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# Concurrent Programming in Java: Design Principles and Patterns

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# Concurrent Programming in Java

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# Topics

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## Concurrency

Models, design forces, Java

## Designing objects for concurrency

Immutability, locking, state dependence, containment, splitting

## Introducing concurrency into applications

Autonomous loops, oneway messages, interactive messages, cancellation

## Concurrent application architectures

Flow, parallelism, layering

## Libraries

Using, building, and documenting reusable concurrent classes

# About These Slides ...

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Some slides are based on joint presentations with David Holmes, Macquarie University, Sydney Australia.

More extensive coverage of most topics can be found in the book

*Concurrent Programming in Java*, Addison-Wesley

and the online supplement

<http://gee.cs.oswego.edu/dl/cpj>

The printed slides contain much more material than can be covered in a tutorial. They include extra background, examples, and extensions. They are not always in presentation order.

Java code examples often omit qualifiers, imports, etc for space reasons. Full versions of most examples are available from the CPJ online supplement.

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# Concurrency

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## Why?

### Availability

Minimize response lag, maximize throughput

### Modelling

Simulating autonomous objects, animation

### Parallelism

Exploiting multiprocessors, overlapping I/O

### Protection

Isolating activities in threads

## Why Not?

### Complexity

Dealing with safety, liveness, composition

### Overhead

Higher resource usage

# Common Applications

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## I/O-bound tasks

- Concurrently access web pages, databases, sockets ...

## GUIs

- Concurrently handle events, screen updates

## Hosting foreign code

- Concurrently run applets, JavaBeans, ...

## Server Daemons

- Concurrently service multiple client requests

## Simulations

- Concurrently simulate multiple real objects

## Common examples

- Web browsers, web services, database servers, programming development tools, decision support tools

# Concurrent Programming

Concurrency is a *conceptual* property of software.

Concurrent programs *might or might not*:

<p><b>Operate across multiple CPUs</b> symmetric multiprocessor (SMPs), clusters, special-purpose architectures, ...</p> <p><b>Parallel</b> programming mainly deals with mapping software to multiple CPUs to improve performance.</p>	<p><b>Share access to resources</b> objects, memory, displays, file descriptors, sockets, ...</p> <p><b>Distributed</b> programming mainly deals with concurrent programs that do <i>NOT</i> share system resources.</p>
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**Concurrent programming** mainly deals with concepts and techniques that apply even if not parallel or distributed.

- Threads and related constructs run on any Java platform
- This tutorial doesn't dwell much on issues *specific* to parallelism and distribution.

# Concurrent Object-Oriented Programming

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Concurrency has always been a part of OOP (since Simula67)

- Not a factor in wide-scale embrace of OOP (late 1980s)
- Recent re-emergence, partly due to Java

Concurrent OO programming differs from ...

## Sequential OO programming

- Adds focus on safety and liveness
- But uses and extends common design patterns

## Single-threaded Event-based programming (as in GUIs)

- Adds potential for multiple events occurring at same time
- But uses and extends common messaging strategies

## Multithreaded systems programming

- Adds encapsulation, modularity
- But uses and extends efficient implementations



# Object Models

Models describe how to think about objects (formally or informally)

Common features

- Classes, state, references, methods, identity, constraints
- Encapsulation
  - Separation between the insides and outsides of objects

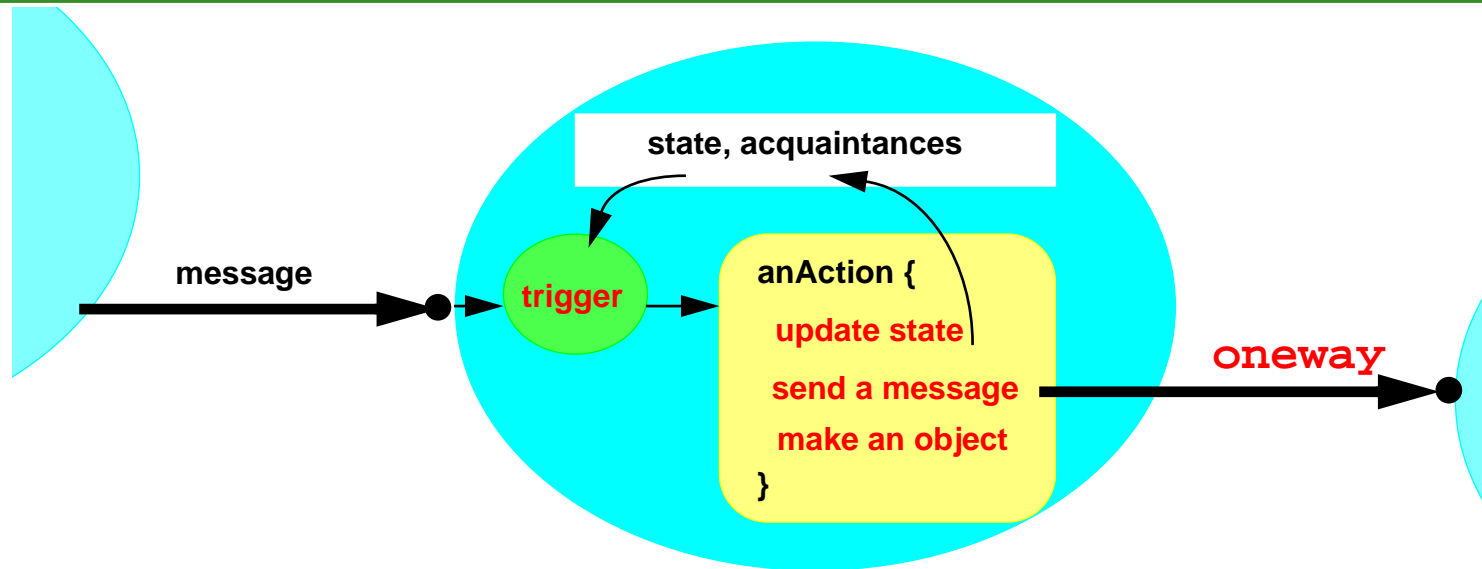
Four basic computational operations

- **Accept a message**
- **Update local state**
- **Send a message**
- **Create a new object**

Models differ in rules for these operations. Two main categories:

- **Active** vs **Passive**
- Concurrent models include features of both
- Lead to uniquely concurrent OO design patterns

# Active Object Models



Every object has a single thread of control (like a **process**) so can do only one thing at a time.

Most actions are **reactive** responses to messages from objects

- But actions may also be autonomous
- But need not act on message immediately upon receiving it

All messages are **oneway**. Other protocols can be layered on.

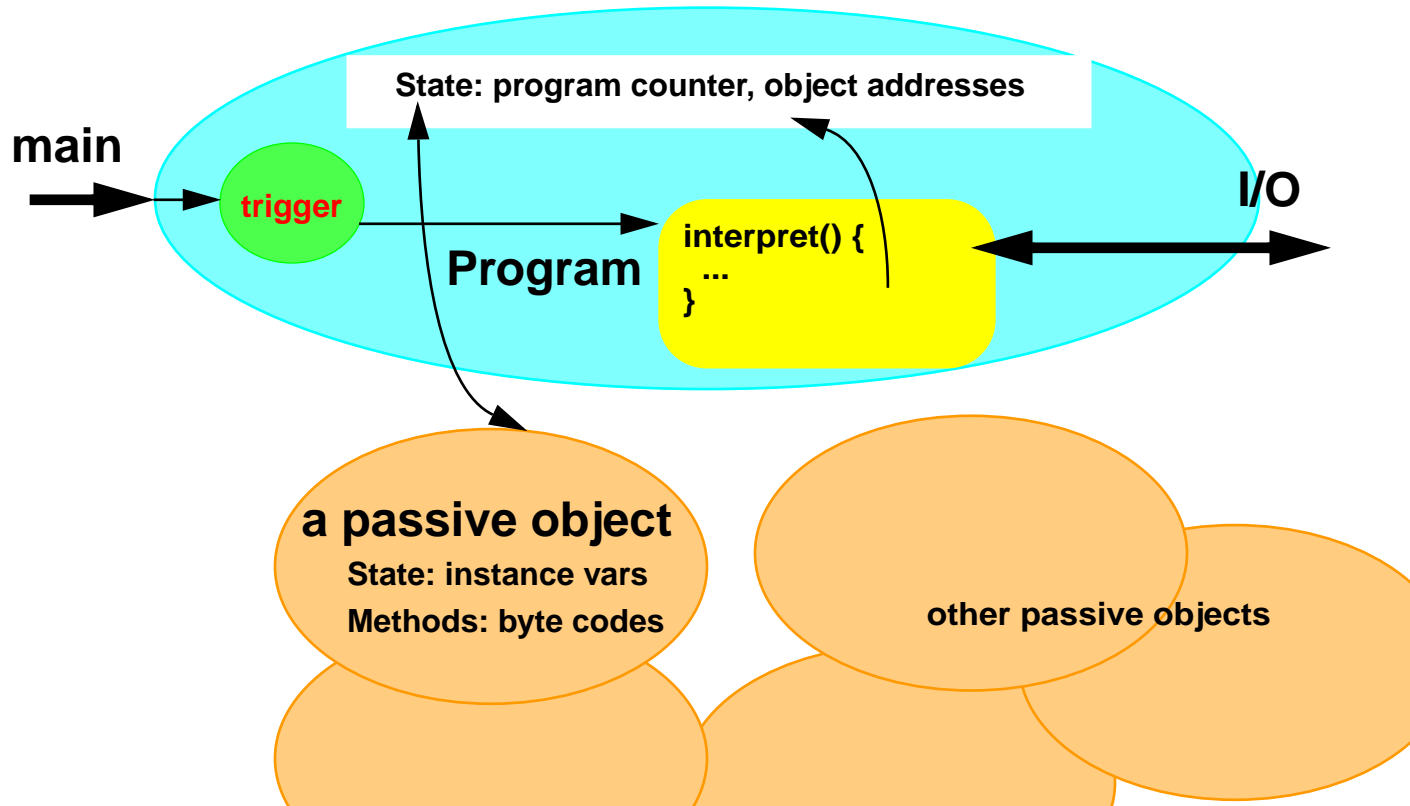
Many extensions and choices of detailed semantics

- Asynchronous vs synchronous messaging, queuing, pre-emption and internal concurrency, multicast channels, ...

# Passive Object Models

In sequential programs, only the single `Program` object is active

- Passive objects serve as the program's data



In single-threaded Java, `Program` is the JVM (interpreter)

- Sequentially simulates the objects comprising the program
- All internal communication based on procedure calls

# Concurrent Object Models

Mixtures of active and passive objects

Normally many fewer threads than passive objects

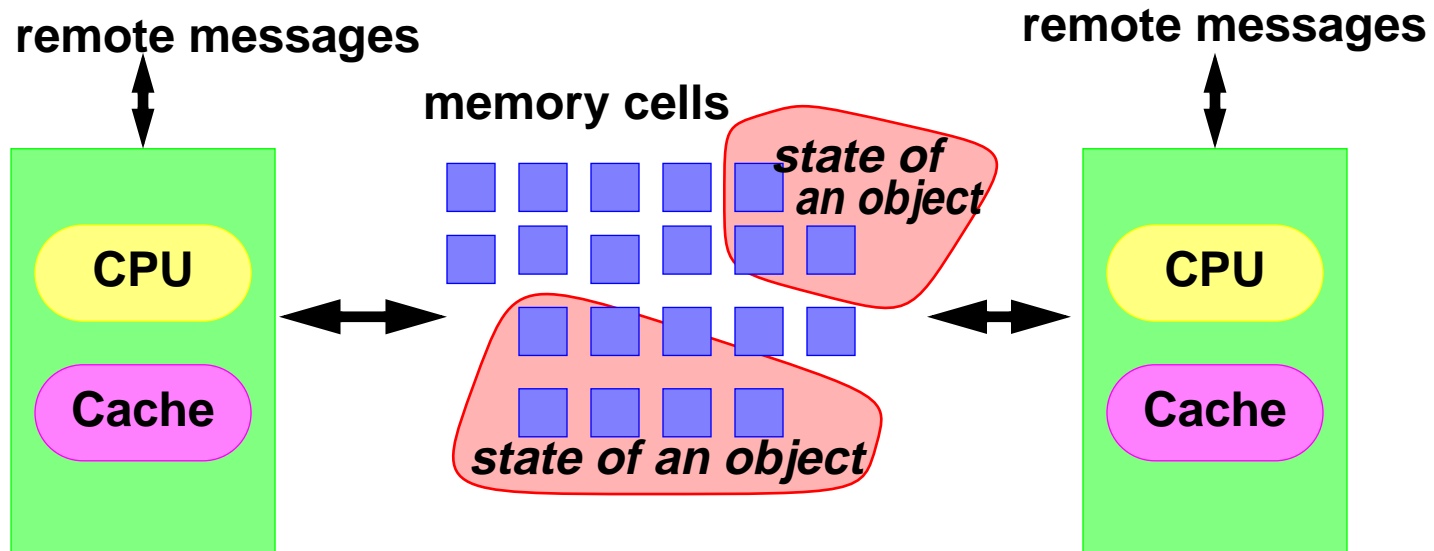
## Dumber Active Objects

- Can perform only one activity
  - in Java, `run()`
- Share most resources with other threads
- Require scheduling in order to coexist

## Smarter Passive Objects

- May simultaneously participate in multiple threads
- Protect themselves from engaging in conflicting activities
- Communicate with objects participating in other threads
- Initiate and control new threads

# Hardware Mappings



## Shared memory multiprocessing

- All objects visible in same (virtual) machine
- Can use procedural message passing
- Usually many more threads than CPUs

## Remote message passing

- Only access objects via Remote references or copying
- Must marshal (serialize) messages

**Mixed** models including database mediation (“three tier”)

# Vertical Objects

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Most OO systems and applications operate at multiple levels

Objects at each level manipulate, manage, and coordinate lower-level **ground** objects as **resources**.

Once considered an arcane systems design principle.  
But now applies to most applications

## Concurrency

- Thread-objects interpret passive objects

## Networking and Distribution

- Server-objects pass around resources

## Persistence and Databases

- Database-objects manage states of ground objects

## Component Frameworks

- Design tools build applications from JavaBeans, etc

## Layered Applications

- Design patterns based on reflection, interpretation, ...

