard `Runnable`
   - Implement `run` method
   - Don’t worry about Threading semantics

2. `java.util.concurrent.Callable`
   - Similar to a `Runnable`, in concept
   - Single method to implement
     - `public V call()`
     1. Can return value
     2. Can throw checked exceptions

Executors

- Entities that execute tasks

- Represented by `java.util.concurrent.Executor`
  - Decouples task submission from execution
  - Does not define how `Runnable` will be executed
  - `Executor` implementation could be:
    - Dedicated single-thread based
    - Thread-pool based
    - Current-thread based
  - Does not define when `Runnable` will be executed
  - Single task submission method

```
public void execute(Runnable cmd)
```

Execution Services

- Entities responsible for execution and management of tasks

- Two types:
  - `java.util.concurrent.ExecutorService`
    - Interface extensions of `Executor`
    - Adds management capabilities to `Executor`
      - Supports blocking - `awaitTermination`
      - Shutdown - `shutdown`
      - Service monitoring - `isShutdown` / `isTerminated`
    - Enhances task handling
      - Submission – supports `Callable and Runnable`
      - Management – returns `Future`

Types of Execution Services [cont.]

- Two types (cont):
  - `java.util.concurrent.ScheduledExecutorService`
    - Interface extensions of `ExecutorService`
    - Adds scheduling capabilities to `ExecutorService`
      - Supports Callable and Runnable
      - Single-schedule execution
      - Fixed-rate scheduled execution
      - Fixed-delay scheduled execution
      - No “date-based” scheduled execution

Task Management

- Every scheduled task has an associated “handle”
- Handle used for task cancellation and monitoring
- Handles are decoupled from:
  - Service - no way to get execution service reference from handle
  - Task - no way to get task reference from handle
- Two types of “handles”
  - `java.util.concurrent.Future`
  - `java.util.concurrent.ScheduledFuture`

NOTE: Handle type dependent on scheduling mechanism

Executor Implementations

- Create your own `Executor` implementation
  - Easiest way is to define a `ThreadFactory`
  - Associate it with `ThreadPoolExecutor`

- Or utilize the built-in implementations
  - `Executors` class is a factory
    - Can be used to create `ExecutorServices`
      - Single thread
      - Cached thread pool
      - Fixed thread pool
      - Scheduled thread pool
    - Can be used to create `Callable` objects out of `Runnable` objects

Execution Framework Example

A Simplistic example

- Intended to illustrate use of an execution service
- Built around scheduled execution of a task
- Task performs HTTP ping-like functionality to determine availability of web server

Execution Framework Example

```java
package examples.concurrent.executer;

import ...

/**...*/
public class TimedPing {

    public static void main(String[] args) throws Exception {

        URL url = new URL(args[0]);
        HttpPinger pinger = new HttpPinger(url);

        //create a scheduled execution service
        //only need one thread to perform ping functionality
        ScheduledExecutorService pingService =
                Executors.newSingleThreadScheduledExecutor();

        //schedule the HttpPinger to ping every ping
        ScheduledFuture future =
                pingService.scheduleAtFixedRate(pinger, 30L,
                                                60L, TimeUnit.SECONDS);

        //schedule a task to cancel the pinger after 5 minutes
        //task should also notify the service to shutdown
        pingService.schedule(new CancelPinger(future, pingService),
                                               60*5, TimeUnit.SECONDS);
    }
}
```

Exec. Framework Example [cont.]

```java
package examples.concurrent.executer;

import ...

/**...*/
public class HttpPinger implements Runnable {

   private boolean keepTesting = true;
   private URL theHostToTest;
   private ScheduledFuture scheduledFuture;

   public HttpPinger(URL url) {
      theHostToTest = url;
   }
```

Exec. Framework Example [cont.]

```java
public void run() {
  try {
    HttpURLConnection connection =
            (HttpURLConnection) theHostToTest.openConnection();

    //just see if we can access it
    connection.setRequestMethod("HEAD");
    connection.connect();

    //the HTTP response code
    int responseCode = connection.getResponseCode();

    if (responseCode != HttpURLConnection.HTTP_OK) {
      System.out.println("Failed attempt");
    } else {
      System.out.println("Connected ok: "+System.currentTimeMillis());
    }
    connection.disconnect();
  } catch (Exception e) {
    e.printStackTrace();
  }
}
}
```

