CMSC 433 – Programming Language Technologies and Paradigms

Composing Objects

Composing Objects

- To build systems we often need to
  - Create thread safe objects
  - Compose them in ways that meet requirements while maintaining safety

Designing Thread-Safe Classes

- For each class you should know:
  - Which variables make up the object's state
  - What invariants/postconditions apply to the state
  - What policies you will use to manage concurrent access to the object's state

Object State

- Primitive fields
- References and the fields reachable from those references

Object Invariants

- Invariants are logical statements that must be true about an object's state, e.g.,
  - lowerBound ≤ upperBound
  - List l is sorted in ascending order
- Postconditions capture the expected effect of an operation, e.g.,
  - For list l, after l.add(x) completes l.contains(x)

Synchronization Policy

- Invariants/postconditions must hold under concurrent access
- If operations can violate invariants/postconditions
  - Operation must be atomic
- If invariants involve multiple variables
  - Must fetch and update all variables in an atomic operation
  - All accesses to any of these variables must be guarded by the same lock

Counter

```
public final class Counter {
  // shared mutable state
  private long value = 0;
  // returns current value
  public synchronized long getValue() {
      return value;
  }
  // increments current value by 1
  public synchronized long increment() {
    if (value == Long.MAX_VALUE)
      throw new IllegalStateException("counter overflow");
      return ++value;
    }
}
```

BuggyNumberRange

```
public class BuggyNumberRange {
    // INVARIANT: lower <= upper
    private volatile int lower = 0;    private volatile int upper = 0;
    public void setLower(int i) {
        if (i > upper)   throw new IllegalArgumentException();
        lower = i;
    }
    public void setUpper(int i) {
        if (i < lower)   throw new IllegalArgumentException();
        upper = i;
    }

    public boolean isInRange(int i) {
        return (i >= lower && i <= upper);
    }
}
```

SimpleNumberRange

```
public class SimpleNumberRange {
private  int lower = 0;    private  int upper = 0;
    public synchronized void setLower(int i) {
        if (i > upper)  throw new IllegalArgumentException();
        lower=i;
    }
    public synchronized void setUpper(int i) {
        if (i < lower)  throw new IllegalArgumentException();
        upper=i;
    }
    public synchronized boolean isInRange(int i) {
        return (i >= lower && i <= upper);
    }
}
```

State Dependent Actions

- State dependent operations are those that are legal in some states, but not in others
- Examples
  - Operations on collections
    - Cant' remove an element from an empty queue
    - Can't add an element to a full buffer
  - Operations involving constrained values
    - Can't withdraw money from empty bank account
  - Operations requiring resources
    - Can't print to a busy printer
  - Operations requiring particular message orderings
    - Can't read an unopened file

State Dependent Actions

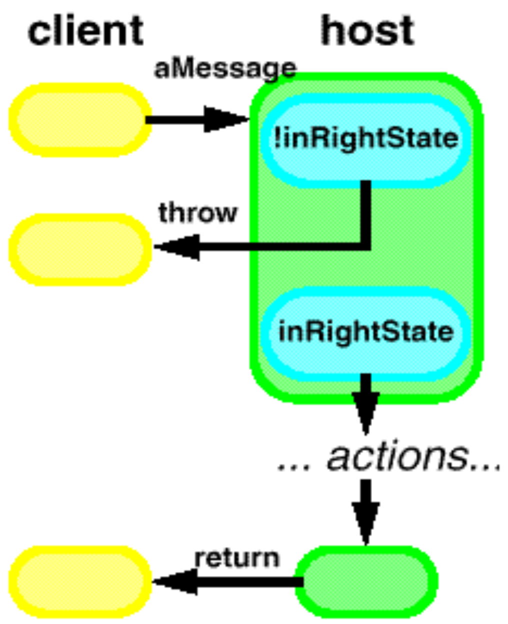
- Some policies for handling state dependence
  - Balking
  - Guarded Suspension
  - Optimistic Retries