# Design Forces

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Three main aspects of concurrent OO design

<b>Policies &amp; Protocol</b>	<b>Object structures</b>	<b>Coding techniques</b>
System-wide design rules	Design patterns, microarchitecture	Idioms, neat tricks, workarounds

Four main kinds of **forces** that must be addressed at each level

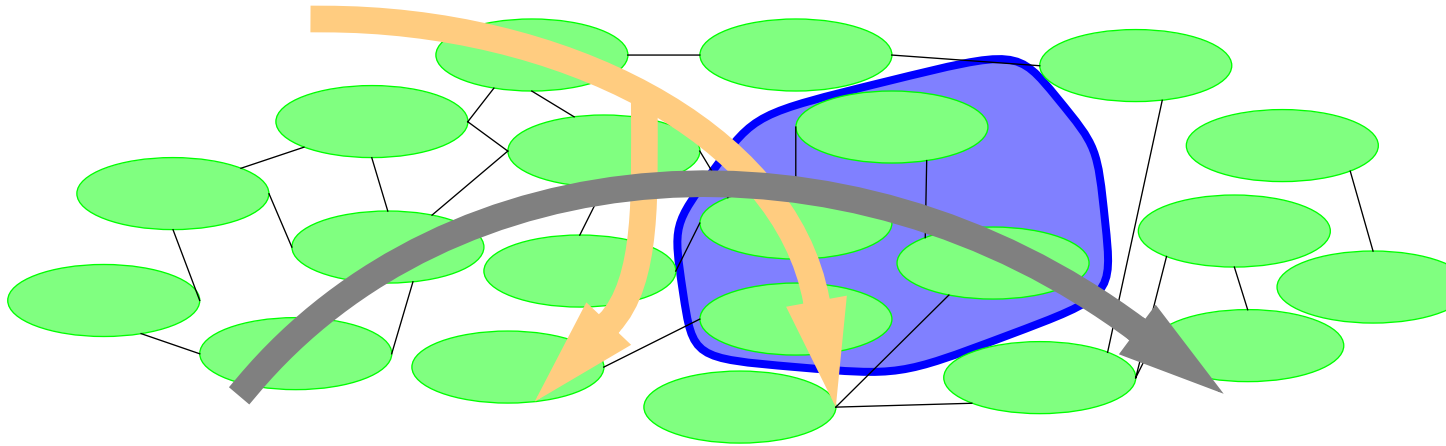
**Safety** — Integrity requirements

**Liveness** — Progress requirements

**Efficiency** — Performance requirements

**Reusability** — Compositional requirements

# Systems = Objects + Activities



## Objects

- ADTs, aggregate components, JavaBeans, monitors, business objects, remote RMI objects, subsystems, ...
- May be **grouped** according to structure, role, ...
- Usable across multiple activities — focus on **SAFETY**

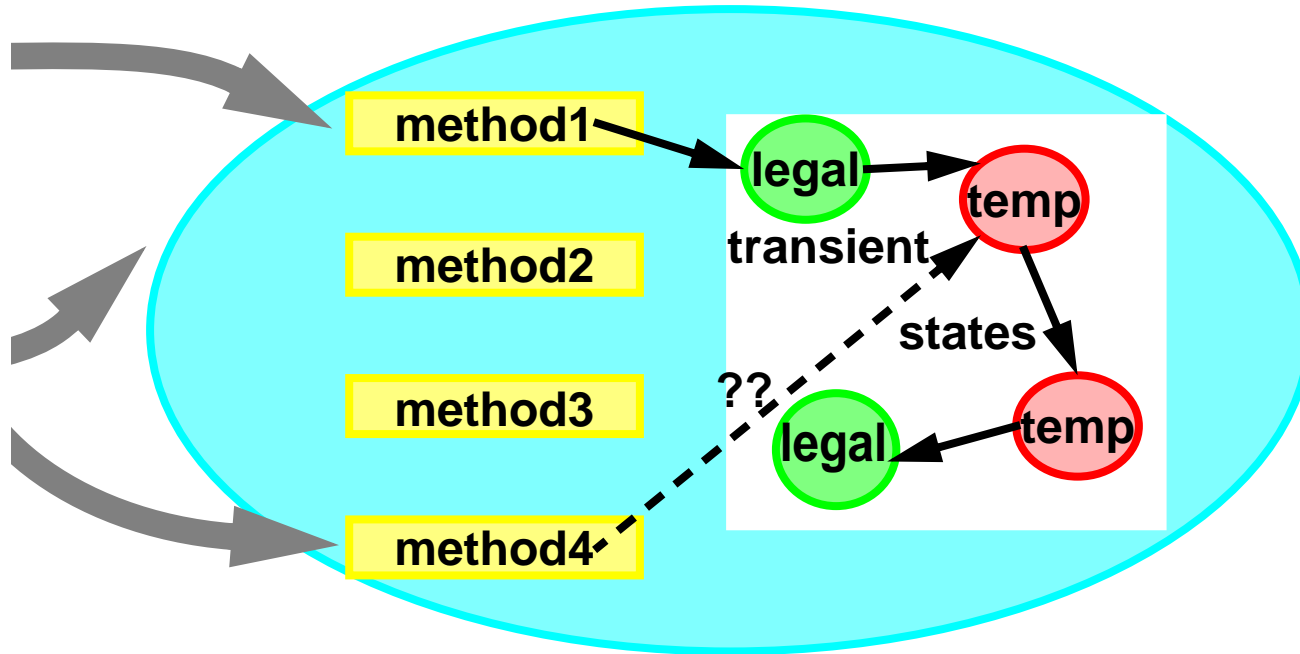
## Activities

- Messages, call chains, threads, sessions, scenarios, scripts, workflows, use cases, transactions, data flows, mobile computations, ...
- May be **grouped** according to origin, function, ...
- Span multiple objects — focus on **LIVENESS**



# Safe Objects

Perform method actions **only** when in consistent states



Usually impossible to predict consequences of actions attempted when objects are in temporarily inconsistent states

- Read/write and write/write conflicts
- Invariant failures
- Random-looking externally visible behavior

Must balance with liveness goals

- Clients want simultaneous access to services

# State Inconsistency Examples

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**A figure is drawn while it is in the midst of being moved**

- Could draw at new X-value, old Y-value
- Draws at location that figure never was at

**Withdraw from bank account while it is the midst of a transfer**

- Could overdraw account
- Could lose money

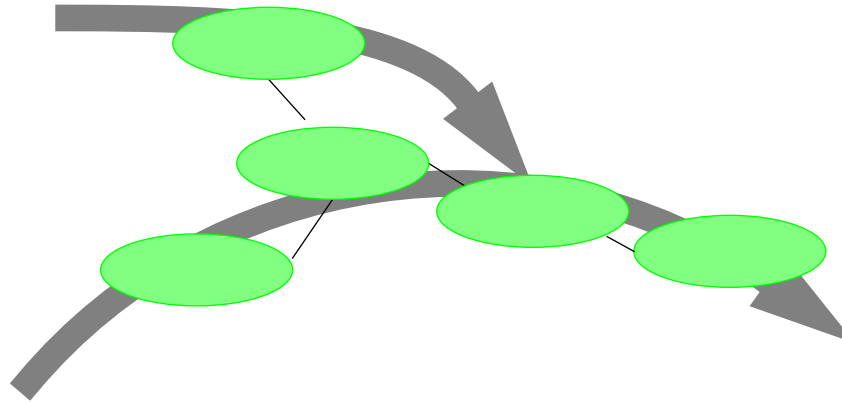
**A storage location is read in the midst of being written**

- Could result in reading some old bytes and some new bytes
- Normally, a nonsense value

# Live Activities

Every activity should progress toward completion

- Every called method should eventually execute



Related to efficiency

- Every called method should execute as soon as possible

An activity might not complete if

- An object does not accept a message
- A method blocks waiting for an event, message or condition that should be, but isn't produced by another activity
- Insufficient or unfairly scheduled resources
- Failures and errors of various kinds

# Design Dualities

Two extreme approaches:

## Safety-first

Ensure that each class is safe, then try to improve liveness as optimization measure.

- Characteristic of top-down OO Design
- Can result in slow, deadlock-prone code

## Liveness-first

Design live ground-level code, then try to layer on safety features such as locking and guarding.

- Characteristic of multithreaded systems programming
- Can result in buggy code full of races

Effective, practical, middle-out approaches combine these.

For example, iteratively improving initial designs to be safe and live across different contexts

# Guaranteeing Safety

**“Nothing bad ever happens”**

Concurrent safety is an extended sense of type safety

- Adds a temporal dimension
- Not completely enforceable by compilers

## Low-level view

- Bits are never misinterpreted
- Protect against storage conflicts on memory cells
  - read/write and
  - write/write conflicts

## High-level view

- Objects are accessible only when in consistent states
- Objects must maintain state and representation invariants
- Presents subclass obligations

# Guaranteeing Liveness

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**“Something eventually happens”**

## Availability

- Avoiding unnecessary blocking

## Progress

- Avoiding resource contention among activities
- Avoiding deadlocks and lockouts
- Avoiding unfair scheduling
- Designing for fault tolerance, convergence, stability

## Citizenship

- Minimizing computational demands of sets of activities

## Protection

- Avoiding contention with other programs
- Preventing denial of service attacks
- Preventing stoppage by external agents

# Concurrency and Efficiency

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Concurrency can be expensive

- Performance profiles may vary across platforms

## Resources

- Threads, Locks, Monitors

## Computation

- Construction, finalization overhead for resources
- Synchronization, context switching, scheduling overhead

## Communication

- Interaction overhead for threads mapped to different CPUs
- Caching and locality effects

## Algorithmic efficiency

- Cannot use some fast but unsafe sequential algorithms

## Paying for tunability and extensibility

- Reduces opportunities to optimize for special cases

# Concurrency and Reusability

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## Added Complexity

- More stringent correctness criteria than sequential code
  - Usually not automatically statically checkable
- Nondeterminism impedes debuggability, understandability

## Added Context Dependence (coupling)

- Components only safe/live when used in intended contexts
  - Need for documentation
- Can be difficult to extend via subclassing
  - “Inheritance anomalies”
- Can be difficult to compose
  - Clashes among concurrency control techniques



# Reuse and Design Policies

**Think locally. Act globally.**

Example design policy domains

<b>State-dependence</b>	<b>Service availability</b>	<b>Flow constraints</b>
What to do if a request logically cannot be performed	Constraints on concurrent access to methods	Establishing message directionality and layering rules

Combat complexity

- High-level design rules and architectural constraints avoid inconsistent case-by-case decisions
- Policy choices are rarely “optimal”, but often religiously believed in anyway.

Maintain openness

- Accommodate any component that obeys a given policy
- Fail but don't break if they do not obey policy

# Three Approaches to Reusability

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## Patterns

### Reusing design knowledge

- Record best practices, refine them to essences
- Analyze for safety, liveness, efficiency, extensibility, etc
- Provide recipes for construction

## Frameworks

### Reusing policies and protocols

- Create interfaces and classes that establish policy choices for a suite of applications
- Provide utilities and support classes
- Mainly use by creating application-dependent (sub)classes

## Libraries

### Reusing code

- Create interfaces that apply in many contexts
- Provide high-quality implementations
- Allow others to create alternative implementations

# Java Overview

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Core Java is a relatively small, boring object-oriented language

Main differences from Smalltalk:

- Static typing
- Support for primitive data types (`int`, `float`, etc)
- C-based syntax

Main differences from C++:

- Run-time safety via Virtual Machine
  - No insecure low-level operations
  - Garbage collection
- Entirely class-based: No globals
- Relative simplicity: No multiple inheritance, etc
- Object-based implementations of `Array`, `String`, `Class`, etc
- Large predefined class library: `AWT`, `Applets`, `net`, etc

# Java Features

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Java solves some software development problems

**Packaging:** Objects, classes, components, packages

**Portability:** Bytecodes, unicode, transports

**Extensibility:** Subclassing, interfaces, class loaders

**Safety:** Virtual machine, GC, verifiers

**Libraries:** `java.*` packages

**Ubiquity:** Run almost anywhere

But new challenges stem from new **aspects** of programming:

**Concurrency:** Threads, locks, ...

**Distribution:** RMI, CORBA, ...

**Persistence:** Serialization, JDBC, ...

**Security:** Security managers, Domains, ...

# Basic Java Constructs

<b>Classes</b>	Descriptions of object features
<b>Instance variables</b>	Fields representing object state
<b>Methods</b>	Encapsulated procedures
<b>Statics</b>	Per-class variables and methods
<b>Constructors</b>	Operations performed upon object creation
<b>Interfaces</b>	Sets of methods implemented by any class
<b>Subclasses</b>	Single inheritance from class <code>Object</code>
<b>Inner classes</b>	Classes within other classes and methods
<b>Packages</b>	Namespaces for organizing sets of classes
<b>Visibility control</b>	<code>private</code> , <code>public</code> , <code>protected</code> , per-package
<b>Qualifiers</b>	Semantic control: <code>final</code> , <code>abstract</code> , etc
<b>Statements</b>	Nearly the same as in C/C++
<b>Exceptions</b>	Throw/catch control upon failure
<b>Primitive types</b>	<code>byte</code> , <code>short</code> , <code>int</code> , <code>long</code> , <code>float</code> , <code>char</code> , <code>boolean</code>

# Particle Applet

```
import java.awt.*;
import java.applet.*;
public class ParticleApplet extends Applet {
    public void init() {
        add(new ParticleCanvas(10));
    }
}

class ParticleCanvas extends Canvas {
    Particle[] particles;
    ParticleCanvas(int nparticles) {
        setSize(new Dimension(100, 100));
        particles = new Particle[nparticles];
        for (int i = 0; i < particles.length; ++i) {
            particles[i] = new Particle(this);
            new Thread(particles[i]).start();
        }
    }

    public void paint(Graphics g) {
        for (int i = 0; i < particles.length; ++i)
            particles[i].draw(g);
    }
} // (needs lots of embellishing to look nice)
```

# Particle Class

```
public class Particle implements Runnable {
    private int x = 0, y = 0;
    private Canvas canvas;
    public Particle(Canvas host) { canvas = host; }

    synchronized void moveRandomly() {
        x += (int) ((Math.random() - 0.5) * 5);
        y += (int) ((Math.random() - 0.5) * 5);
    }

    public void draw(Graphics g) {
        int lx, ly;
        synchronized (this) { lx = x; ly = y; }
        g.drawRect(lx, ly, 10, 10);
    }

    public void run() {
        for(;;) {
            moveRandomly();
            canvas.repaint();
            try { Thread.sleep((int)(Math.random()*10)); }
            catch (InterruptedException e) { return; }
        }
    }
}
```

