CS 351
Design of Large Programs
Concurrency Control

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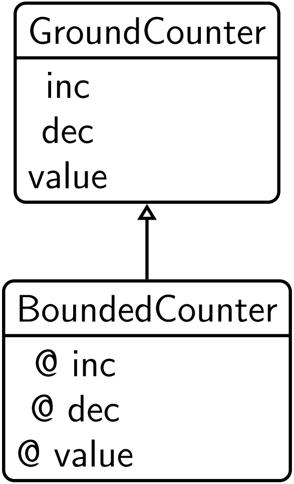
Concurrency Control Definition

- Layering of synchronization and control policies over base mechanisms
- Key assumption: ground classes have been designed to be amenable to the desired forms of control
- Strategies
  - adding policy control in subclasses
  - controlling delegated actions
  - representing messages as objects

Adding Synchronization Via Subclassing

- Ground level class
  - provides non-public methods
  - enforces no invariants
- Subclass
  - implements the synchronization policy, e.g.,
    - atomic updates
    - bounded counter
  - delegates actions to ground methods



Bounded Counter Code

```
public class GroundCounter {
  protected long count;

  protected GroundCounter(long c) {
    count = c;
  }

  protected long value() { return count; }

  protected void inc() {
    ++count;
  }

  protected void dec() {
    --count;
  }
}
```

Bounded Counter Code

```
public class BoundedCounter extends GroundCounter {
  private final long MIN, MAX;

  public BoundedCounter(final long MIN, final long MAX) {
    super(MIN);
    this.MIN = MIN;
    this.MAX = MAX;
  }

  public synchronized long value() { return super.value(); }

  public synchronized void inc() {
    while (value() >= MAX) {
      try { wait(); } catch(InterruptedException e) {};
    }
    super.inc();
    notifyAll();
  }

  public synchronized void dec() {
    while (value() <= MIN) {
      try { wait(); } catch(InterruptedException e) {};
    }
    super.dec();
    notifyAll();
  }
}
```

Anomalies to be Avoided

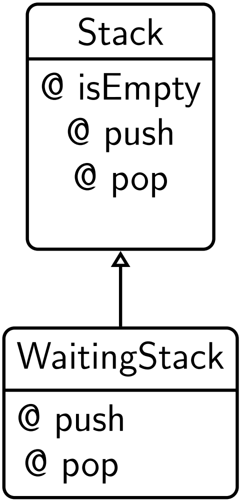
If all relevant variables and methods are declared `protected` the subclass can generally implement the desired policy

Frequent problems

- failing to track all conditions on which the subclass depends
- differences in state representation
- immutable variable in the superclass is being modified
- introducing waits for which the subclass has not matching notifications
- extensions which require a transition from `notify` to `notifyAll`

Layering Guards

- Ground level class
  - ensures atomicity
  - generates exception on empty stack
  - forces a busy wait solution in a concurrent setting
- Subclass
  - eliminates the exception generation
  - adopts a wait/notify protocol
  - delegates select actions to ground methods



Waiting Stack Code

```
public class Stack {
  public synchronized boolean isEmpty() { /* ... */ }
  public synchronized void push(Object x) { /* ... */ }
  public synchronized Object pop() throws StackEmptyException {
    if (isEmpty()) {
      throw new StackEmptyException();
    } else {
      // ...
    }
  }
}
```

```
public class WaitingStack extends Stack {
  public synchronized void push(Object x) {
    super.push(x);
    notifyAll();
  }

  public synchronized Object pop() throws StackEmptyException {
    while(isEmpty()) {
      try { wait(); } catch (InterruptedException e) {}
    }
    return super.pop();
  }
}
```

Conflict Sets et al

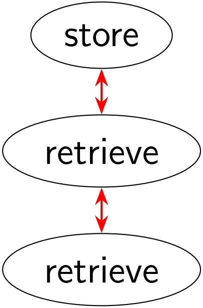
- Design paradigm
  - track the superclass state through the introduction of auxiliary variables
  - block method calls based on the current abstract state of the superclass
- Sample formalizations
  - conflict set
  - conflict graph
  - finite set control

Illustration: Inventory Control

Conflict Set

(store, retrieve)
(retrieve, retrieve)