Policies for State Dependent Actions

- There are different ways to handle state dependence
  - Balking – Ignore or throw exception
  - Guarding – Suspend until you can proceed
  - Trying – proceed, but rollback if necessary
    - Retrying – keep trying until you succeed
    - Timing out – try for a fixed period of time

Balking

- Check state upon method entry
  - Must not change state in course of checking it
- Exit immediately if not in right state
  - Throw exception or return special error value
  - Client is responsible for handling failure



Example: Balking Bounded Buffer

```
public class BalkingBoundedBuffer implements Buffer {
    private List data;
    private final int capacity;

    public BalkingBoundedBuffer(int capacity) {
        data = new ArrayList(capacity);
        this.capacity = capacity;
    }
…
}
```

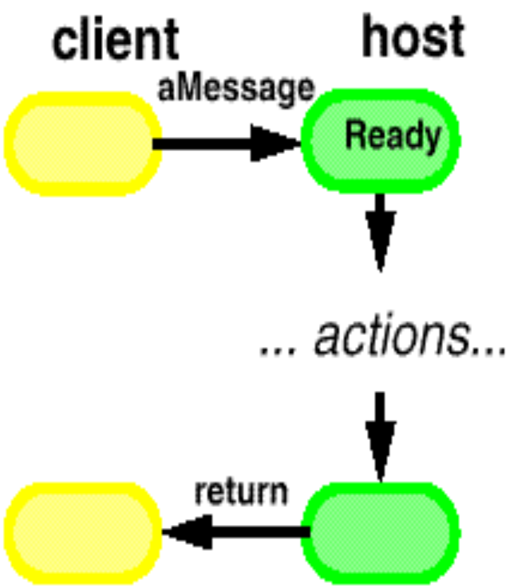
Example: Balking Bounded Buffer

```
    public synchronized Object take() throws Failure {
        if (data.size() == 0) throw new Failure("Buffer empty");
        Object temp = data.get(0);
        data.remove(0);
        return temp;
    }

    public synchronized void put(Object obj) throws Failure {
        if (data.size() == capacity) throw new Failure("Buffer full");
        data.add(obj);
    }
…
}
```

Guarding

- Check state upon entry
  - If not in acceptable state, wait
  - Some some other thread must cause a state change that enables waiting thread to resume operation
- Generalization of locking
  - Locked: wait until not engaged in other methods
  - Guarded: wait until arbitrary predicate holds
- Introduces liveness concerns
  - Relies on actions of other threads to make progress



Guarding Mechanisms

- Busy-waits
  - Thread continually spins until a condition holds
    - while (!condition) ; // spin
      // use condition
  - Usually to be avoided, but can be useful when conditions latch– i.e., once set true, they never become false
- Suspension
  - Thread stops execution until notified that the condition may be true
  - Supported in Java via wait-sets and locks

Guarding Via Suspension

- Waiting for a condition to hold:

```
synchronized (obj) {
    while (!condition) {
      try {
        obj.wait();
      } catch (InterruptedException ex) { ... }
    } // make use of condition
}
```

- Always test a condition in a loop
  - State change may not be what you need
  - Conditions can change more than once before waiting thread resumes operation

Guarding Via Suspension

- Changing a condition:

```
synchronized (obj) {
    condition = true;
    obj.notifyAll(); // or obj.notify()
}
```

Wait-sets and Notification

- Every Java Object has a wait-set
  - Can only manipulate it while holding Object's lock
    - Otherwise IllegalMonitorStateException is thrown
- Threads enter Object's wait-set by invoking wait()
  - wait() atomically releases lock and suspends thread
    - Including a lock held multiple times
    - No other held locks are released
  - Optional timed-wait: wait(long millis)
    - No direct indication that a time-out occurred
    - wait() is equivalent to wait(0) —means wait forever

Wait-sets and Notification

- Threads are released from an Object's wait-set when:
  - notifyAll() is invoked on the Object
    - All threads released
  - notify() is invoked on the Object
    - One thread selected at 'random' for release
  - A specified time-out elapses
  - The Thread has its interrupt() method invoked
    - InterruptedException thrown
  - A spurious wakeup occurs
- Lock is always reacquired before wait() returns
  - Can't be acquired until a notifying Thread releases it
  - Released thread contends with all other threads for the lock
  - If Lock is acquired, then Lock count is restored

