Lecture 11
Concurrent Collections
Collections in Java

• Collection objects group together other objects of the same type
  – Lists
  – Sets
  – Maps
  – Queues
  – Etc.

• They permit objects to be stored and processed later

• They support *iteration*: processing of each element in a collection
  – Iterator objects
  – `for (e : collection) statements`
Sample Collection Classes

- **Set interface**
  - HashSet
  - TreeSet
  - LinkedHashSet

- **List interface**
  - ArrayList
  - LinkedList

- **Map interface**
  - HashMap
  - TreeMap
  - LinkedHashMap

- **Queue interface**
  - LinkedList
  - PriorityQueue
Collections and Thread-Safety

• Previous implementations are not thread-safe
  – Insertion, deletion operations are not synchronized
  – Sharing these objects among threads can lead to erroneous data structures

• But collections are needed in thread programming!
  – You can create your own using locking, wait() / notify() / notifyAll(), etc.
  – Java also provides several mechanisms
Synchronization and the Collections Class

• The Collections class consists of static methods for processing collections
• It includes factory methods for creating synchronized versions of lists / sets / maps
  – Factory methods take relevant collections as inputs
  – They produce collections as outputs, but with all operations synchronized
• List<Integer> list = Collections.synchronizedList(new ArrayList<Integer>());
  – synchronizedList() produces a new list object that contains its argument as private field
  – List methods are “wrapped” inside synchronization code
  – Returned object is thread-safe as a result
Implementing synchronizedList()

- Create new class `SynchronizedList<T>`
  ```java
  ... class SynchronizedList<T> implements List<T> {

      final List<T> list;

      SynchronizedList<T> (List<T> list) { this.list = list; }

      public synchronized int size () {
          return list.size();
      }

      ...
  }
  ```

  - Each method is “wrapped” with synchronization code
  - Lock used is lock of argument list, which is called the `backing list`

- Have `synchronizedList()` return an object in `SynchronizedList<T>`!
  ```java
  public static <T> List<T> synchronizedList (List<T> list) {
      return new SynchronizedList<T> (list);  
  }
  ```
Thread Safety and Compound Actions

• Thread safety guarantees individual method invocations preserve correctness
• What if threads want to perform operations involving multiple actions?
  – Example: removing last element from a list
    ```java
    public static Object getLast (List<Object> l) {
        int lastIndex = l.size() - 1;
        return (l.get(lastIndex));
    }
    ```
    – This can lead to an `IndexOutOfBoundsException`
      • Each thread computes `lastIndex` value
      • First thread then removes element at this position
      • Second thread will try, but position is no longer valid
Implementing Compound Actions

- Thread safety does not guarantee that compound actions will complete successfully
- Solution for synchronized collections: *client-side locking*
  - Client locks data structure while compound action is performed
  - This ensures that state of data structure cannot change unexpectedly
  - Corrected `getLast()`:
    ```java
    public static Object getLast (List<Object> l) {
        synchronized (l) {
            int lastIndex = l.size() - 1;
            return (l.get(lastIndex));
        }
    }
    ```
Iteration and Synchronized Collections

• Iteration: the ultimate compound action!
  – Iteration processes all elements in a collection
  – Without synchronization:
    • One thread can start an iteration
    • Another can modify the collection while the iteration is underway
    • ConcurrentModificationException can be thrown as a result!
    • Iterators that raise this exception are called fail fast

• Solution: lock whole collection throughout iteration

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

– This keeps state of collection consistent
– It does reduce concurrent access to collection
Hidden Iteration

• Consider the following
  – list is a List object
  – The following statement is executed without any synchronization
    System.out.println(list);
  – This can cause a ConcurrentModificationException!

• Why?
  – Implementation of toString() for collections uses iteration
  – During construction of string for list, another thread can modify it

• Moral: compound actions, especially iterative ones, require client-side locking
Concurrent Collections

• Issue with synchronized collections: overly reduced concurrent access
  – If a collection is locked during iterative processing, then no other thread can access it
  – Individual operations can also unduly impede concurrent access
    • Hash tables have several buckets
    • Why lock the whole table to access a single bucket?

