Lecture 10
Composing Objects
State-Dependent Actions

• Recall the specification of a method
  – Precondition: property that must hold of object state (i.e. fields) and inputs in order for method to terminate normally
  – Postcondition: property guaranteed to hold of state, output when precondition is true
  – Exception condition: what happens when method is invoked and precondition does not hold

• Example: slope method in Line class
  – Precondition: point fields must not be vertically aligned
  – Postcondition: slope is returned
  – Exception: ArithmeticException raised if points are vertically aligned

• There is a state-dependency in the behavior of slope!
  – For most states (i.e. ones where points are not vertical) the slope method is well-defined
  – For others (i.e. ones where points are vertically aligned) the method raises an exception
Other Examples of State Dependency

• Operations on collections
  – Can’t remove an element from an empty queue
  – Can’t add element to full buffer

• Operations involving constrained values
  – Can’t withdraw money from empty bank account

• Operations requiring resources
  – Can’t connect to internet if local network is down

• Operations requiring previous operations
  – Can’t read from a file that has not been opened
State-Dependency and Multithreading

• In single-threaded case, one general option for state-dependency: *balking*
  – Operation cannot be performed, so method refuses to perform it
  – This can be achieved by
    • Ignoring
    • Raising an exception
    • Returning a status code

• In multithreaded applications, other possibilities are available because another thread might change the state of the object
  – *Guarded suspension*
  – *Optimistic retries*
Balking Via Ignoring

```java
public class BoundedCounter {
    private int value = 0;
    private int upperBound = 0;

    //INJECTIVE: in all instances 0 <= value <= upperBound

    public synchronized boolean isMaxed() {
        return(value == upperBound);
    }
    ...

    //Pre: none
    //Post: increment value if not maxed; otherwise, do nothing.
    //Exception: none
    public synchronized void inc() { if (!isMaxed()) ++value; }
}
```

• Recall BoundedCounter
  – inc method does nothing if counter value at maximum value
  – Balking via ignoring!
public class BoundedBufferException {

    // Invariant: number of elements is <= maxSize

    private final int maxSize;
    private ArrayList<Object> elements;
    ...

    // Pre: number of elements is below maxSize
    // Post: elt is added to end of list of elements
    // Exception: If number of elements is too high, throw exception.
    public synchronized void put(Object elt) throws Exception {
        if (elements.size() < maxSize) { elements.add(elt); }
        else throw new Exception("Put error");
    }
}

• Consider BoundedBufferException class
  — Stores elements in a queue
  — If queue is full/empty, put/take methods are not defined!
  — In this case, exceptions raised
public class BoundedBufferReturnCode {

    // Invariant: number of elements is <= maxSize
    
    private final int maxSize;
    private ArrayList<Object> elements;

    // Type of return values
    public class ReturnVal { public final Object obj; public final boolean code; ... }

    // Pre: none
    // Post: if list is nonempty, return first element and true; otherwise,
    //       return null and false
    // Exception: none
    public synchronized ReturnVal take() {
        if (elements.size() > 0) {
            Object elt = elements.get(0);
            elements.remove(0);
            return new ReturnVal(elt, true);
        }
        else return new ReturnVal(null, false);
    }
}

• Consider BoundedBufferReturnCode
  – Inner class defined for return values for put, take
  – Inner class includes object, boolean indicating whether operation concluded successfully
Observations on Balking

• Operations do not block when state is correct (assuming no infinite loops)
• When an operation balks, it is up to class user to determine what to do
  – Detect “ignoring”
  – Handle exception
  – Act on return code
Guarded Suspension

- For bounded buffers in a multithreaded environment:
  - If the buffer is empty now, a `take()` operation cannot complete.
  - Another thread could deposit an element later, and a `take()` could succeed!

- In guarded-suspension approaches to state-dependent actions, threads “go to sleep” until the actions they want to perform are possible.

- Needed mechanisms:
  - ... for going to sleep (“suspend”)
  - ... for waking up (“resume”)

Busy-Waiting

• An old-fashioned mechanism for suspend/resume
  – Use a while loop to test for enabledness of state-dependent action
  – When true: exit loop, perform action
  – E.g.
    ```c
    while (!enabled) ; // Suspend via spinning
    // Resume
    ```

• Considerations
  – Consumes computing resources
  – Enabled-ness condition might become false after loop terminates, so synchronization should be used
wait() / notify() / notifyAll()

• A more modern mechanism in Java for suspending / resuming
  – To suspend, a thread performs a wait()
  – Other threads perform notify() / notifyAll() to enable resumption of suspended threads

• Benefits
  – No consumption of cycles while suspended
  – Synchronization taken care of (we will see how in a moment)