Wait-sets and Notifications

- notify() can only be used safely when
  - Only one thread can benefit from the change of state
  - All threads are waiting for the same change of state
    - Or else another notify() is done by the released thread
  - These conditions hold in all subclasses
- Any Java Object can be used just for its wait-set and/or lock

Guarded Bounded Buffer

```
public synchronized Object take() throws Failure {
  while (data.size() == 0)
        try {
          wait();
        } catch(InterruptedException ex) { throw new Failure(); }
  Object temp = data.get(0);
  data.remove(0);
  notifyAll();
  return temp
}
```

Guarded Bounded Buffer

```
public synchronized void put(Object obj) throws Failure {
  while (data.size() == capacity)
     try {
       wait();
     } catch(InterruptedException ex) { throw new Failure(); }
  data.add(obj);
  notifyAll();
}
```

notify vs. notifyAll()

- Suppose put() and take() used notify() instead of notifyAll()
- Capacity is 1
- Four threads – two just call put() and two just call take()

Deadlock

T1	T2	T3	T4	data.size	Wait Set
take				0	T1
	take			0	T1,T2
		put		1	T2
		put		1	T2,T3
			put	1	T2,T3,T4
take				0	T3,T4
take				0	T1, T3,T4
	take			0	T1, T2,T3,T4

Timing Out

- Intermediate points between balking and guarding
  - Can vary timeout parameter from zero to infinity
- Can't be used for high-precision timing or deadlines
  - Time can elapse between wait and thread resumption
  - Time can elapse after checking the time
- Java implementation constraints
  - wait(ms) does not automatically tell you if it returned because of a notification or because of a timeout
  - Must check for both. Order and style of checking can matter, depending on
    - If always OK to proceed when condition holds
    - If timeouts signify errors
    - No way to establish with 100% certainty that timeout occurred

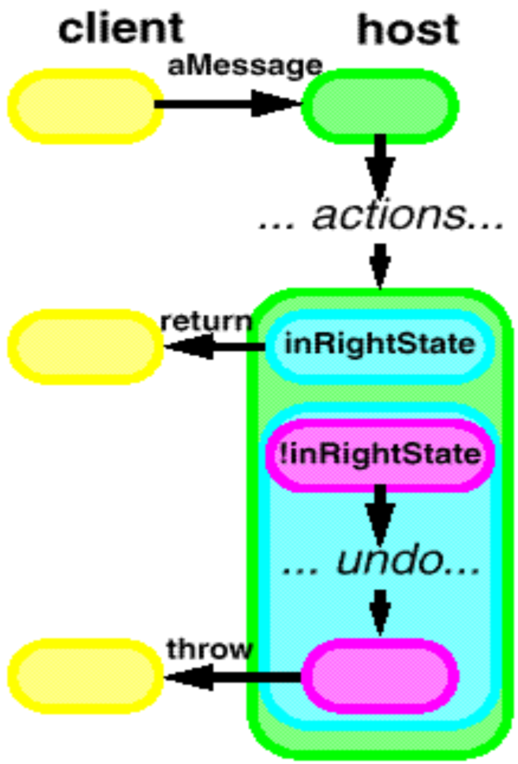
Timeout Example

```
// assume timeout > 0
public synchronized void put(Object obj, long timeout)  throws Failure {
      long timeleft = timeout;
      long start = System.currentTimeMillis();

      while (data.size() == capacity) {
        try { wait(timeleft); }
        catch(InterruptedException ex) { throw new Failure(); }
        if (data.size() < capacity) // notified, timed-out or spurious?
          break; // condition holds - don't care if we timed out
        else { // maybe a timeout
          long elapsed = System.currentTimeMillis() - start;
          timeleft = timeleft- elapsed;
          if (timeleft <= 0) throw new Failure("Timed-out");
        }  // spurious so wait again
       }
      data.add(obj);
      notifyAll();
}
```