Conflict Graph



Finite State control

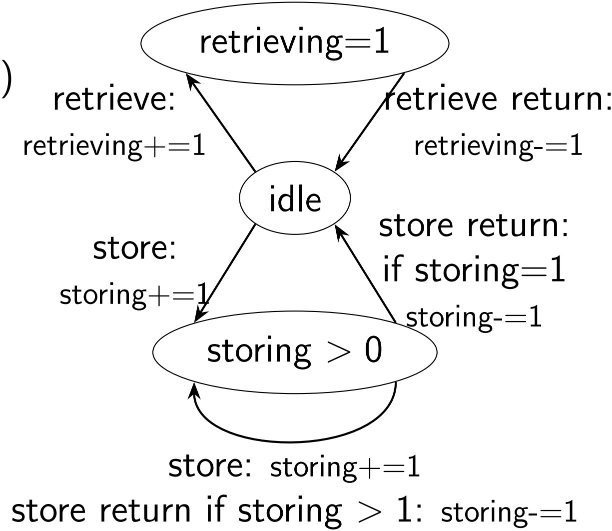


Illustration: Inventory Code

```
public class Inventory extends GroundInventory {
  protected int storing = 0;
  protected int retrieving= 0;

  public void store(String desc, Object item,
                    String supplier) {
    synchronized (this) {
      while (retrieving != 0) {
        try { wait(); } catch (InterruptedException e) {}
      }
      ++storing;
    }

    super.store(desc, item, supplier);

    synchronized (this) {
      if (--storing == 0) {
        notifyAll();
      }
    }
  }
```

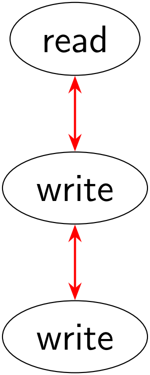
Illustration: Inventory Code

```
public void retrieve(String desc, Object item,
                     String supplier) {
  synchronized (this) {
    while (storing != 0) {
      try { wait(); } catch (InterruptedException e) {
    }
    ++retrieving;
  }

  super.retrieve(desc, item, supplier);

  synchronized (this) {
    if (--retrieving == 0) {
      notifyAll();
    }
  }
}
```

Readers and Writers: A Common Design Pattern

- A simple conflict graph
- Readily ensured safety
- Major variations when it comes to liveness and lack of starvation

Conflict Graph



General Pattern

- Track the number of waiting and active readers and writers
- Bracket the read/write operations with before/after control code
- Same design accommodates a wide range of policies

General Pattern Code

```
public abstract class ReadWrite {
  protected int activeReaders = 0;
  protected int activeWriters = 0;
  protected int waitingReaders = 0;
  protected int waitingWriters = 0;

  protected abstract void doRead();
  protected abstract void doWrite();

  public void read() {
    beforeRead();
    doRead();
    afterRead();
  }

  public void write() {
    beforeWrite();
    doWrite();
    afterWrite();
  }
```

Control Code: before/afterRead

```
protected synchronized void beforeRead() {
  ++waitingReaders;
  while (!allowReader()) {
    try { wait(); } catch (InterruptedException e) {}
  }
  --waitingReaders;
  ++activeReaders;
}

protected synchronized void afterRead() {
  --activeReaders;
  notifyAll();
}
```

Control Code: before/afterWrite

```
protected synchronized void beforeWrite() {
  ++waitingWriters;
  while (!allowWriter()) {
    try { wait(); } catch (InterruptedException e) {}
  }
  --waitingWriters;
  ++activeWriters;
}

protected synchronized void afterWrite() {
  --activeWriters;
  notifyAll();
}
```

Policy: Reading Priority

- Direct enforcement of the conflict set rules
  - readers can read unless a writer is writing
  - a writer can start writing if no other thread is reading or writing
- Writers can be starved if readers continue to use the resource

```
protected boolean allowReader() {
  return activeWriters == 0;
}

protected boolean allowWriter() {
  return activeReaders == 0 && activeWriters == 0;
}
```

Policy: Reading Preemption

- Writer starvation is prevented by blocking new reading threads once a writer is waiting
- Readers can be kept out by multiple writers waiting in line

```
protected boolean allowReader() {
  return waitingWriters == 0 && activeWriters == 0;
}

protected boolean allowWriter() {
  return activeReaders == 0 && activeWriters == 0;
}
```

Policy: Turn Taking

- If both readers and writers are waiting, alternate between readers and writers
- Still, there is no guarantee that no readers or writers are blocked forever