Exec. Framework Example [cont.]

```java
package examples.concurrent.executer;

import java.util.concurrent.ExecutorService;
import java.util.concurrent.ScheduledFuture;

/**...*/
public class CancelPinger implements Runnable {

   private ScheduledFuture future;
   private ExecutorService service;

   public CancelPinger(ScheduledFuture f, ExecutorService pingService) {
      future = f;
      service = pingService;
   }

   public void run() {
      future.cancel(false);
      service.shutdown();
   }
}
```

Lab: Task Execution

- **GOAL:** Implement the example. Allow more than one “pinger” to exist and “ping” the health of a website. After a website has been determined to be up (10 successful pings), change the frequency (the delay) from ever 30 seconds to every minute.

- **HINT:** You will need more than a single threaded executor.

- **DURATION:** 45 minutes
  - 30 minutes - development
  - 15 minutes - group code review.

Working with Synchronizers

The Great Barrier Reef

Synchronizers

- Utility classes
  - Used to help coordinate control flow of Threads
  - Have their own state to determine “go” or “wait”
  - Potential replacements for synchronization blocks
- Three broad types:
  - Latches
  - Barriers
  - Semaphores

Latches

- Synchronizer that delays progress of threads
  - Threads are delayed until a terminal state is reached
  - Once reached, all threads can proceed

- Function like a gate:
  - When gate is closed, can't go through
  - When gate is open, can go through
  - Once gate is open, stays open

- Useful when trying to synchronize:
  - Resource initialization
  - Service startup
  - Application shutdown

`CountDownLatch`

- Implementation of a latch
  - Forces threads to wait until a predefined number of "events" occur
  - Utilizes a counter
  - As events occur, counter decrements
  - When `count` becomes 0, latch is released
- Can not be reused

Latch Example : LatchWaiter

```
package examples.concurrent.advanced;

import java.util.concurrent.CountDownLatch;

/**...*/
public class LatchWaiter extends Thread {

  private CountDownLatch latch;

  public LatchWaiter(CountDownLatch latch) {
    this.latch = latch;
  }

  public void run() {
    try {
      latch.await();
    } catch (InterruptedException e) { }
    System.out.println("All threads completed, waiter is going to work");
  }
}
```

Latch Example : BusBoy(s)

```java
package examples.concurrent.advanced;

import java.util.Random;
import java.util.concurrent.CountDownLatch;

/**...*/
public class BusBoy extends Thread {

    private static Random randomGenerator = new Random();

    private CountDownLatch latch;

    BusBoy(CountDownLatch latch) {
        this.latch = latch;
    }

    public void run() {
        try {
            latch.countDown();
            System.out.println("BusBoy cleaning table " + latch.getCount());
            int sleepTime = Math.abs(randomGenerator.nextInt());
            Thread.sleep(sleepTime);

        } catch(InterruptedException ie) {
            System.out.println(ie);
        }
    }
}
```

Latch Example : SmokeBreak

```java
package examples.concurrent.advanced;

import java.util.concurrent.CountDownLatch;

/**...*/
public class SmokeBreak {

  public static void main(String[] args) {
    CountDownLatch latch = new CountDownLatch(5);

    LatchWaiter waiter = new LatchWaiter(latch);
    waiter.start();

    for(int i=0;i<5;i++) {
      new BusBoy(latch).start();
    }
  }
}
```

Barriers

- Block threads until some “event” occurs
  - Used to “join” groups of threads
  - All threads must reach rendezvous point at same time
  - Once all threads reach barrier, then proceed
- Threads don’t die when they reach barrier
  - Different than `Thread.join()`
  - They can continue processing
- Could be implemented using `wait` / `notify` mechanics
  - But might be messy
  - And potentially error prone

Barriers : `CyclicBarrier`

- Provides “blocking” point for threads
  - Constructed with number of threads in party
  - Each thread calls `await` when it gets to point
  - `CyclicBarrier` blocks `await` thread until all members of party arrive
  - Once all arrive, releases threads
- Can be reused - `reset` the barrier

CyclicBarrier Example : BusBoyBarrier

```java
package examples.concurrent.advanced;

import ...

/**...*/
public class BusBoyBarrier extends Thread {

  private static Random randomGenerator = new Random();

  private CyclicBarrier barrier;

  BusBoyBarrier(CyclicBarrier barrier) {
    this.barrier = barrier;
  }

  public void run() {
    try {
      System.out.println("BusBoy cleaning table ");
      int sleepTime = Math.abs(randomGenerator.nextInt());
      Thread.sleep(1000);
      System.out.println("BusBoys waiting: " + barrier.getNumberWaiting());
      barrier.await();

    } catch(InterruptedException ie) {
      System.out.println(ie);
    } catch (BrokenBarrierException e) {
      System.out.println(e);
    }
  }
}
```