# Java Concurrency Support

**Thread** class represents state of an independent activity

- Methods to start, sleep, etc
- Very weak guarantees about control and scheduling
- Each Thread is a member of a **ThreadGroup** that is used for access control and bookkeeping
- Code executed in threads defined in classes implementing:

```
interface Runnable { public void run(); }
```

**synchronized** methods and blocks control atomicity via locks

- Java automates local read/write atomicity of storage and access of values of type byte, char, short, int, float, and Object references, but not double and long
- **synchronized** statement also ensures cache flush/reload
- **volatile** keyword controls per-variable flush/reload

**Monitor** methods in class Object control suspension and resumption:

- **wait(), wait(ms), notify(), notifyAll()**



# Class Thread

## Constructors

**Thread(Runnable r)** constructs so `run()` calls `r.run()`

— Other versions allow names, ThreadGroup placement

## Principal methods

<code>start()</code>	activates <code>run()</code> then returns to caller
<code>isAlive()</code>	returns true if started but not stopped
<code>join()</code>	waits for termination (optional timeout)
<code>interrupt()</code>	breaks out of wait, sleep, or join
<code>isInterrupted()</code>	returns interruption state
<code>getPriority()</code>	returns current scheduling priority
<code>setPriority(int priorityFromONEtoTEN)</code>	sets it

## Static methods that can only be applied to current thread

<code>currentThread()</code>	reveals current thread
<code>sleep(ms)</code>	suspends for (at least) <code>ms</code> milliseconds
<code>interrupted()</code>	returns and clears interruption status

# Designing Objects for Concurrency

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Patterns for safely representing and managing state

## Immutability

- Avoiding interference by avoiding change

## Locking

- Guaranteeing exclusive access

## State dependence

- What to do when you can't do anything

## Containment

- Hiding internal objects

## Splitting

- Separating independent aspects of objects and locks

# Immutability

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## Synopsis

- Avoid interference by avoiding change
- Immutable objects never change state
- Actions on immutable objects are always safe and live

## Applications

- Objects representing values
  - Closed Abstract Data Types
  - Objects maintaining state representations for others
  - Whenever object identity does not matter
- Objects providing stateless services
- Pure functional programming style

# Stateless Service Objects

```
class StatelessAdder {  
    int addOne(int i) { return i + 1; }  
    int addTwo(int i) { return i + 2; }  
}
```

There are no special concurrency concerns:

- There is no per-instance state
  - No storage conflicts
- No representational invariants
  - No invariant failures
- Any number of instances of `addOne` and/or `addTwo` can safely execute at the same time. There is no need to preclude this.
  - No liveness problems
- The methods do not interact with any other objects.
  - No concurrent protocol design

# Freezing State upon Construction

```
class ImmutableAdder {  
    private final int offset_; // blank final  
  
    ImmutableAdder(int x) { offset_ = x; }  
  
    int add(int i) { return i + offset_; }  
}
```

Still no safety or liveness concerns

Java (blank) `final`s enforce most senses of immutability

- Don't cover cases where objects eventually **latch** into values that they never change from

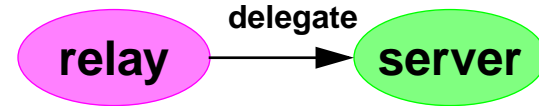
Immutability is often used for closed Abstract Data Types in Java

- `java.lang.String`
- `java.lang.Integer`
- `java.awt.Color`
- But **not** `java.awt.Point` or other AWT graphical representation classes (A design error?)

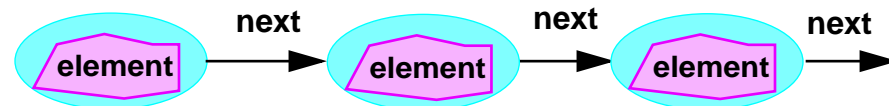
# Applications of Immutability

## Immutable references to mutable objects

```
class Relay {
    private final Server delegate;
    Relay(Server s) { delegate = s; }
    void serve()      { delegate.serve(); }
}
```



## Partial immutability

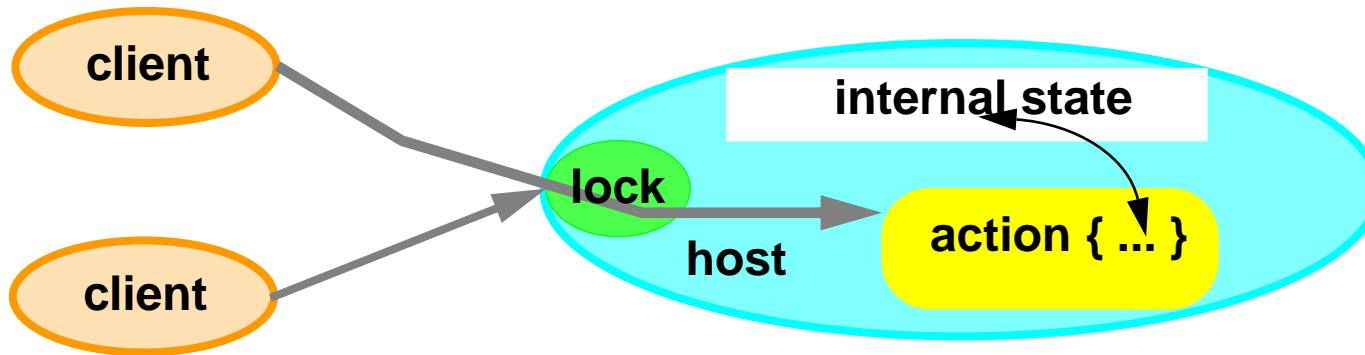


Methods dealing with immutable aspects of state do not require locking

```
class FixedList { // cells with fixed successors
    private final FixedList next; // immutable
    FixedList(FixedList nxt)      { next = nxt; }
    FixedList successor()          { return next; }

    private Object elem = null; // mutable
    synchronized Object get()     { return elem; }
    synchronized void set(Object x) { elem = x; }
}
```

# Locking



Locking is a simple **message accept** mechanism

- Acquire object lock on entry to method, release on return

Precludes storage conflicts and invariant failures

- Can be used to guarantee atomicity of methods

Introduces potential liveness failures

- Deadlock, lockouts

Applications

- Fully synchronized (atomic) objects
- Most other reusable objects with mutable state

# Synchronized Method Example

```
class Location {  
  
    private double x_, y_;  
  
    Location(double x, double y) { x_ = x; y_ = y; }  
  
    synchronized double x() { return x_; }  
  
    double y() {  
        synchronized (this) {  
            return y_;  
        }  
    }  
  
    synchronized void moveBy(double dx, double dy) {  
        x_ += dx;  
        y_ += dy;  
    }  
}
```



# Java Locks

## Every Java Object possesses one lock

- Manipulated only via `synchronized` keyword
- Class objects contain a lock used to protect `statics`
- Scalars like `int` are not Objects so can only be locked via their enclosing objects

`Synchronized` can be either method or block qualifier

`synchronized void f() { body; }` is equivalent to:

```
void f() { synchronized(this) { body; } }
```

Java locks are **reentrant**

- A thread hitting `synchronized` passes if the lock is free or it already possesses the lock, else waits
- Released after passing as many `}`'s as `{`'s for the lock — cannot forget to release lock

`Synchronized` also has the side-effect of clearing locally **cached** values and forcing reloads from main storage

# Storage Conflicts

```
class Even {
    int n = 0;
    public int next(){ // POST?: next is always even
        ++n;
        ++n;
        return n;
    }
}
```

Postcondition may fail due to storage conflicts. For example, one possible execution trace when *n* starts off at 0 is:

Thread 1	Thread 2
read 0	
write 1	
	read 1
	write 2
read 2	read 2
	write 3
	return 3
write 3	
return 3	

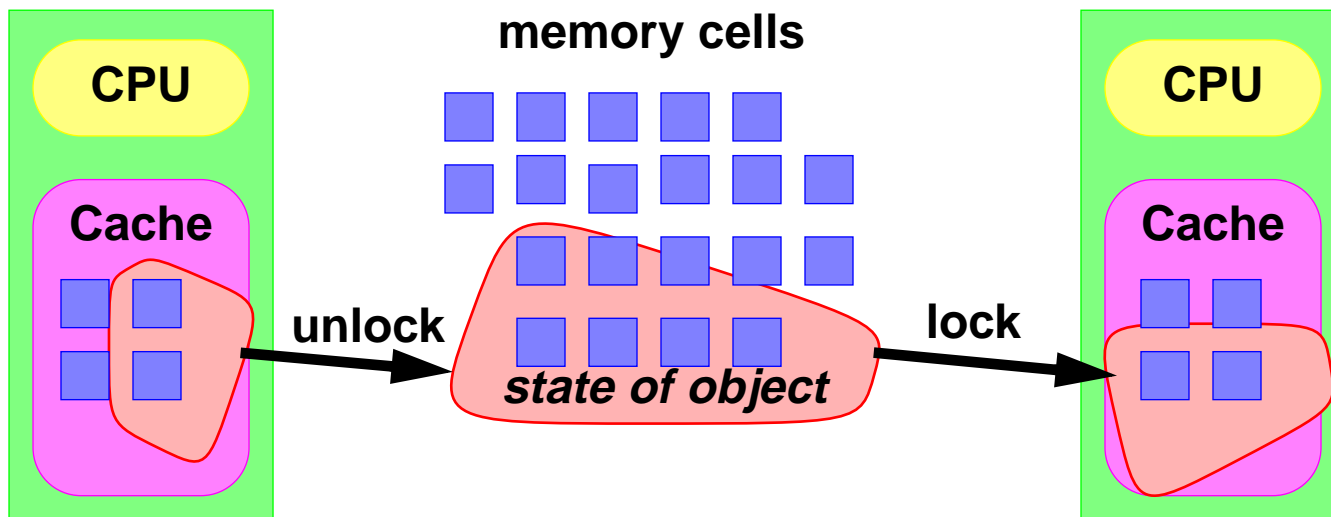
Declaring `next` method as `synchronized` precludes conflicting traces, as long as all other methods accessing *n* are also `synchronized`

# Locks and Caching

Locking generates messages between threads and memory

Lock acquisition forces reads from memory to thread cache

Lock release forces writes of cached updates to memory



Without locking, there are **NO** promises about if and when caches will be flushed or reloaded

- Can lead to unsafe execution
- Can lead to nonsensical execution

# Memory Anomalies

Should **acquire lock before use** of any field of any object, and **release after update**

If not, the following are possible:

- Seeing **stale** values that do not reflect recent updates
- Seeing **inconsistent states** due to out-of-order writes during flushes from thread caches
- Seeing **incompletely initialized** new objects

Can declare `volatile` fields to force per-variable load/flush.

- Has very limited utility.
- `volatile` never usefully applies to reference variables
  - The referenced object is not necessarily loaded/flushed, just the reference itself.
  - Instead, should use synchronization-based constructions

# Fully Synchronized Objects

Objects of classes in which **all** methods are synchronized

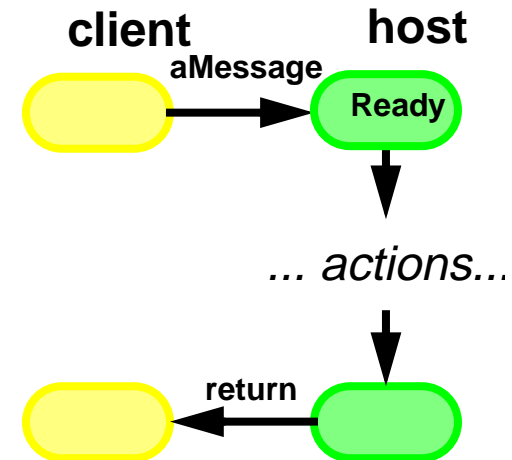
- Always safe, but not always live or efficient

Only process one request at a time

- All methods are locally sequential

Accept new messages only when **ready**

- No other thread holds lock
- Not engaged in another activity
- But methods may make self-calls to other methods during same activity without blocking (due to reentrancy)



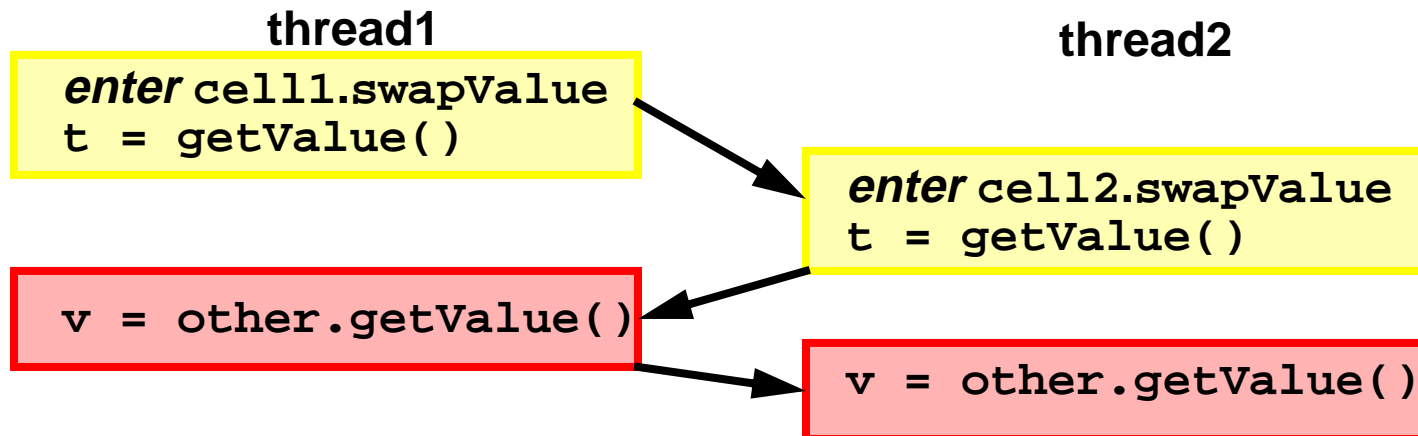
Constraints

- **All** methods must be synchronized: Java unsynchronized methods execute even when lock held.
- No public variables or other encapsulation violations
- Methods must not suspend or infinitely loop
- Re-establish consistent state after exceptions

# Deadlock

```
class Cell {  
    private long value_;  
  
    synchronized long getValue() { return value_;}  
    synchronized void setValue(long v) {value_ = v;}  
  
    synchronized void swapValue(Cell other) {  
        long t = getValue();  
        long v = other.getValue();  
        setValue(v);  
        other.setValue(t);  
    }  
}
```

SwapValue is a **transactional** method. Can deadlock in trace:



# Lock Precedence

Can prevent deadlock in transactional methods via **resource-ordering** based on Java hash codes (among other solutions)

```
class Cell {
    long value;

    void swapValue(Cell other) {
        if (other == this) return; // alias check

        Cell fst = this; // order via hash codes
        Cell snd = other;
        if (fst.hashCode() > snd.hashCode()) {
            fst = other; snd = this;
        }
        synchronized(fst) {
            synchronized (snd) {
                long t = fst.value;
                fst.value = snd.value;
                snd.value = t;
            }
        }
    }
}
```

# Holding Locks

```
class Server {  
    double state;  
    Helper helper;  
    public synchronized void svc() {  
        state = illegalValue;  
        helper.operation();  
        state = legalValue;  
    }  
}
```

Potential problems with holding locks during downstream calls

**Safety:** What if `helper.operation` throws exceptions?

**Liveness:** What if `helper.operation` causes deadlock?

**Availability:** Cannot accept new `svc` requests during helper op

Rule of Thumb (with many variants and exceptions):

**Always lock when updating state**

**Never lock when sending message**

Redesign methods to avoid holding locks during downstream calls,  
while still preserving safety and consistency



# Synchronization of Accessor Methods

```
class Queue {  
    private int sz_ = 0; // number of elements  
  
    public synchronized void put(Object x) {  
        // ... increment sz_ ...  
    }  
    public synchronized Object take() {  
        // ... decrement sz_ ...  
    }  
    public int size() { return sz_; } // synch?  
}
```

Should `size()` method be synchronized?