• Package java.util.concurrent contains implementations of several **concurrent collections**
  – These relax the “lock the whole data structure” approach of synchronized collections
  – The gain: more concurrency
  – The price to pay: changes to some operations
ConcurrentHashMap

- A concurrent implementation of `HashMap`
  - Maps keys to values, like `HashMap`
  - Uses *lock striping* to improve concurrent access
    - 16 locks used to control access
    - If there are \( k \) buckets, each lock guards \( k/16 \) buckets
    - If two threads are attempting to access buckets guarded by different locks, they can do so concurrently!
    - Locks are also ReadWrite locks (will learn more about this later)

- Benefit of lock striping: more concurrent access, so better performance

- Drawback: no way to lock whole table at user level
  - This means some operations that require access to whole table (e.g. `size()`, `isEmpty()`) are approximations
  - This makes compound actions impossible to implement at user level

- Iterators are *weakly consistent* rather than fail-fast
  - Tolerate concurrent modification
  - Traverse elements as they existed when iterator was constructed
  - May (or may not) reflect modifications to collection after iterator is constructed
ConcurrentHashMap and Built-In Compound Actions

• There is no way to lock entire ConcurrentHashMap
• To address compound-action problem, ConcurrentHashMap implements several of these directly (K is key type, V is value type)
  – V putIfAbsent(K key, V value)
    If key is not mapped to a value in table, map it to value and return null; otherwise, return the value key is mapped to
  – boolean remove(K key, V value)
    Return true if key is mapped to value, in which case also remove mapping; otherwise, return false
  – boolean replace(K key, V oldValue, V newValue)
    Return true if key is mapped to oldValue, in which case also replace oldValue by newValue
  – V replace(K key, V newValue)
    If key is mapped to some value, replace it with newValue and return the old value; otherwise, return null
CopyOnWriteArrayList

• Another concurrent collection, this one intended to support lists
• In synchronized lists, must lock entire list to access a single element or to iterate
  – This is because another thread may modify list during processing
  – Especially for iteration, this greatly reduces concurrency
• For CopyOnWriteArrayList lists, a copy-replace mechanism is used instead
  – No locking needed to read a list
  – When a list is modified, a local copy of the list is created
  – When the update is complete, the modified list is republished
  – When an iterator is created, reference to backing array stored, so iterator sees state of list in effect when iterator was created: no ConcurrentModificationException ever thrown!
• This is a good idea when ...???
  – Most list operations do not involve modification (because no locking needed)
  – Iteration is used frequently
Queues

• Data structures allowing insertion at one end, removal at another
  – FIFO (first-in, first-out) queues: elements stored in order of insertion
  – Priority queues: elements accessed in priority order (next element to be removed is one with highest priority)

• Java Queue interface

```java
interface Queue<E> extends Collection<E> {
    boolean offer(E x); // try to insert, return true if successful, false otherwise
    boolean add(E x) throws IllegalStateException;
        // try to insert, return true if successful, throw exn if not
    E poll(); // retrieve and remove; return null if empty
    E remove() throws NoSuchElementException;
        // retrieve and remove; throw exn if empty
    E peek(); // retrieve, don’t remove, return null if empty
    E element() throws NoSuchElementException;
        // retrieve, don’t remove, throw exn if empty
}
```

• Thread-safe non-blocking implementation: `ConcurrentLinkedQueue<E>`
Blocking Queues

• Like queues, but add new blocking operations for insertion, removal
  – void put(E e);
    Add element into queue, blocking until there is space
  – E take();
    Remove and return lead element from queue, blocking until queue is non-empty

• Timed versions of offer, poll also available
  – boolean offer(E e, long timeout, TimeUnit unit)
    Insert element, waiting up to timeout for insertion to succeed
  – E poll(long timeout, TimeUnit unit)
    Retrieve, remove lead element, waiting up to timeout before returning null