CyclicBarrier Example : SmokeBreak

```java
package examples.concurrent.advanced;

import java.util.concurrent.CyclicBarrier;

/**...*/
public class SmokeBreak {

  public static void main(String[] args) {
    CyclicBarrier barrier = new CyclicBarrier(5, new Runnable() {
      public void run() {
        System.out.println("BusBoy Smoke Break");
      }
    });

    for(int i=0;i<5;i++) {
      new BusBoyBarrier(barrier).start();
    }

  }
}
```

`Exchanger`

- Barrier with data passing semantics

- Used with two threads
  - Meet at rendezvous point
  - Once there, `exchange` data
  - Continue on processing

`Semaphore`

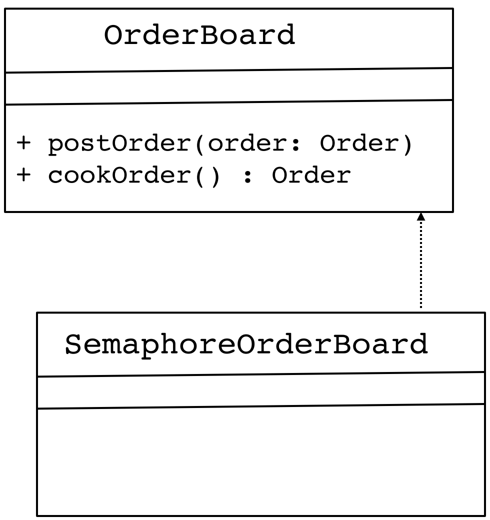
Formalization of counting semaphore

- Counting associated with set number of permits
- `Semaphore` with one permit is considered a mutex
- Removes counting semantics found in many synchronization techniques

Semaphore [cont.]

- Permits provide access control
  - Initialized to the number of resources it controls
  - Two key methods:
    - `acquire`
      - Decreases the number of available permits
      - Will wait if no permits available
    - `release` - increases number of available permits
  - Thread can hold more than one permit
  - Permit can be released by non-holding thread

OrderBoard Redesign



- `SemaphoreOrderBoard`
  - Implementation of `OrderBoard`
  - Uses two Semaphores
    - `fullSem` - initialized with 5 permits
    - `emptySem` - initialized with 0 permits
  - No synchronization - uses synchronized list
  - No queue empty / full management
  - Simplifies original `OrderBoard`

Semaphore Example

```java
package examples.concurrent.advanced;

import java.util.ArrayList;
import java.util.List;
import java.util.Collections;
import java.util.concurrent.Semaphore;

/**...*/
public class SemaphoreOrderBoard implements OrderBoard {

   private List<Order> orders;
   private Semaphore fullSem, emptySem;


   /**...*/
   public SemaphoreOrderBoard() {
      orders = Collections.synchronizedList(new ArrayList<Order>());
      fullSem = new Semaphore(5);
      emptySem = new Semaphore(0);
   }
```

Semaphore Example [cont.]

```
/**...*/
public void postOrder(Order toBeProcessed) {
  try {
    fullSem.acquire(); //decrease permits by one
    orders.add(toBeProcessed);
  } catch (Exception e) {
    e.printStackTrace();
  } finally {
    emptySem.release(); //increase permits by one
  }
}
```

Semaphore Example [cont.]

```java
    /**...*/
    public Order cookOrder() {
        Order tmpOrder = null;
        try {
            emptySem.acquire(); //decrease permits by one
            tmpOrder = orders.remove(0);
        } catch (Exception e) {
            e.printStackTrace();
        } finally {
            if(orders.size() < 3)
                fullSem.release(); //increae permits by one
        }

        return tmpOrder;
    }
}
```

Lab: Rewrite Order Board

- **GOAL:** Refactor the order board to use a Semaphore concurrency library. The resulting code should be less complex, less lines of code. Yet the functionality will be exactly the same.

- **NOTE:** Keep an old copy of the order board around. It will be used in other upcoming labs.

- **DURATION:** 45 minutes
  - 30 minutes - development
  - 15 minutes - group code review.