**Pro:**

- Prevents clients from obtaining stale cached values
- Ensures that transient values are never returned
  - For example, if `put` temporarily set `sz_ = -1` as flag

**Con:**

- What could a client ever do with this value anyway?

Sync **always** needed for accessors of mutable **reference** variables

# Locking and Singletons

Every Java Class object has a lock. **Both static and instance methods** of Singleton classes should use it.

```
public class Singleton { // lazy initialization
    private int a;
    private Singleton(){ a = 1;}

    private static Class lock = Singleton.class;
    private static Singleton ref = null;

    public static Singleton instance(){
        synchronized(lock) {
            if (ref == null) ref = new Singleton();
            return ref;
        }
    }
    public int getA() {
        synchronized(lock) { return a; }
    }
    public void setA(int v){
        synchronized(lock) { a = v; }
    }
}
```

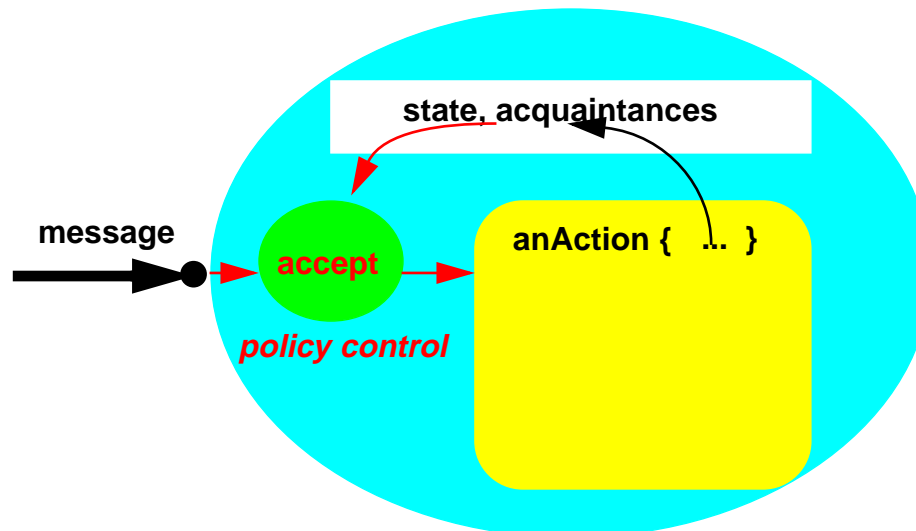
# State Dependence

Two aspects of action control:

- A **message** from a client
- The internal **state** of the host

Design Steps:

- Choose **policies** for dealing with actions that can succeed only if object is in particular logical state
- Design **interfaces** and protocols to reflect policy
- Ensure objects able to **assess** state to implement policy



There is not a separate *accept* mechanism in Java. So must implement policies in action methods themselves.

# Examples of State-Dependent Actions

---

Operations on collections, streams, databases

- Remove an element from an empty queue

Operations on objects maintaining constrained values

- Withdraw money from an empty bank account

Operations requiring resources

- Print a file

Operations requiring particular message orderings

- Read an unopened file

Operations on external controllers

- Shift to reverse gear in a moving car

# Policies for State Dependent Actions

Some policy choices for dealing with pre- and post- conditions

<b>Blind action</b>	Proceed anyway; no guarantee of outcome
<b>Inaction</b>	Ignore request if not in right state
<b>Balking</b>	Fail (throw exception) if not in right state
<b>Guarding</b>	Suspend until in right state
<b>Trying</b>	Proceed, check if succeeded; if not, roll back
<b>Retrying</b>	Keep trying until success
<b>Timing out</b>	Wait or retry for a while; then fail
<b>Planning</b>	First initiate activity that will achieve right state

# Interfaces and Policies

## Boring running example

```
interface BoundedCounter {  
    static final long MIN = 0;  
    static final long MAX = 10;  
  
    long value(); // INV: MIN <= value() <= MAX  
                // INIT: value() == MIN  
  
    void inc();   // PRE: value() < MAX  
    void dec();   // PRE: value() > MIN  
}
```

## Interfaces alone cannot convey policy

- But can suggest policy
  - For example, should `inc` throw exception? What kind?
  - Different methods can support different policies
- But can use manual annotations
  - Declarative constraints form basis for implementation

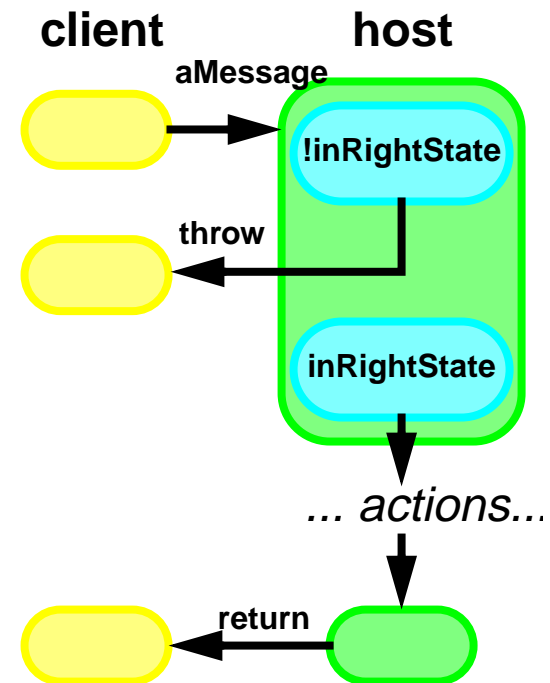
# Balking

## Check state upon method entry

- Must not change state in course of checking it
- Relevant state must be **explicitly** represented, so can be checked upon entry

## Exit immediately if not in right state

- Throw exception or return special error value
- Client is responsible for handling failure



## The simplest policy for fully synchronized objects

- Usable in both sequential and concurrent contexts
  - Often used in Collection classes (`Vector`, etc)
- **In concurrent contexts, the host must always take responsibility for entire check-act/check-fail sequence**
  - Clients cannot preclude state changes between check and act, so host must control

# Balking Counter Example

```
class Failure extends Exception { }

class BalkingCounter {
    protected long count_ = MIN;
    synchronized long value() { return count_;}

    synchronized void inc() throws Failure {
        if (count_ >= MAX) throw new Failure();
        ++count_;
    }

    synchronized void dec() throws Failure {
        if (count_ <= MIN) throw new Failure();
        --count_;
    }
}
// ...

void suspiciousUsage(BalkingCounter c) {
    if (c.value() > BalkingCounter.MIN)
        try { c.dec(); } catch (Failure ignore) {}
}

void betterUsage(BalkingCounter c) {
    try { c.dec(); } catch (Failure ex) {cope();}
}
```



# Collection Class Example

```
class Vec {           // scaled down version of Vector
    protected Object[] data_; protected int size_=0;

    public Vec(int cap) { data_=new Object[cap]; }

    public int size() { return size_; }

    public synchronized Object at(int i)
        throws NoSuchElementException {
        if (i < 0 || i >= size_ )
            throw new NoSuchElementException();
        return data_[i];
    }
    public synchronized void append(Object x) {
        if (size_ >= data_.length) resize();
        data_[size_++] = x;
    }
    public synchronized void removeLast()
        throws NoSuchElementException {
        if (size_ == 0)
            throw new NoSuchElementException();
        data_[--size_] = null;
    }
}
```

# Policies for Collection Traversal

How to apply operation to collection elements without interference

## Balking iterators

- Throw exception on access if collection was changed. Implement via **version numbers** updated on each change
  - Used in JDK1.2 collections
- But can be hard to recover from exceptions

## Snapshot iterators

- Make immutable copy of base collection elements. Or conversely, **copy-on-write** during each update.
- But can be expensive

## Indexed traversal

- Clients **externally** synchronize when necessary
- But coupled to particular locking policies

## Synchronized aggregate methods

- Support **apply-to-all** methods in collection class
- But deadlock-prone

# Synchronized Traversal Examples

```
interface Procedure { void apply(Object obj); }

class XVec extends Vec {
    synchronized void applyToAll(Procedure p) {
        for (int i=0;i<size_;++i) p.apply(data_[i]);
    }
}

class App {
    void printAllV1(XVec v) { // aggregate synch
        v.applyToAll(new Procedure() {
            public void apply(Object x) {
                System.out.println(x);
            }
        });
    }

    void printAllV2(XVec v) { // client-side synch
        synchronized (v) {
            for (int i = 0; i < v.size(); ++i)
                System.out.println(v.at(i));
        }
    }
}
```

# Guarding

Generalization of locking for state-dependent actions

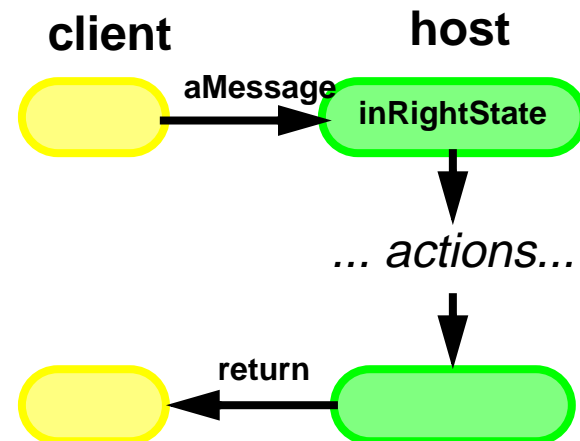
- **Locked:** Wait until **ready** (not engaged in other methods)
- **Guarded:** Wait until **an arbitrary state predicate** holds

Check state upon entry

- If not in right state, wait
- Some other action in some other thread may eventually cause a state change that enables resumption

Introduces liveness concerns

- Relies on actions of other threads to make progress
- Useless in sequential programs



# Guarding via Busy Waits

```
class UnsafeSpinningBoundedCounter { // don't use
    protected volatile long count_ = MIN;
    long value() { return count_; }

    void inc() {
        while (count_ >= MAX); // spin
        ++count_;
    }
    void dec() {
        while (count_ <= MIN); // spin
        --count_;
    }
}
```

**Unsafe** — no protection from read/write conflicts

**Wasteful** — consumes CPU time

But busy waiting can sometimes be useful; generally when

- The conditions **latch**  
— once set true, they never become false
- You are sure that threads are running on multiple CPUs  
— Java doesn't provide a way to determine or control this

# Guarding via Suspension

```
class GuardedBoundedCounter {
    protected long count_ = MIN;

    synchronized long value() { return count_; }

    synchronized void inc()
        throws InterruptedException {
        while (count_ >= MAX) wait();
        ++count_;
        notifyAll();
    }

    synchronized void dec()
        throws InterruptedException {
        while (count_ <= MIN) wait();
        --count_;
        notifyAll();
    }
}
```

Each wait relies on a balancing notification

- Generates programmer obligations

Must recheck condition upon resumption

# Java Monitor Methods

Every Java Object has a wait set

- Accessed only via monitor methods, that can only be invoked under synchronization of target

**wait()**

- Suspends thread
- Thread is placed in **wait set** for target object
- Synch lock for target is released

**notify()**

- If one exists, **any** thread **T** is chosen from target's wait set
- **T** must re-acquire synch lock for target
- **T** resumes at wait point