• Dangers
  – A suspended thread is dependent on other threads to wake it up
  – If no other thread performs notify() / notifyAll(), then thread sleeps forever
How `wait/notify/notifyAll` Work

- In addition to its intrinsic lock, every Java object has a `wait-set`
  - Wait-set contains threads that are waiting on the object
  - Threads in the wait-set are suspended
- Threads enter wait-set of object `obj` by performing `obj.wait()`;
  - Thread is added to wait-set of `obj`
  - Thread releases all its locks on `obj`, but not other locks
  - Thread is then suspended
- Other threads can release waiting threads by performing `obj.notify()` or `obj.notifyAll()`
  - `obj.notify()`: one waiting thread selected “at random” for resumption
  - `obj.notifyAll()`: all waiting threads selected for resumption
- When thread selected for resumption the following happens behind the scenes
  - It is removed from wait-set
  - It tries to reacquire its locks on the object it was waiting on
    - If it succeeds, it proceeds
    - Otherwise, it blocks waiting for the lock to become available
  - Note: thread should double-check condition for state-dependent action when it resumes!
Example: BoundedBufferWait

```java
public synchronized void put(Object elt) throws InterruptedException {
    while (elements.size() == maxSize) wait();
    elements.add(elt);
    notifyAll();
}
```

- In `put()` / `take()` operations, `wait()` executed when state does not allow action
- When an operation succeeds, waiting threads notified
- When a thread wakes up, it must check that condition it was waiting for holds!
  - This is why loop is used with `wait()` inside. You should do this always unless you have an ironclad argument for not needing a loop!
  - Just because a thread is resumed does not mean it is safe to proceed
- When a thread modifies the state of the object (e.g. by successfully adding an element) it must notify sleeping threads
- `InterruptedException`?
  - `wait()` is a blocking operation, meaning it could never terminate
  - Any thread can be interrupted (a topic for a later date) by another thread
  - This exception is raised in this case, because a blocked thread may need some cleanup
**notify() / notifyAll()**

- **Consider** `take()` operation in `BoundedBufferWait`:
  
  ```java
  public synchronized Object take() throws InterruptedException {
      while (elements.size() == 0)
          wait();
      Object elt = elements.get(0);
      elements.remove(0);
      notifyAll();
      return elt;
  }
  ```

- **Doesn’t this introduce a race condition?**
  - `notifyAll()` called before return of element
  - Could this cause problems?

- **Answer: no**
  - `notify() / notifyAll()` do not release locks
  - So lock on buffer only released when `take()` operation terminates
Why `notifyAll()`?

- `put()` / `take()` **use `notifyAll()`** rather than `notify()`
  - It seems wasteful to wake everyone up!
  - Why not just wake up one thread?

- There is a reason!
  - Waiting threads are potentially concerned with different conditions
    - Putters are waiting for buffer not to be full
    - Takers are waiting for buffer not to be empty
  - **If you use `notify()`**, you only wake up one thread
  - **If you wake up the wrong thread**, you can wind up in a deadlock!
notify() and Deadlock

• Suppose `put()`, `take()` reimplemented with `notify()` rather than `notifyAll()`, e.g.

```java
public synchronized void put(Object elt) throws InterruptedException {
    while (elements.size() == maxSize) wait();
    elements.add(elt);
    notify();
}
```

• Now supposed we have:
  – `BoundedBufferWait with maxSize == 1`
  – Four threads `T_1, ..., T_4`
  – A deadlock can happen!
## Deadlock Scenario

<table>
<thead>
<tr>
<th>Time</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>elements.size()</th>
<th>Wait-set</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>take (w)</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>T1</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>take (w)</td>
<td></td>
<td></td>
<td>0</td>
<td>T1, T2</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>put</td>
<td></td>
<td>1</td>
<td>T2</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>put (w)</td>
<td></td>
<td>1</td>
<td>T2, T3</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>put (w)</td>
<td>1</td>
<td>T2, T3, T4</td>
</tr>
<tr>
<td>5</td>
<td>take (0)</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>T3, T4</td>
</tr>
<tr>
<td>6</td>
<td>take (w)</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>T1, T3, T4</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>take (w)</td>
<td></td>
<td></td>
<td>0</td>
<td>T1, T3, T4, T2</td>
</tr>
</tbody>
</table>

**Legend**
- `op(w)` – operation waits / "rewaits"
- `op(i)` – operation begun at time i completes
- `op` – operation begins and completes without waiting
When To Use `notify()`

- Only use `notify()` if
  - Every thread in wait-set is guaranteed to be waiting on same condition
  - Condition is guaranteed to be true when thread executing `notify()` surrenders its lock on object