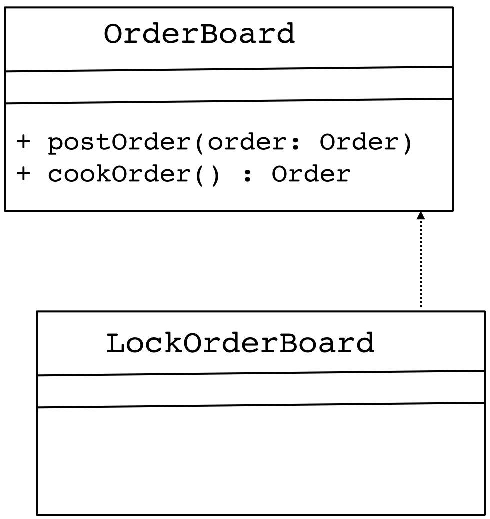
Other Concurrency Packages

`java.util.concurrent.locks`

- Locking and waiting condition framework
  - Alternative to monitor lock mechanism
  - Provides greater flexibility
    - Locks do not require synchronized blocks
    - Locks support re-entrance and fairness policies
    - Locks have multiple conditions
    - Waiting based on condition not “object lock”

- Key components:
  - `java.util.concurrent.locks.Lock`
  - `java.util.concurrent.locks.Condition`
  - `java.util.concurrent.locks.ReentrantLock`

OrderBoard Redesign



- `LockOrderBoard`
  - Implementation of `OrderBoard`
  - Uses one Lock
    - `ReentrantLock`
    - Used to synchronize access to orders list
  - Access controlled by two conditions
    - `full`
    - `empty`
  - Queue empty / full management

Lock Example

```java
package examples.concurrent.advanced;

import java.util.ArrayList;
import java.util.List;
import java.util.concurrent.locks.Condition;
import java.util.concurrent.locks.Lock;
import java.util.concurrent.locks.ReentrantLock;

/**...*/
public class LockOrderBoard implements OrderBoard {

  List<Order> orders;

  Lock fullLock = new ReentrantLock();
  Condition full = fullLock.newCondition();
  Condition empty = fullLock.newCondition();


  public LockOrderBoard() {
    orders = new ArrayList<Order>();
  }
```

Lock Example [cont.]

```java
public void postOrder(Order toBeProcessed) {
    try {
        fullLock.lock();
        while(orders.size() == 5) {
            full.await();
        }
        orders.add(toBeProcessed);
        empty.signalAll();
    } catch(Exception e) {
        e.printStackTrace();
    }
    fullLock.unlock();

}
```

Lock Example [cont.]

```java
public Order cookOrder() {
  Order returnValue = null;
  try {
    fullLock.lock();
    while(orders.size() == 0) {
      empty.await();
    }
    returnValue = orders.remove(0);
    full.signalAll();
  } catch(Exception e) {
    e.printStackTrace();
  }
  fullLock.unlock();
  return returnValue;
}
}
```

`java.util.concurrent.atomic`

- Toolkit of classes
  - Provide atomic manipulation of variables
  - Uses lock-free thread-safe implementation
- Extends `volatile` using `compareAndSet` functionality
  - Relies on enhancements made to JVM
  - Take advantage of compare-and-swap or load-linked/store-condition hardware based operations
  - Foundational for entire concurrency package
- May or may not be used at application development level

Summary

- Java SE 5.0 exponentially expands concurrent programming in Java
- Concurrency libraries provide standardization to common concurrent problems
- Concurrency libraries provide:
  - Concurrent collections
  - Synchronizers
  - Locks
  - Atomic wrappers

Advanced Concurrency Lab

- **GOAL**: Create a basic site map creation utility.

  The site map creation utility should generate a text file containing all of the domain-specific URLs found on a given website. Associated with each domain, should be a indicator denoting whether the URL was accessible. The site map utility does not need to track images, only <a href> tags.

  Use multiple threads to make the utility efficient. There should be one thread that finds <a href>s, and one thread that processes <a href>s.

  When all of the <a href>s are processed, the application should generate a text file and then shut-down gracefully.

- **HINTS:** A map could be used to represent the "indexed" site. A queue could be used as the shared resource representing the unindexed / untested elements of the site.

Advanced Concurrency Lab

- **DURATION:** 120 minutes
  - 100 minutes – development (consider pair programming)
  - 20 minutes – group code review