**notifyAll()** is same as **notify()** except **all** threads chosen

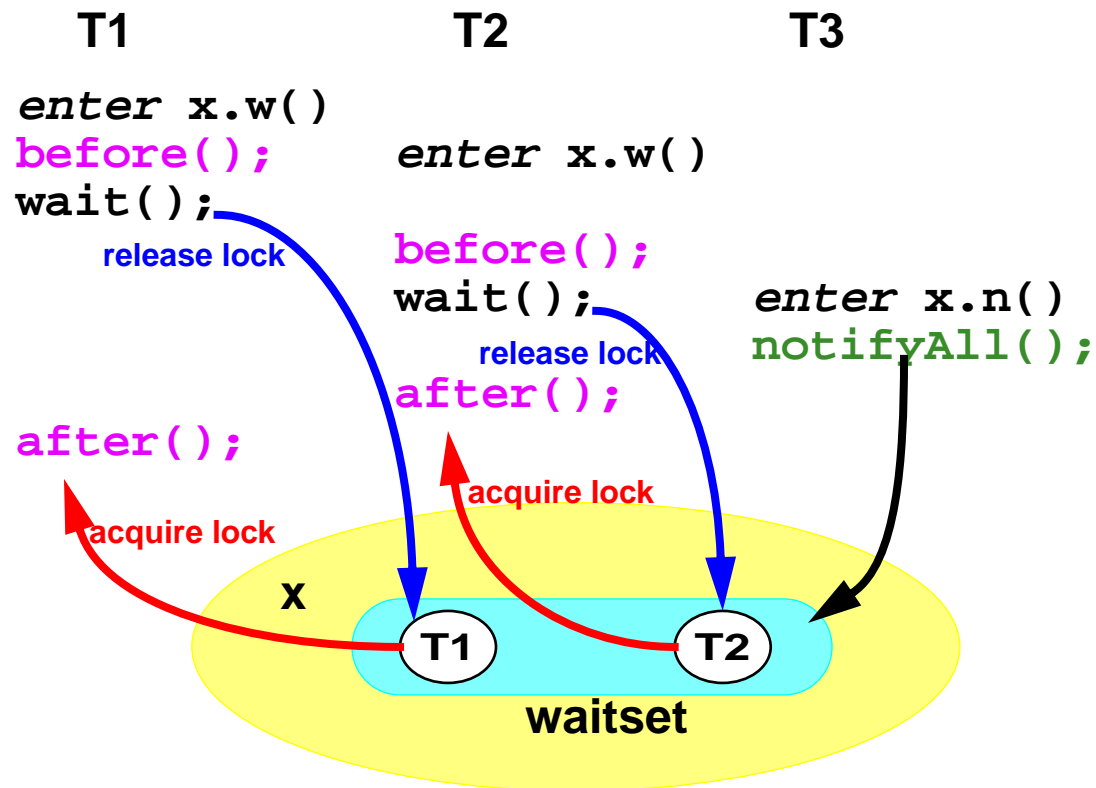
**wait(ms)** is same as **wait()** except thread is automatically notified after **ms** milliseconds if not already notified

**Thread.interrupt** causes a wait (also sleep, join) to abort.  
Same as notify except thread resumed at the associated catch

# Monitors and Wait Sets

```
class X {
    synchronized void w() {
        before(); wait(); after();
    }
    synchronized void n() { notifyAll(); }
}
```

One possible trace for three threads accessing instance x:

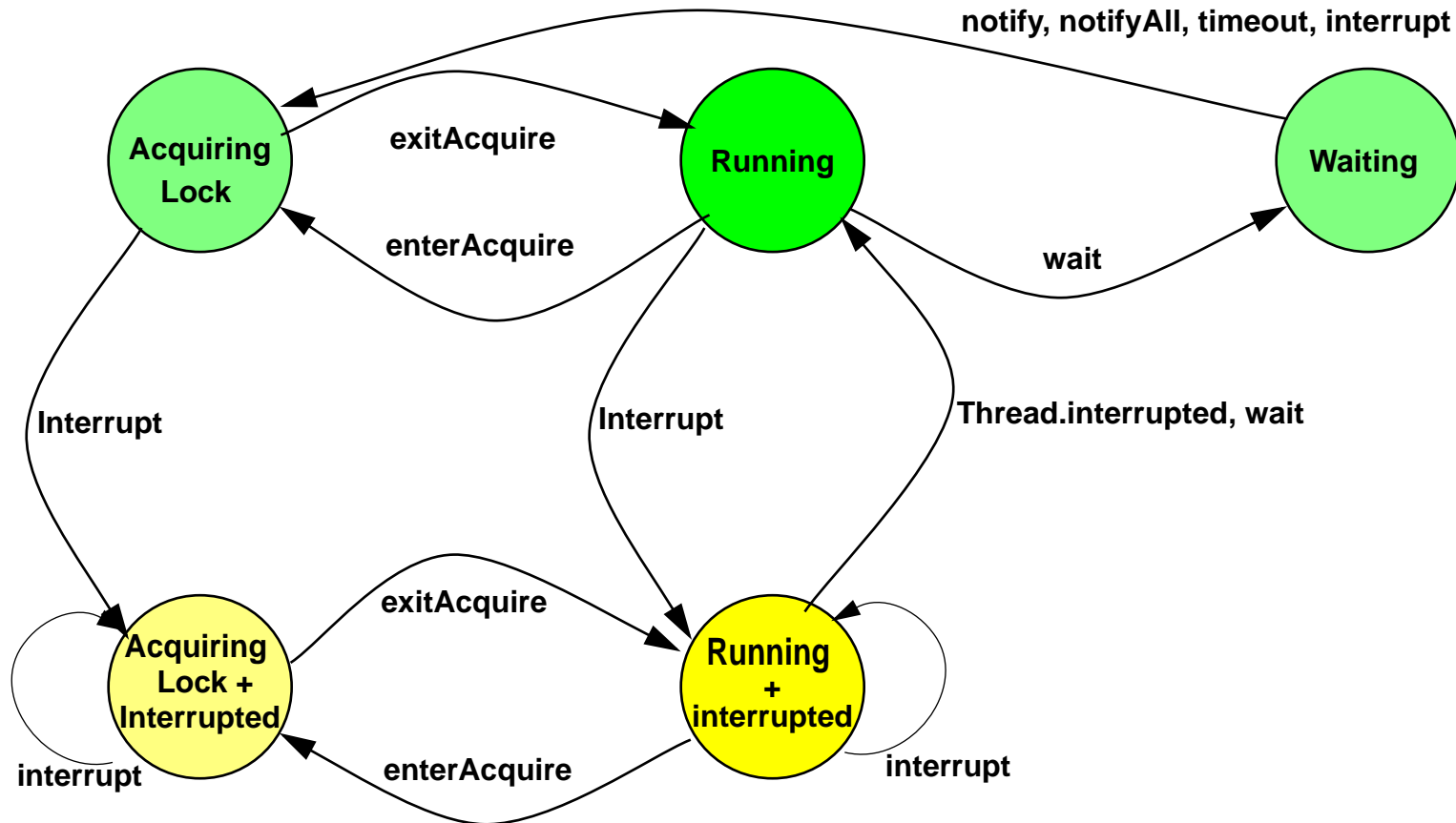




# Interactions with Interruption

Effect of `Thread.interrupt()`:

- If thread not waiting, set the `isInterrupted()` bit
- If thread is waiting, force to exit `wait` and throw `InterruptedException` upon resumption



# Fairness in Java

Fairness is a system-wide progress property:

Each blocked activity will eventually continue when its enabling condition holds. (*Many variants of definition*)

- Threads waiting for lock eventually enter when lock free
- Guarded wait loops eventually unblock when condition true

Usually implemented via First-in-First-Out scheduling policies

- FIFO lock and wait queues
- Sometimes, along with preemptive time-slicing

**Java does not guarantee fairness**

- Potential **starvation**
  - A thread never gets a chance to continue because other threads are continually placed before it in queue
- FIFO usually not strictly implementable on SMPs
- But JVM implementations usually approximate fairness
- Manual techniques available to improve fairness properties

# Timeouts

Intermediate points between balking and guarding

- Can vary timeout parameter from zero to infinity

Useful for heuristic detection of failures

- Deadlocks, crashes, I/O problems, network disconnects

But **cannot** be used for high-precision timing or deadlines

- Time can elapse between wait and thread resumption

Java implementation constraints

- `wait(ms)` does **not** automatically tell you if it returns because of notification vs 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

# Timeout Example

```
class TimeOutBoundedCounter {
    protected long TIMEOUT = 5000;
    // ...
    synchronized void inc() throws Failure {

        if (count_ >= MAX) {
            long start = System.currentTimeMillis();
            long waitTime = TIMEOUT;
            for (;;) {
                if (waitTime <= 0) throw new Failure();
                try { wait(waitTime); }
                catch (InterruptedException e) {
                    throw new Failure();
                }
                if (count_ < MAX) break;
                long now = System.currentTimeMillis();
                waitTime = TIMEOUT - (now - start);
            }
            ++count_;
            notifyAll();
        }
        synchronized void dec() throws Failure; //similar
    }
}
```

# Buffer Supporting Multiple Policies

```
class BoundedBuffer {
    Object[] data_;
    int putPtr_ = 0, takePtr_ = 0, size_ = 0;
    BoundedBuffer(int capacity) {
        data_ = new Object[capacity];
    }

    protected void doPut(Object x){ // mechanics
        data_[putPtr_] = x;
        putPtr_ = (putPtr_ + 1) % data_.length;
        ++size_;
        notifyAll();
    }

    protected Object doTake() { // mechanics
        Object x = data_[takePtr_];
        data_[takePtr_] = null;
        takePtr_ = (takePtr_ + 1) % data_.length;
        --size_;
        notifyAll();
        return x;
    }

    boolean isFull(){ return size_ == data_.length;}
    boolean isEmpty(){ return size_ == 0; }
```

## Buffer (continued)

```
synchronized void put(Object x)
    throws InterruptedException {
    while (isFull()) wait();
    doPut(x);
}
```

```
synchronized Object take() {
    throws InterruptedException {
    while (isEmpty()) wait();
    return doTake();
}
```

```
synchronized boolean offer(Object x) {
    if (isFull()) return false;
    doPut(x);
    return true;
}
```

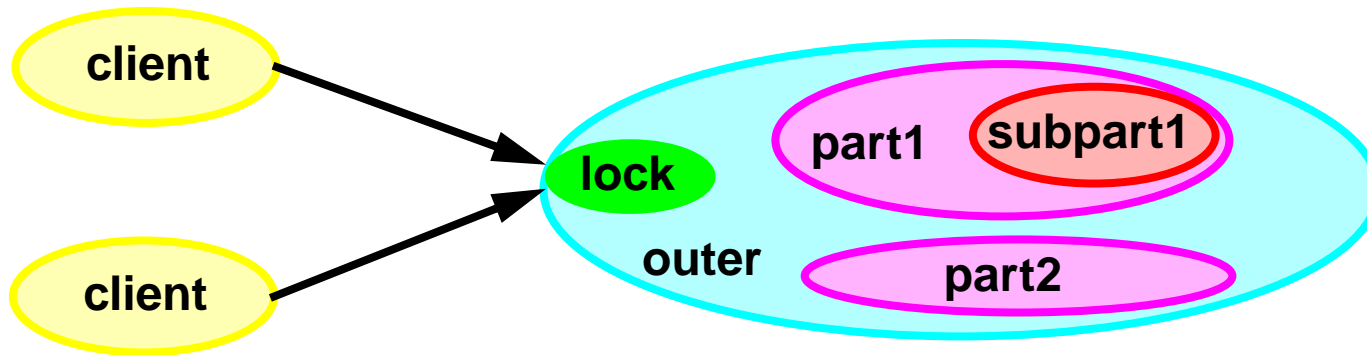
```
synchronized Object poll() {
    if (isEmpty()) return null;
    return doTake();
}
```

## Buffer (continued)

```
synchronized boolean offer(Object x, long ms) {
    if (isFull()) {
        if (ms <= 0) return false;
        long start = System.currentTimeMillis();
        long waitTime = ms;
        for (;;) {
            try { wait(waitTime); }
            catch (InterruptedException e) {
                return false;
            }
            if (!isFull()) break;
            long now = System.currentTimeMillis();
            waitTime = ms - (now - start);
            if (waitTime <= 0) return false;
        }
    }
    return doTake();
}

synchronized Object poll(long ms); // similar
}
```

# Containment



Structurally guarantee exclusive access to **internal** objects

- Control their visibility
- Provide concurrency control for their methods

## Applications

- Wrapping unsafe sequential code
- Eliminating need for locking ground objects and variables
- Applying special synchronization policies
- Applying different policies to the same mechanisms



# Containment Example

```
class Pixel {  
    private final java.awt.Point pt_;  
  
    Pixel(int x, int y) { pt_ = new Point(x, y); }  
  
    synchronized Point location() {  
        return new Point(pt_.x, pt_.y);  
    }  
  
    synchronized void moveBy(int dx, int dy){  
        pt_.x += dx; pt_.y += dy;  
    }  
}
```

`Pixel` provides synchronized access to `Point` methods

- The reference to `Point` object is immutable, but its fields are in turn mutable (and public!) so is unsafe without protection

Must make **copies** of inner objects when revealing state

- This is the most common way to use `java.awt.Point`, `java.awt.Rectangle`, etc

# Implementing Containment

Strict containment creates **islands** of isolated objects

- Applies recursively
- Allows inner code to run faster

Inner code must be **communication-closed**

- No unprotected calls in to or out from island

Outer objects **must never leak identities** of inner objects

- Can be difficult to enforce and check

Outermost objects must **synchronize** access

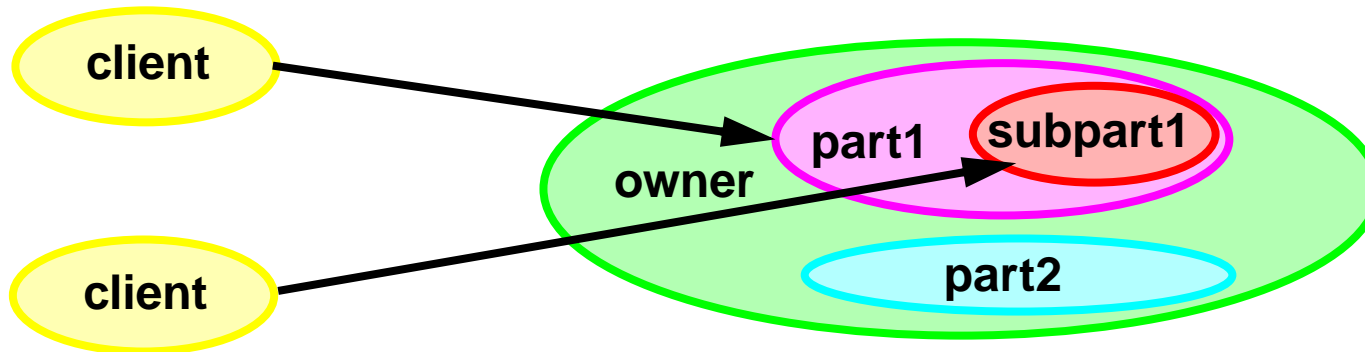
- Otherwise, possible thread-caching problems

Seen in concurrent versions of many delegation-based patterns

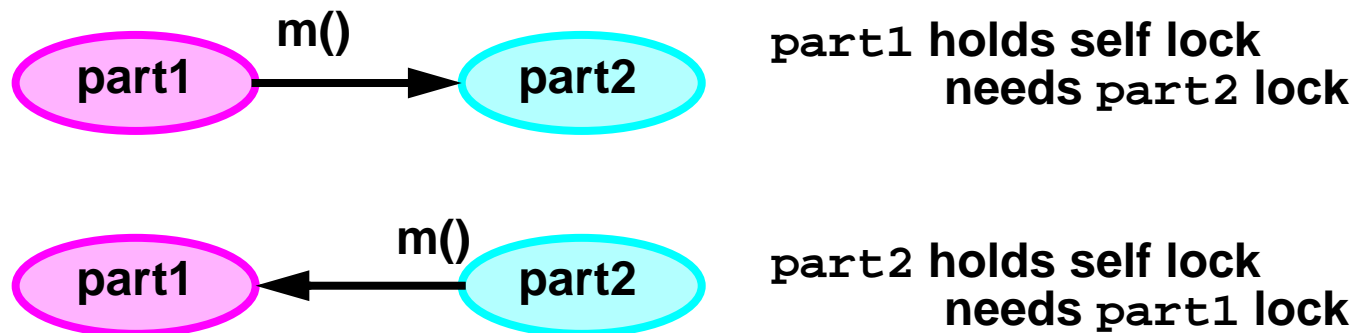
- Adapters, decorators, proxies

# Hierarchical Locking

Applies when logically contained parts are **not hidden** from clients



Avoids deadlocks that could occur if parts fully synchronized



Can eliminate this potential deadlock if all locking in all methods in all `Parts` relies on the common owner's lock.