Optimistic Policies: Trying

- Isolate state into versions
  - e.g. by grouping into a helper class
- Isolate state changes to atomic commit method that swaps in new state
- On method entry
  - Record initial state
  - Apply action to new state
- Only commit if
  - Action succeeds and initial state was unchanged
- If can’t commit: fail or retry
  - Failures are clean (no side effects)
  - Retry policy is variation of a busy-wait
- Only applicable if actions fully reversible
  - No I/O or thread construction unless safely cancellable
  - All internally called methods must be undoable



Optimistic Techniques

- May be more efficient than guarded waits when:
  - Conflicts are rare and when running on multiple CPUs
- However, retrying can cause livelock
  - Infinite retries with no progress
  - Should arrange to fail after a certain time or number of attempts

Optimistic Bounded Counter

```
public class OptimisticBoundedCounter {
    …
    public synchronized Long count() { return count;}
    private synchronized boolean commit(Long oldc, Long newc) {
      boolean success = (count == oldc);
      if (success) count = newc;
      return success;
    }
    public void inc() {
      for (;;) { // retry-based
        Long c = count(); // record current state
        long v = c.longValue();
        if (v < MAX && commit(c, new Long(v+1)))  break;
        Thread.yield(); // a good idea in spin loops
      }
    }
    …
}
```

Instance Confinement

- Even if an object is not thread-safe, there may still be ways to use it safely, e.g.,
  – Confine its use to a single thread
  – Ensure all accesses to it are guarded by a lock

Instance Confinement

```
public class PersonSet {
    private final Set<Person> mySet = new HashSet<Person>();
    // HashSet is not thread-safe
    public synchronized void addPerson(Person p) {
        mySet.add(p);
    }
    public synchronized boolean containsPerson(Person p) {
        return mySet.contains(p);
    }
```

Monitor Pattern

- The PersonSet class uses the Monitor Pattern
  - Object enforces mutually exclusive access to its own state
- Have to be careful when we combine monitors

Containment of Unsafe Objects

```
public static class Statistics {
    public long requests;
    public double avgTime;
    public Statistics(long requests, double avgTime) {
       this.requests = requests;
       this.avgTime = avgTime;
    }
…
}
```

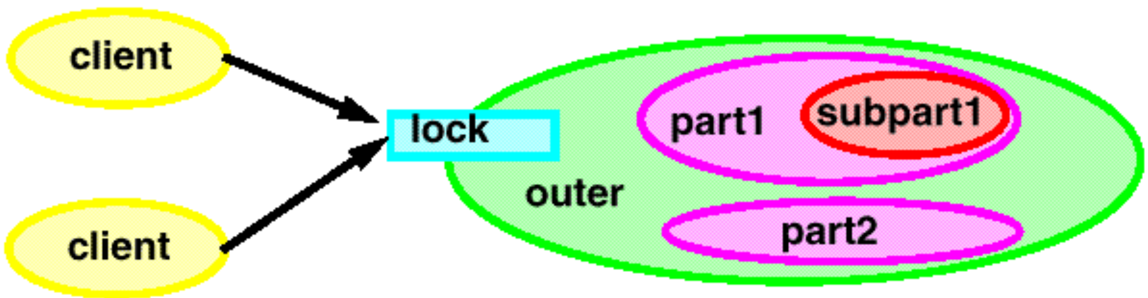
- Fields are public and mutable, so instances can't be shared

Containment of Unsafe Objects

```
class Container{ …
  private final Statistics stats = new Statistics(0,0.0);
  public synchronized Statistics getStatistics() {
        return new Statistics(stats.requests, stats.avgTime);
  }
  private void someFunc() {
     …
     synchronized(this) {
       double total = stats.avgTime*stats.requests + elapsed;
       stats.avgTime = total / (++stats.requests);
     }
  }
```

- Can use it in another class
- Don’t want to expose mutable state so we make copies of it