Policy: Turn Taking

```
private boolean canWrite;

public synchronized void afterRead() {
  canWrite = true; // ...previous afterRead code...
}
public synchronized void afterWrite() {
  canWrite = false; // ...previous afterWrite code...
}

protected boolean allowReader() {
  if (waitingWriters > 0 && waitingReaders > 0) {
    return !canWrite && activeWriters == 0;
  }
  return waitingWriters == 0 && activeWriters == 0;
}

protected boolean allowWriter() {
  if (waitingWriters > 0 && waitingReaders > 0) {
    return canWrite && activeWriters == 0;
  }
  return activeReaders == 0 && activeWriters == 0;
}
```

Policy: Custom Scheduler

- Each reader/writer makes a request and gets a ticket number
- Each request and its type (read/write) is placed in a queue according with some policy that optimizes throughput and ensures fairness
- A writer starts working when its ticket is first in the queue
- A reader starts working when its ticket is part of a sequence of read requests at the front of the queue
- Tickets are returned upon completion of the operation
- Ticket counter is reset when no tickets are out

Basic Adapter Concept

- An *adapter* is a specialized wrapper that offers a new interface based on an existing class
- The main advantages are
  - flexibility
    - a range of services based on an existing class
    - dynamic changes of the base class in use
  - reduced coding effort
  - reuse of legacy code
- Adapters do not have access to protected fields and methods
  - this is distinct from subclassing

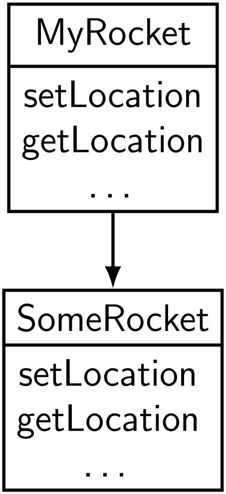
Example: Rocket

- Internal state
  - location (point in 3D space, meters)
  - velocity (3D vector, meters/sec)
  - flight time (seconds)
- Methods
  - read/update location
  - read/update velocity
  - increment flight time

Delegation

The interface is the same as that of the ground class

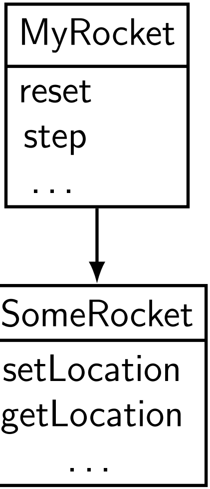
- actions are simply redirected
- returned values are passed up
- What is the gain?
  - flexibility



Refactoring

Different methods are provided and coded in terms of the ground class

```
public void reset() {
  setFlightTime(0);
  setLocation(new PosPoint());
  setVelocity(new VelVec());
}

public void step(VelVec vel) {
  flightTime++;
  velocity = vel;
  location.add(velocity);
}
```



Superposition

Superposition – a process by which variables are introduced to monitor the state of the ground class

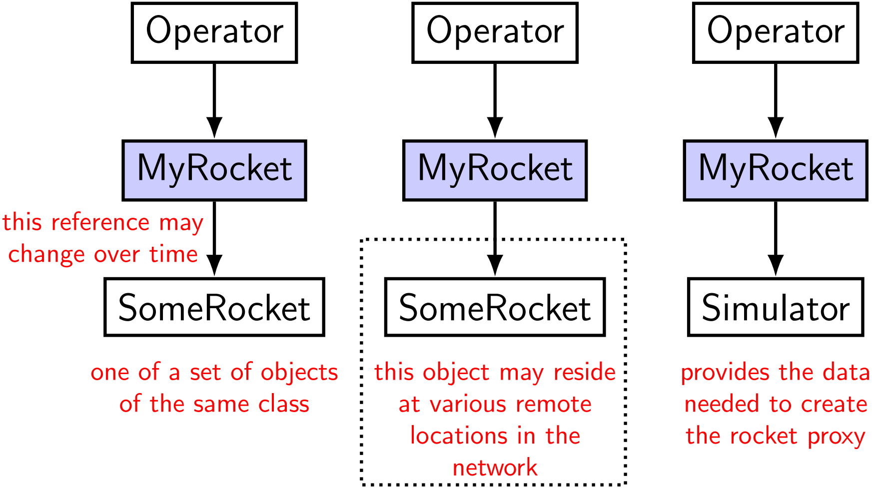
- to extend functionality without actually affecting the state
- to facilitate reasoning about the computation

```
public void step(VelVec vel) {
  flightTime++;
  velocity = vel;
  location.add(velocity);
  if(velocity.compare(MAX_SAFE_VEL) > 0) {
    unsafeCount++;
  }
}
```