Extreme case: one **Giant Lock** for entire subsystem

Can use either internal or external conventions

# Internal Hierarchical Locking

Visible components protect themselves using their owners' locks:

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

Or implement using inner classes — Owner is outer class:

```
class Container {  
    class Part {  
        public void m() {  
            synchronized(Container.this){ bareAction(); }  
        } } }  
}
```

Can extend to frameworks based on shared Lock objects, transaction locks, etc rather than synchronized blocks

# External Hierarchical Locking

Rely on callers to provide the locking

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

Used in AWT

- `java.awt.Component.getTreeLock()`

Can sometimes avoid more locking overhead, at price of fragility

- Can manually minimize use of `synchronized`
- Requires that all callers obey conventions
- Effectiveness is context dependent
  - Breaks encapsulation
  - Doesn't work with fancier schemes that do not directly rely on `synchronized` blocks or methods for locking

# 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();
    }
}

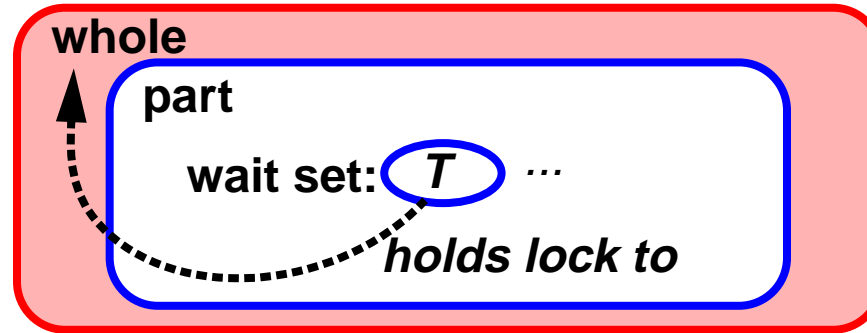
class Whole {
    final Part part_ = new Part();

    synchronized void rely() { part_.await(); }

    synchronized void set(boolean c){
        part_.signal(c); }
}
```

What happens when `Whole.rely()` called?

# Nested Monitors



If thread `T` calls `whole.rely`

- It waits within `part`
- The lock to `whole` is **retained** while `T` is suspended
- No other thread will ever unblock it via `whole.set`

→ **Nested Monitor Lockout**

Policy clash between guarding by `Part` and containment by `whole`

Never wait on a hidden contained object in Java while holding lock

# Avoiding Nested Monitors

Adapt internal hierarchical locking pattern

Can use inner classes, where Part waits in Whole's monitor

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

Create special Condition objects

- Condition methods are never invoked while holding locks
- Some concurrent languages build in special support for Condition objects
  - But generally only deal with one-level nesting
- Can build Condition class library in Java



# Splitting Objects and Locks

---

## Synopsis

- Isolate **independent** aspects of state and/or behavior of a host object into helper objects
- The host object delegates to helpers
- The host may change which helpers it uses dynamically

## Applications

- Atomic state updates
  - Conservative and optimistic techniques
- Avoiding deadlocks
  - Offloading locks used for status indicators, etc
- Improving concurrency
  - Reducing lock contention for host object
- Reducing granularity
  - Enabling fine-grained concurrency control

# Isolating Dependent Representations

Does `Location` provide strong enough semantic guarantees?

```
class Location { // repeated
    private double x_, y_;
    synchronized double x() { return x_; }
    synchronized double y() { return y_; }
    synchronized void moveBy(double dx, double dy) {
        x_ += dx; y_ += dy;
    }
}
```

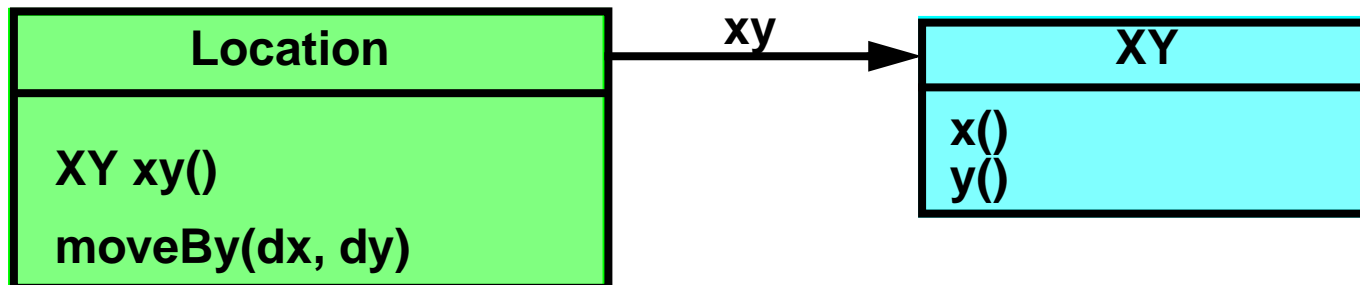
No protection from interleaving problems such as:

Thread 1: `x=loc.x(); .....`; `y=loc.y();`

Thread 2: `.....; loc.moveBy(1,6);.....;`

Thread 1 can have incorrect view (old `x`, new `y`)

Avoid by splitting out dependent representations in separate class



# Conservative Representation Updates

```
class XY { // immutable
    private final double x_, y_;
    XY(double x, double y) { x_ = x; y_ = y; }
    double x() { return x_; }
    double y() { return y_; }
}

class LocationV2 {
    private XY xy_;

    LocationV2(double x, double y) {
        xy_ = new XY(x, y);
    }
    synchronized XY xy() { return xy_; }

    synchronized void moveBy(double dx, double dy) {
        xy_ = new XY(xy_.x() + dx, xy_.y() + dy);
    }
}
```

Locking `moveBy()` ensures that the two accesses of `xy_` do not get different points

Locking `xy()` avoids thread-cache problems by clients

# Optimistic Representation Updates

```
class LocationV3 {
    private XY xy_;

    private synchronized boolean commit(XY oldp,
                                         XY newp){
        boolean success = (xy_ == oldp);
        if (success) xy_ = newp;
        return success;
    }

    LocationV3(double x,double y){xy_=new XY(x,y);}

    synchronized XY xy() { return xy_; }

    void moveBy(double dx,double dy) {
        while (!Thread.interrupted()){
            XY oldp = xy();
            XY newp = new XY(oldp.x()+dx, oldp.y()+dy);
            if (commit(oldp, newp)) break;
            Thread.yield();
        }
    }
}
```

# Optimistic Update Techniques

Every public state update method has four parts:

→ **Record current version**

Easiest to use reference to immutable representation

- Or can assign version numbers, transaction IDs, or time stamps to mutable representations

→ **Build new version, without any irreversible side effects**

All actions before `commit` must be reversible

- Ensures that failures are clean (no side effects)
- No I/O or thread construction unless safely cancellable
- All internally called methods must also be reversible

→ **Commit to new version if no other thread changed version**

Isolation of state updates to single atomic `commit` method can avoid potential deadlocks

→ **Otherwise fail or retry**

Retries can **livelock** unless proven *wait-free* in given context

# Optimistic State-Dependent Policies

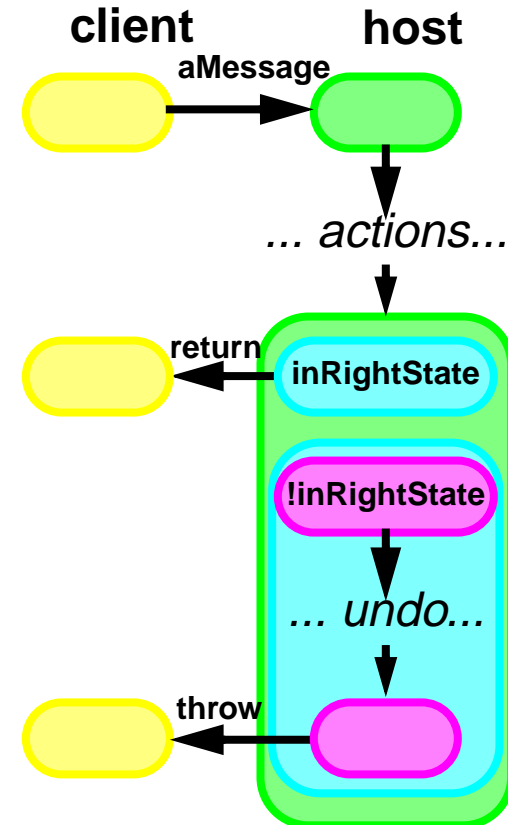
As with optimistic updates, isolate state into versions, and isolate state changes to `commit` method

In each method:

- Record current version
- Build new version
- `Commit` to version if success **and** no one changed version
- Otherwise fail or retry

Retry policy is a tamed busy wait. Can be more efficient than guarded waits if

- Conflicts are rare
- Guard conditions usually hold
- Running on multiple CPUs



# Optimistic Counter

```
class OptimisticBoundedCounter {
    private Long count_ = new Long(MIN);
    long value() { return count().longValue(); }
    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() throws InterruptedException{
        for (;;) {          // retry-based
            if (Thread.interrupted())
                throw new InterruptedException();
            Long c = count();
            long v = c.longValue();
            if (v < MAX && commit(c, new Long(v+1)))
                break;
            Thread.yield();
        }
    }

    public void dec() // symmetrical
}
```

# Splitting Locks and Behavior

Associate a helper object with an **independent** subset of state and functionality.

Delegate actions to helper via **pass-through** method

```
class Shape {  
    // Assumes size & dimension are independent  
  
    int height_ = 0;  
    int width_ = 0;  
  
    synchronized void grow() { ++height_; ++width_;}  
  
    Location l = new Location(0,0); // fully synched  
  
    void shift() { l.moveBy(1, 1); } // Use l's synch  
}
```

**grow** and **shift** can execute simultaneously

When there is no existing object to delegate independent actions:

- Use an arbitrary Object as a lock, and protect associated methods using synchronized block on that lock
  - Useful for concurrent data structures

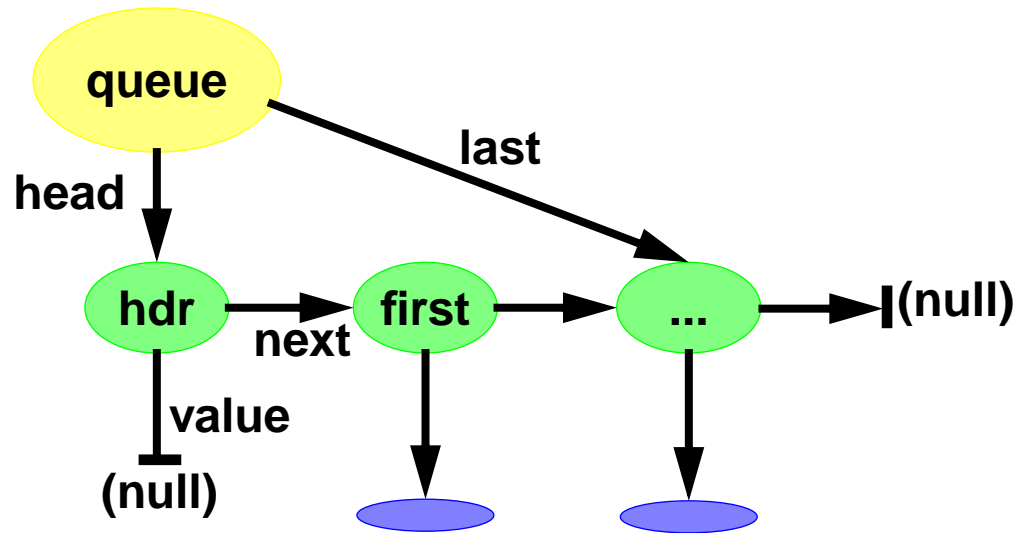


# Concurrent Queue

```
class TwoLockQueue {
    final static class Node {
        Object value; Node next = null;
        Node(Object x) { value = x; }
    }
    private Node head_ = new Node(null); // dummy hdr
    private Node last_ = head_;
    private Object lastLock_ = new Object();

    void put(Object x) {
        synchronized (lastLock_) {
            last_ = last_.next = new Node(x);
        }
    }
    synchronized Object poll() { // null if empty
        Object x = null;
        Node first = head_.next; // only contention pt
        if (first != null) {
            x = first.value; first.value = null;
            head_ = first; // old first becomes header
        }
        return x;
    }
}
```

## Concurrent Queue (continued)



`puts` and `polls` can run concurrently

- The data structure is crafted to avoid contending access
  - Rely on Java atomicity guarantees at only potential contention point
- But multiple `puts` and multiple `polls` disallowed

Weakens semantics

- `poll` may return null if another thread is in midst of `put`
- Balking policy for `poll` is nearly forced here
  - But can layer on blocking version

# Introducing Concurrency into Applications

---

Three sets of patterns

Each associated with a reason to introduce concurrency

## Autonomous Loops

Establishing independent cyclic behavior

## Oneway messages

Sending messages without waiting for reply or termination

- Improves availability of sender object

## Interactive messages

Requests that later result in reply or callback messages

- Allows client to proceed concurrently for a while

Most design ideas and semantics stem from **active object models**.

# Autonomous Loops

---

Simple non-reactive active objects contain a run loop of form:

```
public void run() {  
    while (!Thread.interrupted())  
        doSomething();  
}
```

Normally established with a constructor containing:

```
new Thread(this).start();
```

Perhaps also setting priority and daemon status

Normally also support other methods called from other threads

Requires standard safety measures

## Common Applications

- Animations
- Simulations
- Message buffer Consumers
- Polling daemons that periodically sense state of world

# Autonomous Particle Class

```
public class Particle implements Runnable {
    private int x = 0, y = 0;
    private Canvas canvas;
    public Particle(Canvas host) { canvas = host; }

    synchronized void moveRandomly() {
        x += (int) ((Math.random() - 0.5) * 5);
        y += (int) ((Math.random() - 0.5) * 5);
    }

    public void draw(Graphics g) {
        int lx, ly;
        synchronized (this) { lx = x; ly = y; }
        g.drawRect(lx, ly, 10, 10);
    }

    public void run() {
        for(;;) {
            moveRandomly();
            canvas.repaint();
            try { Thread.sleep((int)(Math.random()*10)); }
            catch (InterruptedException e) { return; }
        }
    }
}
```

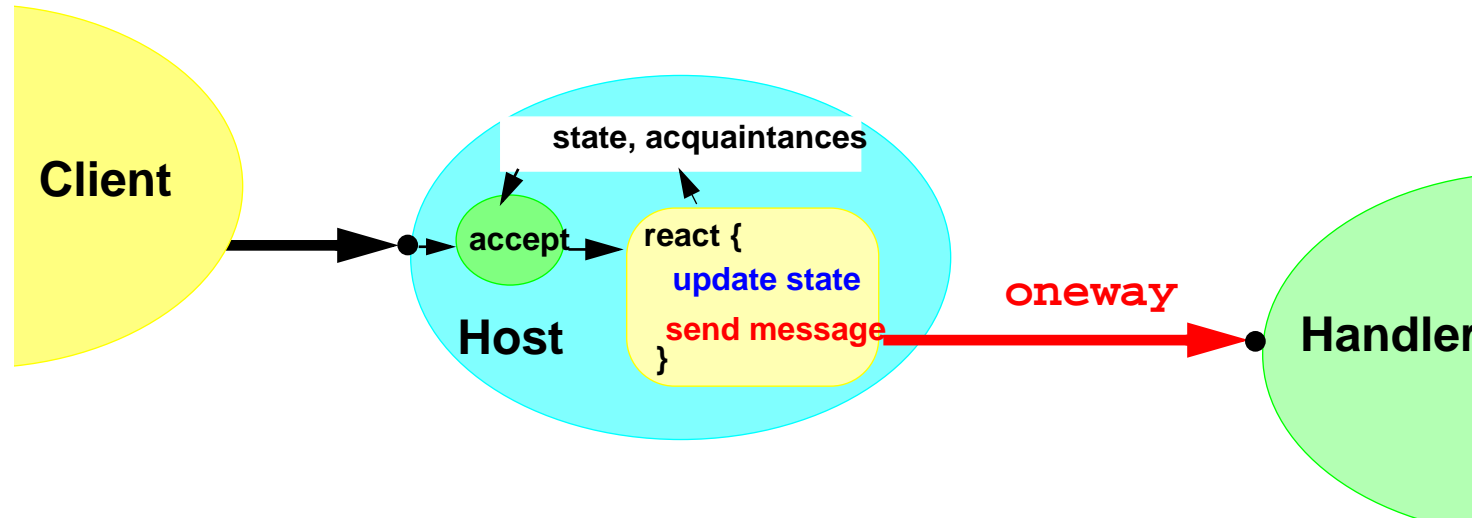
# Particle Applet

```
import java.awt.*;
import java.applet.*;
public class ParticleApplet extends Applet {
    public void init() {
        add(new ParticleCanvas(10));
    }
}

class ParticleCanvas extends Canvas {
    Particle[] particles;
    ParticleCanvas(int nparticles) {
        setSize(new Dimension(100, 100));
        particles = new Particle[nparticles];
        for (int i = 0; i < particles.length; ++i) {
            particles[i] = new Particle(this);
            new Thread(particles[i]).start();
        }
    }

    public void paint(Graphics g) {
        for (int i = 0; i < particles.length; ++i)
            particles[i].draw(g);
    }
} // (needs lots of embellishing to look nice)
```

# Oneway Messages



Conceptually oneway messages are sent with

- No need for replies
- No concern about failure (exceptions)
- No dependence on termination of called method
- No dependence on order that messages are received

But may sometimes want to **cancel** messages or resulting activities

# Oneway Message Styles

<b>Events</b>	Mouse clicks, etc
<b>Notifications</b>	Status change alerts, etc
<b>Postings</b>	Mail messages, stock quotes, etc
<b>Activations</b>	Applet creation, etc
<b>Commands</b>	Print requests, repaint requests, etc
<b>Relays</b>	Chain of responsibility designs, etc

## Some semantics choices

**Asynchronous:** Entire message send is independent

- By far, most common style in reactive applications

**Synchronous:** Caller must wait until message is *accepted*

- Basis for **rendezvous** protocols

**Multicast:** Message is sent to **group** of recipients

- The group might not even have any members



# Messages in Java

---

## Direct method invocations

- Rely on standard call/return mechanics

## Command strings

- Recipient parses then dispatches to underlying method
- Widely used in client/server systems including HTTP

## EventObjects and service codes

- Recipient dispatches
- Widely used in GUIs, including AWT

## Request objects, asking to perform encoded operation

- Used in distributed object systems — RMI and CORBA

## Class objects (normally via .class files)

- Recipient creates instance of class
- Used in Java Applet framework

## Runnable commands

- Basis for thread instantiation, mobile code systems

# Design Goals for Oneway Messages

---

## Object-based forces

### Safety

- Local state changes should be atomic (normally, locked)
  - Typical need for locking leads to main differences vs single-threaded Event systems
- Safe guarding and failure policies, when applicable

### Availability

- Minimize delay until host can accept another message

## Activity-based forces

### Flow

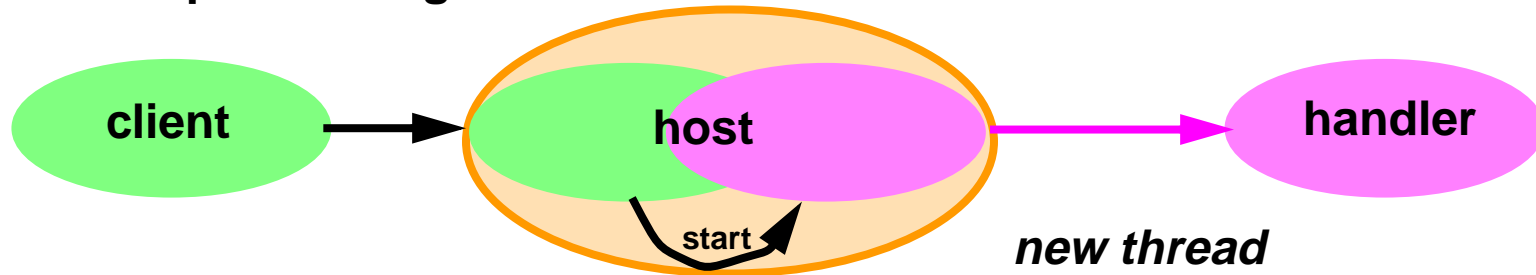
- The activity should progress with minimal contention

### Performance

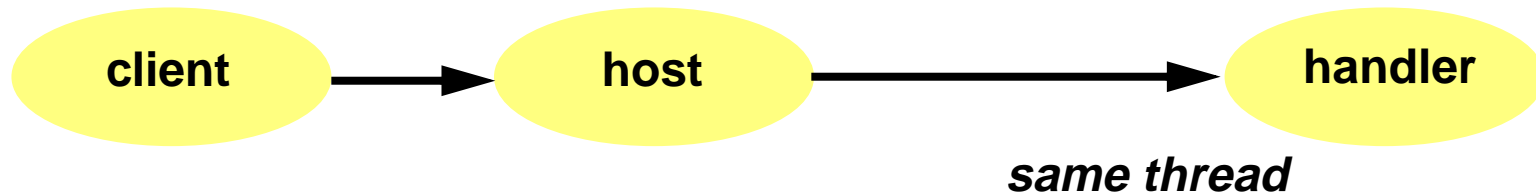
- Minimize overhead and resource usage

# Design Patterns for Oneway Messages

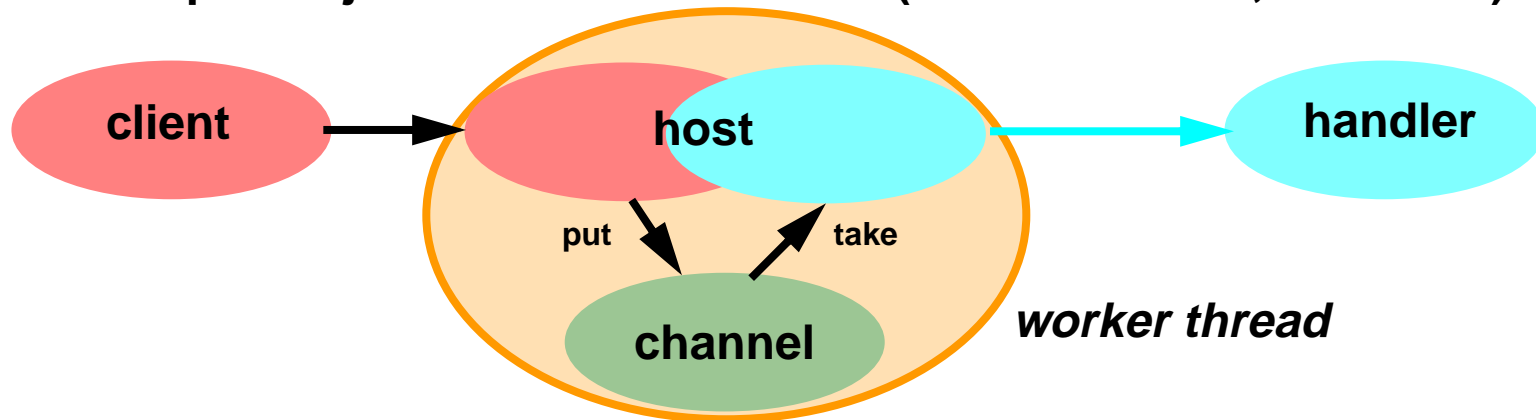
## Thread-per-Message



## Thread-per-Activity via Pass-throughs



## Thread-per-Object via Worker Threads (variants: Pools, Listeners)



# Reactive Methods

Code scaffolding for illustrating patterns:

```
class Host {  
    // ...  
    private long localState_; // Or any state vars  
    private Handler handler_; // Message target  
  
    public void react(...) {  
        updateState(...);  
        sendMessage(...);  
    }  
  
    private synchronized void updateState(...) {  
        // Assign to localState_;  
    }  
  
    private void sendMessage(...) {  
        // Issue handler.process(...)  
    }  
}
```

**react()** may be called directly from client, or indirectly after decoding command, event, etc

# Thread-per-Message

```
class Host { //...
    public void react(...) {
        updateState(...);
        sendMessage(...);
    }

    synchronized void sendMessage(...) {

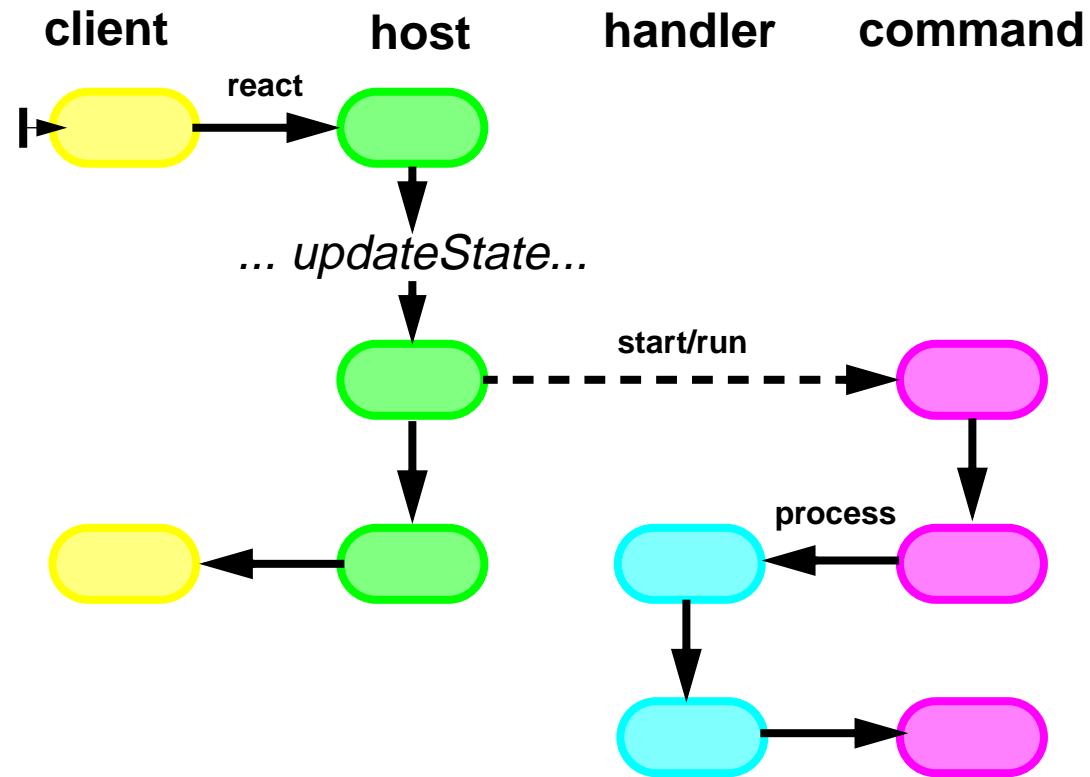
        Runnable command = new Runnable() { // wrap
            final Handler dest = handler_;
            public void run() {
                dest.process(...);
            }
        };
        new Thread(command).start();           // run
    }
}
```

**Runnable** is the standard Java interface describing argumentless, resultless command methods (aka *closures*, *thunks*)

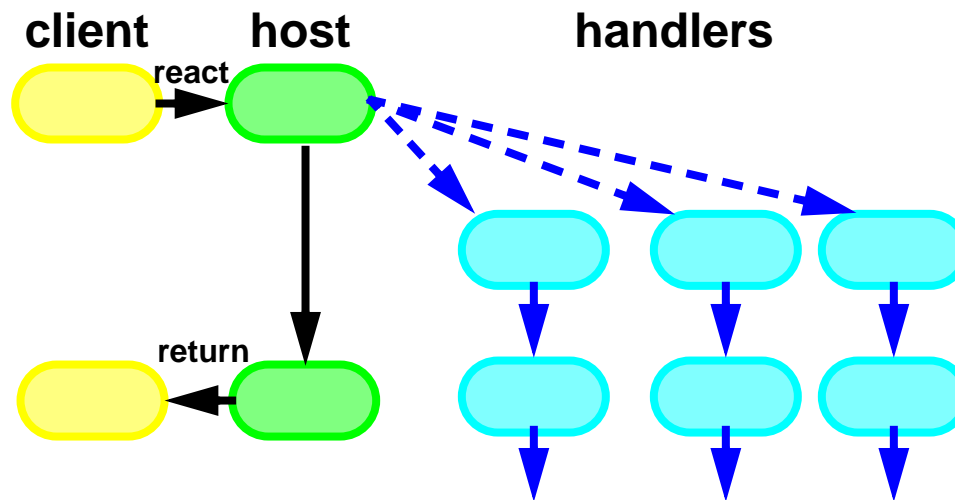
**Synchronization** of `sendMessage` desirable if `handler_` or `process()` arguments not fixed/final

Variants: Thread-per-connection (sockets)

# Thread-per-Message Protocol



# Multicast TPM



Multicasts can either

- Generate one thread per message, or
- Use a single thread for all messages

Depends on whether OK to wait each one out before sending next one

# TPM Socket-based Server