Containment



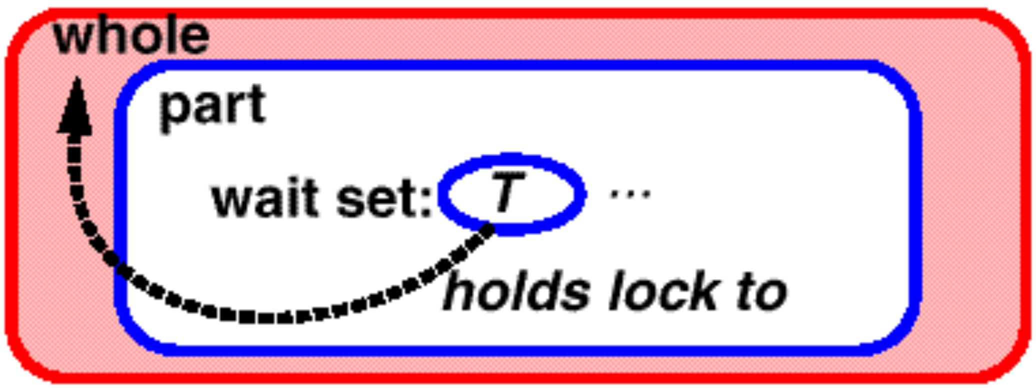
- Strict containment creates islands of objects
  - Applies recursively
- Allows inner code to run faster
  - Can be used with legacy sequential code
- Requires inner code to be communication closed
  - No unprotected calls into or out of island
- Requires outer objects to never leak inner references

Containment and Monitor Methods

```
class Part {
    protected boolean cond = false;
    synchronized void await() {
      while (!cond)  try { wait(); } catch(InterruptedException ex) { ... }
    }
    synchronized void signal( boolean c) {
      cond = c; notifyAll();
    }
  }
class Whole{
    final Part part = new Part();
    synchronized void rely() { part.await(); }
    synchronized void set( boolean c){ part.signal(c);}
  }
```

What happens if Whole.rely() is called while cond is false?

Nested Monitors



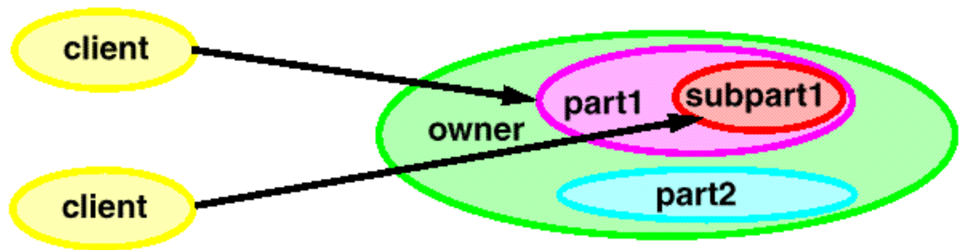
- When thread T calls Whole.rely
  - T waits in part
  - While suspended T still holds lock on Whole
  - No other thread will ever unblock T via Whole.set
    - Nested Monitor Lockout

Avoiding Nested Monitors

- Possible fix
  - Let owner object provide lock and wait-set

```
class Whole { // ...
      class Part { // ...
        public void await() {
          synchronized (Whole.this) {
             while (...) Whole.this.wait();
             //...
          }
        }
      }
    }
```

Hierarchical Containment Locking



- Parts are not hidden from clients
- Parts use lock provided by common owner
  - Can use either internal or external conventions

Internal Containment Locking

- Parts use their owners as locks

```
class Part {
    protected Container owner_; // Never null
    public Container owner() {return owner_; }
    private void bareAction() { /* ... unsafe ... */ }
    public void m() {
        synchronized (owner()){ bareAction(); }
    }
}
```

- Parts don’t deadlock when invoking each other’s methods
- Parts must be aware that they are contained

External Containment Locking

- Can require callers to provide the lock

```
class Client {
  void f(Part p) {
      synchronized (p.owner()) {
          p.bareAction();
      }
   }
}
```

Subclassing Unsafe Code

- If a class is not thread-safe, can create a subclass that adds synchronization

```
class SafeClass extends UnSafeClass{
    synchronized void foo() {
      super.foo();
    }
}
```

  – and instantiate it instead

- Can also use unrelated wrapper classes and delegation