Proxy – A Useful Design Pattern

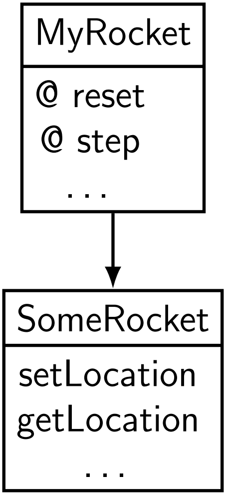
- Proxy – an object that stands in place of another
  - displays an appropriate veneer
  - delegates all actions
- The original object may be a
  - concrete object – present in the system and having the same interface
  - abstract object – the result of refactoring

Illustration: Proxy Examples



Synchronized Adapters

- In the presence of concurrency, objects designed to function in a single threaded environment need to be protected
- The wrapper can provide the needed synchronization (when the ground object is private)



Synchronized Adapters with Access Control

- An adapter can also introduce blocking of threads in a way that is sensitive to the state of the ground object
- Illustration: block thread waiting for a specific target velocity to be reached and release it when
    - a reset has been issued (return false)
    - the target velocity has been reached or exceeded (return true)

Synchronized Adapters with Access Control

```java
public synchronized void step(VelVec vel) {
  // ...
  notifyAll();
}

public synchronized void reset() {
  // ...
  notifyAll();
}

public synchronized boolean targetVelocity(VelVec vel) {
  // mag returns integer magnitude of vector
  while (mag(velocity) != 0 && mag(velocity) < mag(vel)) {
    try { wait(); } catch (InterruptedException e) { }
  }
  if(mag(velocity) == 0) return false; // reset issued
  else return true; // target velocity reached
}
```

Synchronized Adapters with Access Control

```
public synchronized void step(VelVec vel) {
  // ...
  notifyAll();
}

public synchronized void reset() {
  // ...
  notifyAll();
}

public synchronized boolean targetVelocity(VelVec vel) {
  // mag returns integer magnitude of vector
  while (mag(velocity) != 0 && mag(velocity) < mag(vel)) {
    try { wait(); } catch (InterruptedException e) { }
  }
  if(mag(velocity) == 0) return false; // reset issued
  else return true; // target velocity reached
}
```

Does this work as expected?

What's wrong?

When `notifyAll` is invoked in a synchronized method M_1:

1. An arbitrarily chosen waiting thread T is removed from the waiting set
2. T blocks while re-obtaining the lock
   - T blocks AT LEAST until M_1 releases the lock – if another synchronized method M_2 acquires the lock first, T continues to block!
3. T resumes from the point of wait

A thread in `step` may change shared state before T resumes from the wait in `targetVelocity`!

Synchronized Adapters with Access Control

```java
public synchronized void step(VelVec vel) {
  // ...
  notifyAll();
}

public synchronized void reset() {
  // ...
  tracking = false;
  notifyAll();
}

public synchronized boolean targetVelocity(VelVec vel) {
  tracking = true; // remains true unless reset
  while (tracking && mag(velocity) < mag(vel)) {
    try { wait(); } catch (InterruptedException e) { }
  }
  if(!tracking) return false;
  tracking = false;
  return true;
}
```

Extending Atomicity

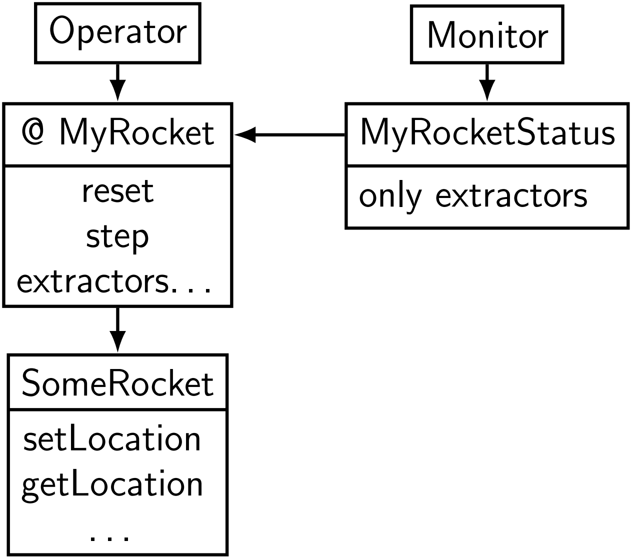
- An adapter can augment existing methods with additional functionality while making the entire operation atomic
- Illustration: augment the step method to include a logging action

```
public synchronized void step(VelVec vel) {
  flightTime++;
  velocity = vel;
  location.add(velocity);
  Log.addEntry(flightTime, location);
}

class Log {
  public static synchronized void addEntry(int time,
                                            PosPoint loc) {
    // store/print entry...
  }
}
```