- Otherwise: use `notifyAll()`
Timed Waiting

• Problem with `wait()`: unbounded waiting
  – You do not know how long a thread might wait before being able to continue
  – In some applications this leads to unacceptable performance variability
• Variant: `wait(long millis)`
  – Wait for at least specified # of milliseconds
  – At time-out, exit wait-set
  – How do you tell if exit from wait-set is due to notification or timeout?
    • You don’t
    • You have to check this yourself
• Intermediate between balking, guarded suspension
Example:

**BoundedBufferTimedWaiting**

```java
public synchronized void put(Object elt, long allowedDuration) throws Exception, InterruptedException {
    long startTime = System.currentTimeMillis();
    long timeLeft = allowedDuration;
    while (elements.size() == maxSize) {
        wait(timeLeft);
        // Check if buffer has space
        if (elements.size() < maxSize) {
            break; // Break out of loop
        }
    }
    // Check if time has expired
    long elapsed = System.currentTimeMillis() - startTime;
    timeLeft = allowedDuration - elapsed;
    if (timeLeft <= 0) throw new Exception("Timeout");
    elements.add(elt);
    notifyAll();
}
```

- Argument to put includes upper bound on time to wait
- The handling of resumption includes a check for how much time has elapsed
- When “re-waiting” the new timeout value must be recalculated based on how waiting has already occurred!
Nested Monitor Lockout

• Suppose we want to build a layer on top of BoundedBufferWait
  – New class should not insert null objects into buffer
  – A new invariant is being defined: buffer should contain no null objects

• An approach: instance confinement!
  – Make a new class for enforcing new invariant
  – Include a private field containing a BoundedBufferWait object
  – Implement a new put method to handle null objects

• Does it work?
public class BoundedBufferWaitNoNull {

    private final BoundedBufferWait buffer;

    BoundedBufferWaitNoNull(int capacity) {
        buffer = new BoundedBufferWait(capacity);
    }

    public synchronized boolean put(Object elt) throws InterruptedException {
        if (elt != null) {
            buffer.put(elt);
            return true;
        }
        else return false;
    }

    public synchronized Object take() throws InterruptedException {
        return buffer.take();
    }
}
BoundedBufferWaitNoNull Does Not Work

• What happens if a thread calls take on a BoundedBufferWaitNoNull object when the buffer is empty?
  – Object calls `buffer.take()`
  – Since buffer is empty, thread enters wait-set, releases lock on inner BoundedBufferWait object
  – Thread still holds lock on BBWNN object, though

• Deadlock!
  – This phenomenon is called *Nested Monitor Lockout*
  – Issue is that lock is held on outer object even though waiting is occurring on inner object
  – While outer-object lock is held, no other thread can use it!
Solving Nested Monitor Lockout

• Don’t synchronize in outer class
  But sometimes you need to, in order to preserve new invariants

• Reprogram inner class so that object on which locking is to be performed is provided as argument to inner-class constructor
  – Requires reprogramming methods in inner so that this lock is used
  – Solves problem, at cost of rework of inner class
public class BoundedBufferWaitLockParam {

    final int maxSize;
    final ArrayList<Object> elements;
    final Object syncLock;

    BoundedBufferWaitLockParam(Object lock, int maxSize) {
        this.maxSize = maxSize;
        elements = new ArrayList<Object>();
        syncLock = lock;
    }

    public void put(Object elt) throws InterruptedException {
        synchronized (syncLock) {
            while (elements.size() == maxSize) syncLock.wait();
            elements.add(elt);
            syncLock.notifyAll();
        }
    }

    ...

}
Optimistic Retrying

• Another mechanism for handling state-dependency

• Idea:
  – Make copy of current state
  – Apply operation if it is applicable
  – “Commit” updated state if copied state, current state are the same
  – Copying, commit operation only operations that locks

• Why even do this?
  – Locking is expensive
  – If operations “usually succeed”, and contention for object is low, it may be more efficient to do this
Example:
**BoundedCounterOptimistic**

```java
// State copying method
public synchronized int current() { return value; }

// Commit method
public synchronized boolean commit(int oldState, int newState) {
    if (value == oldState) {
        value = newState;
        return true;
    } else return false;
}

public void inc() {
    for (;;) { // Retry-based
        int currentState = current();
        if ((currentState < upperBound) && (commit(currentState, currentState+1))) break;
        else Thread.yield();
    }
}
```

- Only state-copying, commit methods are synchronized!
  - Other methods call these, also rely on thread-confinement due to local variables
  - For more complicated classes state copying can be performed piecemeal, so long as invariants respected
- New state commitment is simple in this application
  - With more complex objects, need to ensure that creation of new state does not induce changes that cannot be undone