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;

    //INVARIANT: 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!
Balking Via Exceptions

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 \texttt{take()} operation cannot complete
  – Another thread could deposit an element later, and a \texttt{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 \texttt{wait() / notify() / notifyAll()} Work

• In addition to its intrinsic lock, every Java object has a \textit{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 \texttt{obj} by performing \texttt{obj.wait();}
  – Thread is added to wait-set of \texttt{obj}
  – Thread releases all its locks on \texttt{obj}, but not other locks
  – Thread is then suspended
• Other threads can release waiting threads by performing \texttt{obj.notify()} or \texttt{obj.notifyAll()}
  – \texttt{obj.notify()}: one waiting thread selected “at random” for resumption
  – \texttt{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: \texttt{thread should double-check condition for state-dependent action when it resumes!}
Example: BoundedBufferWait

// Pre: number of elements is below maxSize
// Post: elt is added to end of elements, waiting threads notified
// Exception: If number of elements is too high, suspend.
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
class BoundedBufferWait {
    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>take (w)</td>
<td></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
        }
        else {
            // 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!
More on Thread States

- Recall Thread object states from Lecture 2
  - Allowed states are **NEW**, **RUNNABLE**, **TERMINATED**, **BLOCKED**, **WAITING**, **TIMED_WAITING**
  - Thread object is in
    - **NEW** state when it is created, but before it is started
    - **RUNNABLE** when it is started
    - **TERMINATED** when it has exited
- What about other states?
  - **BLOCKED**: thread is waiting to acquire a lock
  - **WAITING**: thread has executed a wait() operation but has not yet been notified
  - **TIMED_WAITING**: thread has executed wait(n) operation (or Thread.sleep() operation)
Thread State Transition Graph

- **NEW**
  - Creation
  - `start()`

- **RUNNABLE**
  - `start()`
  - `exit`
  - `request lock`
  - `acquire lock`
  - `wait(n), Thread.sleep()`

- **WAITING**
  - `wait()`
  - `notification`

- **BLOCKED**
  - `request lock`
  - `acquire lock`
  - `wait(n), Thread.sleep()`

- **TIMED_WAITING**
  - `sleep() done`
  - `notification, wait(n) timeout`

- **TERMINATED**

**Notes:**
- Threads in **WAITING, TIMED_WAITING** state can throw **InterruptedException**
- Need to handle these exceptions when relevant operations called!
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();
        }
    }

    ...
}

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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

// 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