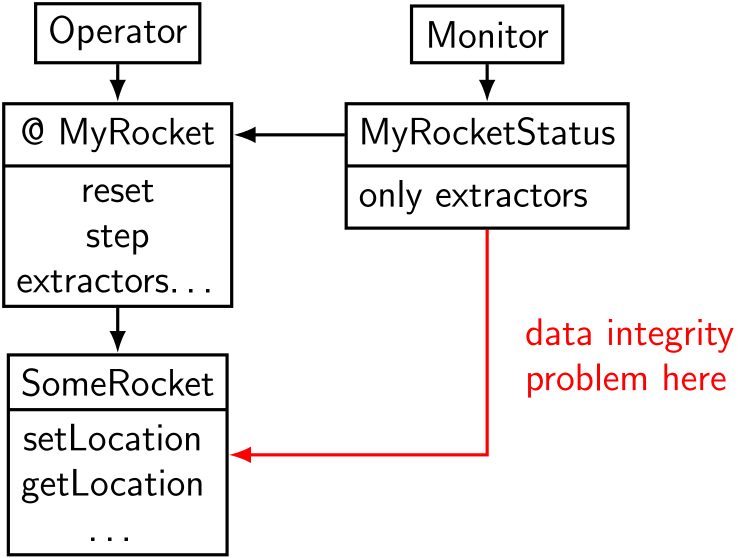
Read Only Adapters

- It is often the case that data needs to be protected against unauthorized modification
- A read-only wrapper gives full access to the object data without the risk of being modified

Read Only Adapters



Read Only Adapters



Programming Concerns

- The methods of the immutable object should be declared final
- The base object B should not be leaked to users of the immutable object X

```
public final class MyRocketStatus {
  private final int flightTime;
  private final PosPoint location;
  public MyRocketStatus(MyRocket rocket) {
    flightTime = rocket.getFlightTime();
    location = rocket.getLocation();
  }
  public int getFlightTime() { return flightTime; }
  public PosPoint getLocation() { return location; }
}

public class Log {
  public static synchronized void addEntry(MyRocketStatus stat) {
    // store/print status...
  }
}
```

Acceptor

- receives requests in the form of messages
- interprets the messages within the context of a system
- by considering pending requests
- by analyzing the program state
- by enforcing execution rules
- initiates actions performed by underlying ground objects

```
public interface Acceptor {
  public void accept(MessageType m);
}
```

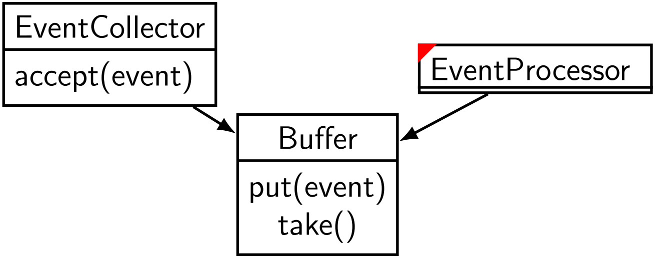
Design Strategies

- An acceptor may
  - employ its own private ground objects
  - delegate actions to ground objects
  - employ a dispatch table
  - generate a thread for each response
  - maintain state information
  - schedule multiple agents
  - maintain history logs
  - filter and modify messages
- Acceptors may work in tandem

Event Loops

Key concepts and components

- event – the class of messages accepted
- buffer – holder of messages to be processed
- collector – recipient of events and known to event producers
- processor – event dispatcher knowing the ground objects



Sample Code Using Bounded Buffer

```
public class EventCollector implements Acceptor {
  protected BlockingQueue<Event> buff;

  public EventCollector() {
    buff = new ArrayBlockingQueue<>(100);
    new EventProcessor(buff);
  }

  public synchronized void accept(Event e) {
    buff.put(e);
  }
}
```

Sample Code Using Bounded Buffer

```
public class EventProcessor implements Runnable, Acceptor {
  protected BlockingQueue<Event> buff;
  public EventProcessor(BlockingQueue<Event> b) {
    buff = b;
    new Thread(this).start();
  }

  public void run() {
    while (true) {
      accept(buff.take());
    }
  }

  public void accept(Event e) {
    switch (e.eventCode()) {
      // dispatch...
    }
  }
}
```