• Null elements may not be inserted
  – NullPointerException thrown if this is attempted
  – null only used as a “sentinel value”

• Blocking queues are thread-safe
  – Implementations support multiple users
  – Specialized access pattern for queues is exploited in implementations
Blocking Queue Implementations

- **LinkedBlockingQueue**
  - FIFO
  - May be bounded or unbounded
- **ArrayBlockingQueue**
  - FIFO
  - Bounded
- **PriorityBlockingQueue**
  - Ordered by priority
  - Unbounded
- **SynchronousQueue**
  - Capacity is 0!
  - Net effect: put and take operations between threads are synchronized
  - Sometimes called a *rendezvous channel*
The Producer-Consumer Pattern

• A common multi-threaded paradigm
  – Producer threads generate data to be processed
  – Consumer threads retrieve data and process it

• Issues
  – Producers might go faster than consumers
  – Want any free consumer to pick up a piece of data
  – Want producers to generate data without reference to which consumer will process it

• The Producer-Consumer Pattern
  – Use a blocking queue (*work queue*) to hold data!
  – Producers insert into queue; block when it is full
  – Consumers retrieve data from queue; block when it is empty
The Producer-Consumer Pattern

Producers

Consumers

Work Queue
Programming Producer-Consumer Applications

• General strategy
  – Create classes for producers, consumers
  – Ensure constructors take a `BlockingQueue` argument (this is the work queue)
  – In main method class:
    • Create work queue
    • Create producers / consumers using this queue
    • Start threads

• This establishes that producers, consumers access same queue
Example

- **ProducerThread.java**
  ```java
  public class ProducerThread extends Thread {
      private final BlockingQueue<Integer> queue;  // Work queue
      ...
      public ProducerThread(BlockingQueue<Integer> queue) { this.queue = queue; }
  }
  ```

- **ConsumerThread.java**
  ```java
  public class ConsumerThread extends Thread{
      private final BlockingQueue<Integer> queue;  // Work queue
      ...
      public ConsumerThread(BlockingQueue<Integer> queue) { this.queue = queue; }
  }
  ```

- **ProducerConsumerRandomizeTester.java**
  ```java
  public static void main(String[] args) {
      BlockingQueue<Integer> workQueue = new ArrayBlockingQueue<Integer>(10);
      ...
      for (int i=0; i < numConsumers; i++) {
          new ConsumerThread(workQueue).start();
      }
      for (int i=0; i < numProducers; i++) {
          new ProducerThread(workQueue).start();
      }
  }
  ```
Blocking Queues and InterruptedException

- Consider following in ProducerThread.java
  ```java
  private void enqueue(int i) {
    try {
      queue.put(i);
    }
    catch (InterruptedException e) {
      Thread.currentThread().interrupt();
      throw new RuntimeException("Interrupted Producer");
    }
  }
  ```
  - This method is used for putting elements into the blocking queue
  - It calls `queue.put()`, which can wait
    - If the queue is full, then thread executing `queue.put()` is suspended
    - When the queue has an empty slot, the thread may be reawakened
  - This means that `enqueue()` is also a waiting method!

- Waiting methods can throw `InterruptedException` when they are interrupted
  - Threads can interrupt each other, i.e. request each other to stop!
    - If thread T1 executes `T2.interrupt()`, it is requesting that T2 cease executing
    - T2 is not required to oblige
    - If T2 is executing normally a status flag is set
  - If a thread is waiting (i.e. its thread-state is WAITING, TIMED_WAITING) then this exception is generated for T2
    - The status flag is not set in this case
  - T2 then has the opportunity to decide what to do re: interruption (usually: clean-up and halt)
What To Do about `InterruptedException`?

- Propagate it
- Catch it and raise another exception
- Catch it and do some other actions
  - In real applications it is a good idea to set the interrupt status to reflect fact that thread has been interrupted
  - This can be done by invoking the static method `Thread.currentThread().interrupt();`
    - This sets the interrupt status of the current thread
    - Other threads can now see that this thread has indeed been interrupted