CMSC 433 Fall 2013
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(Some slides due to Rance Cleaveland)

Lecture 7
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!

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>`

```
… class SynchronizedList<T> implements List<T> {

      final List<T> list;

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

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

  - Each method is “wrapped” with synchronization code
  - Lock used is lock of wrapping object, as opposed to the wrapping object, or *backing list*
- Have `synchronizedList()` return an object in `SynchronizedList<T>`!

```
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

```
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()`:

```
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

```
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 `ConcurrentHashTable`
- 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

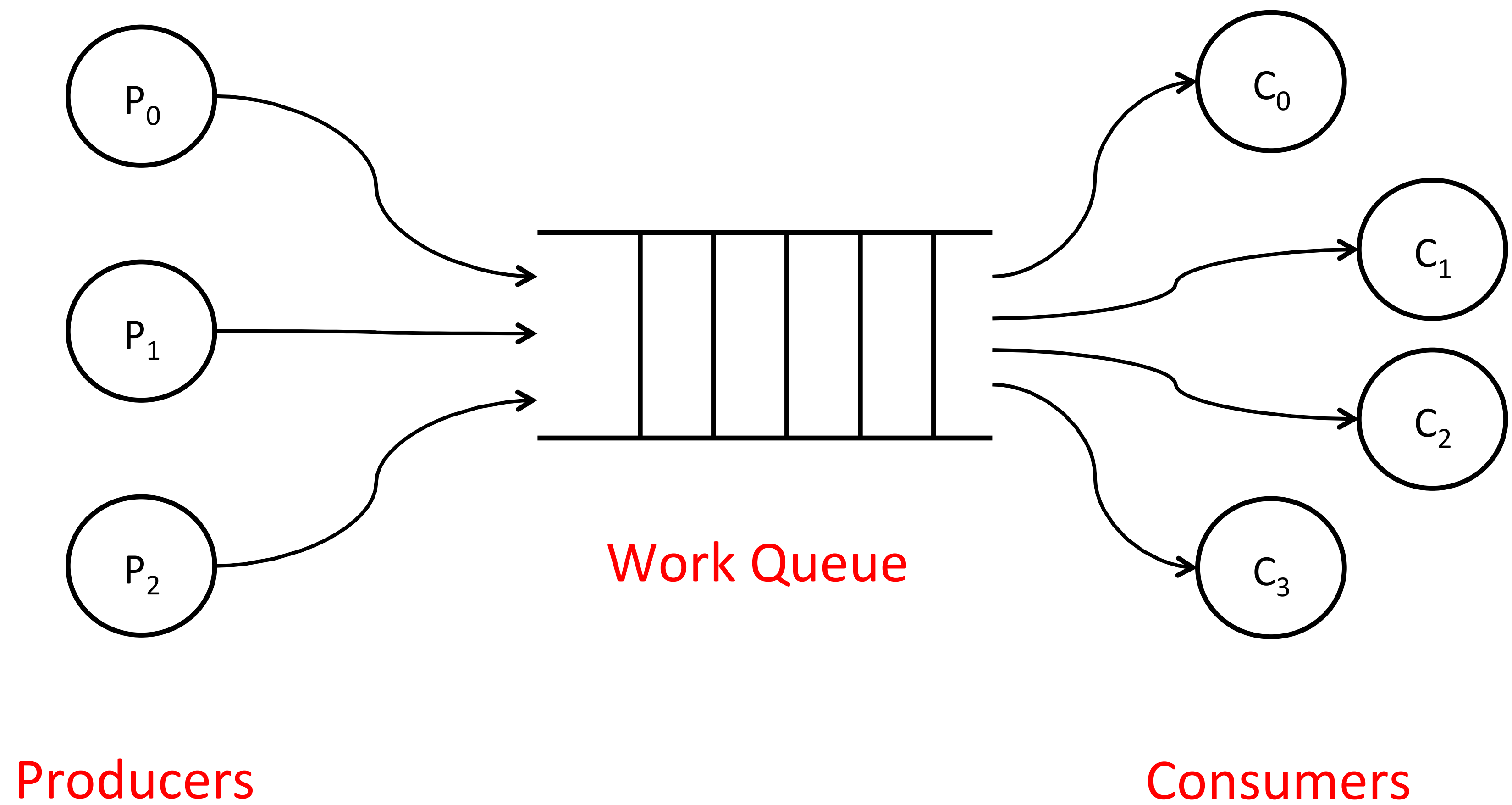
- Data structures allowing insertion at one end, removal at another
  - FIFO (first-in, first-out) queues: elements stored in order of insertion
  - Priority queues: elements accessed in priority order (next element to be removed is one with highest priority)
- Java Queue interface

```
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>`

The Producer-Consumer Pattern

must block on queue ops



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
  - Producers retrieve data from queue; block when it is empty

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, wating 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*