```
class Server implements Runnable {
    public void run() {
        try {
            ServerSocket socket = new ServerSocket(PORT);
            for (;;) {
                final Socket connection = socket.accept();
                new Thread(new Runnable() {
                    public void run() {
                        new Handler().process(connection);
                    }
                }).start();
            }
        } catch (Exception e) { /* cleanup; exit */ }
    }
}

class Handler {
    void process(Socket s) {
        InputStream i = s.getInputStream();
        OutputStream o = s.getOutputStream();
        // decode and service request, handle errors
        s.close();
    }
}
```



# Thread Attributes and Scheduling

Each Thread has an integer priority

- From `Thread.MIN_PRIORITY` to `Thread.MAX_PRIORITY` (currently 1 to 10)
- Initial priority is same as that of the creating thread
- Can be changed at any time via `setPriority`
- `ThreadGroup.setMaxPriority` establishes a ceiling for all threads in the group

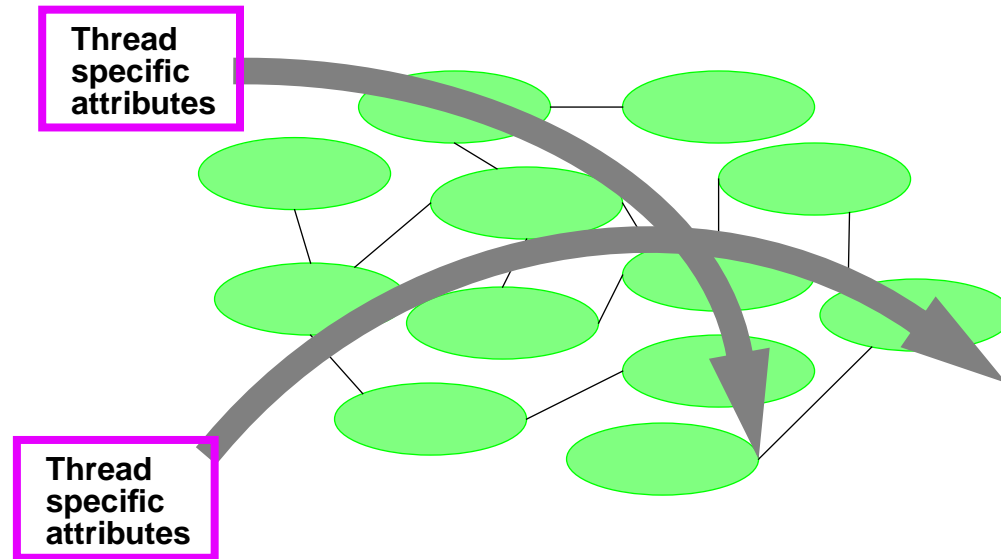
JVM schedulers give **preference** to threads with higher priority

- But *preference* is left vague, implementation-dependent
- No guarantees about fairness for equal-priority threads
  - Time-slicing is permitted but not required
- No guarantees whether highest-priority or longest-waiting threads acquire locks or receive notifications before others

**Priorities can only be used heuristically**

- Build custom Queues to control order of sequential tasks
- Build custom Conditions to control locking and notification

# Adding Thread Attributes



Thread objects can hold non-public **Thread-Specific** contextual attributes for all methods/objects running in that thread

- Normally preferable to `static` variables

Useful for variables that **apply per-activity, not per-object**

- Timeout values, transaction IDs, Principals, current directories, default parameters

Useful as tool to eliminate need for locking

- Used internally in JVMs to optimize memory allocation, locks, etc via per-thread caches

# Implementing Thread-Specific Storage

```

class GameThread extends Thread { // ...
    private long movementDelay_ = 3;
    static GameThread currentGameThread() {
        return (GameThread)(Thread.currentThread());
    }
    static long getDelay() {
        return currentGameThread().movementDelay_;
    }
    static long setDelay(long t) {
        currentGameThread().movementDelay_ = t;
    }
}
class Ball { // ...
    void move() { // ...
        Thread.sleep(GameThread.getDelay());
    }
}
class Main { ... new GameThread(new Game()) ... }

```

Define contextual attributes in special Thread subclasses

- Can be accessed without locking if all accesses are always via `Thread.currentThread()`
- Enforce via **static** methods in Thread subclass

# Using ThreadLocal

`java.lang.ThreadLocal` available in JDK1.2

- An alternative to defining special Thread subclasses

Uses internal hash table to associate data with threads

- Avoids need to make special Thread subclasses when adding per-thread data
  - Trade off flexibility vs strong typing and performance

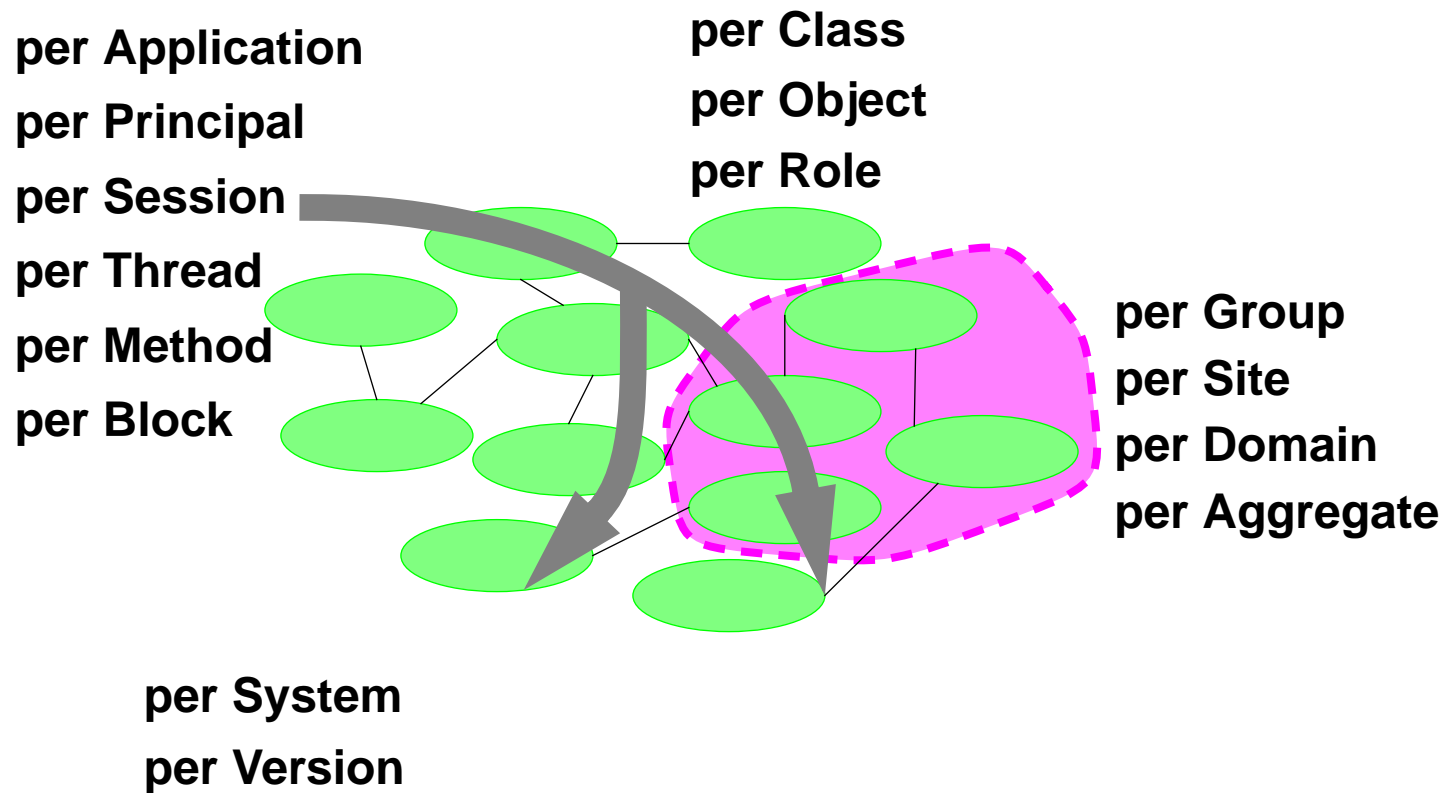
```
class Ball {  
    static ThreadLocal delay = new ThreadLocal();  
    void move() { // ...  
        if (delay.get()==null) delay.set(new Long(3));  
        long d = ((Long)(delay.get())).longValue();  
        Thread.sleep(d);  
    }  
}
```

Can extend to implement **inherited** Thread contexts

Where new threads by default use attributes of the parent thread that constructed them

# Other Scoping Options

Choices for maintaining context information



# Choosing among Scoping Options

## Reusability heuristics

- Responsibility-driven design
- Factor commonalities, isolate variation
- Simplify Programmability
  - Avoid long parameter lists
  - Avoid awkward programming constructions
  - Avoid opportunities for errors due to policy conflicts
  - Automate propagation of bindings

## Conflict analysis

**Example: Changing per-object bindings via tuning interfaces can lead to conflicts when objects support multiple roles**

- Settings made by one client impact others
- Common error with Proxy objects
- Replace with per-method, per-role, per-thread

# Thread-per-Activity via Pass-Throughs

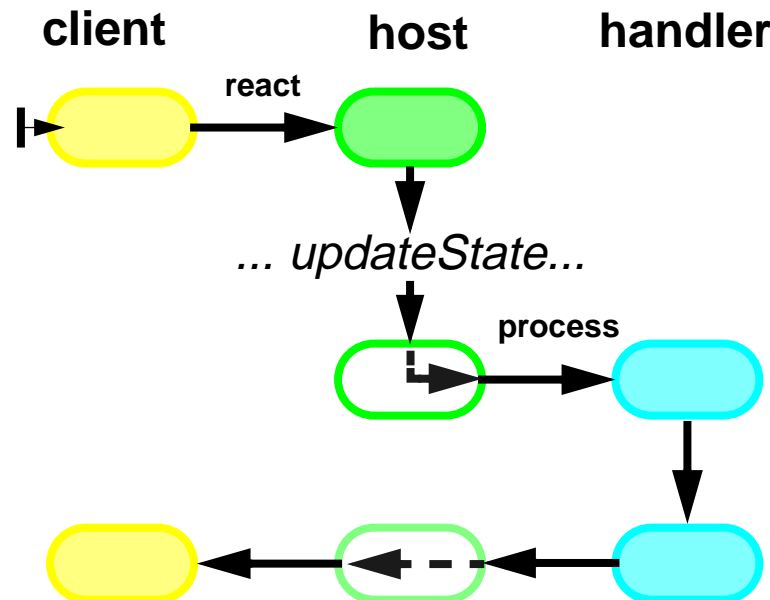
```
class Host { //...

    void reactV1(...) { // no synch
        updateState();           // isolate in synched method
        sendMessage(...);
    }
    void sendMessage(...) { // no synch
        handler_.process(...); // direct call
    }
}
```

A kind of **forwarding** — conceptually removing host from call chain

**Callers** of react must wait for `handler.process` to terminate, or generate their own threads

**Host** can respond to another react call from another thread immediately after updating state



# Using Pass-Throughs

Common approach to writing AWT Event handlers, JavaBeans methods, and other event-based components.

But somewhat **fragile**:

- There is no “opposite” to `synchronized`
  - Avoid self calls to react from `synchronized` methods
- Need care in accessing representations at call-point
  - If `handler_` variable or `process` arguments not fixed, copy values to locals while under synchronization
- **Callers** must be sure to create thread around call if they cannot afford to wait or would lock up

Variants

## Bounded Thread-per-Message

- Keep track of how many threads have been created. If too many, fall back to pass-through.

## Mediated

- Register handlers in a common mediator structured as a pass-through.



# Multicast Pass-Throughs

```
class Host { //...
    CopyOnWriteSet handlers_;

    synchronized void addHandler(Handler h) {
        handlers_.add(h); // copy
    }

    void sendMessage(...) {
        Iterator e = handlers_.iterator();
        while (e.hasNext())
            ((Handler)(e.next())).process(...);
    }
}
```

Normally use **copy-on-write** to implement target collections

- Additions are much less common than traversals

AWT uses `java.awt.AWTEventMulticaster` class

- Employs variant of `FixedList` class design
- But coupled to AWT Listener framework, so cannot be used in other contexts

# Thread-Per-Object via Worker Threads

Establish a producer-consumer chain

## Producer

Reactive method just places **message** in a **channel**

**Channel** might be a buffer, queue, stream, etc

**Message** might be a Runnable command, event, etc

## Consumer

Host contains an autonomous loop thread of form:

```
while (!Thread.interrupted()) {  
    m = channel.take();  
    process(m);  
}
```

Common variants

## Pools

Use more than one worker thread

## Listeners

Separate producer and consumer in different objects

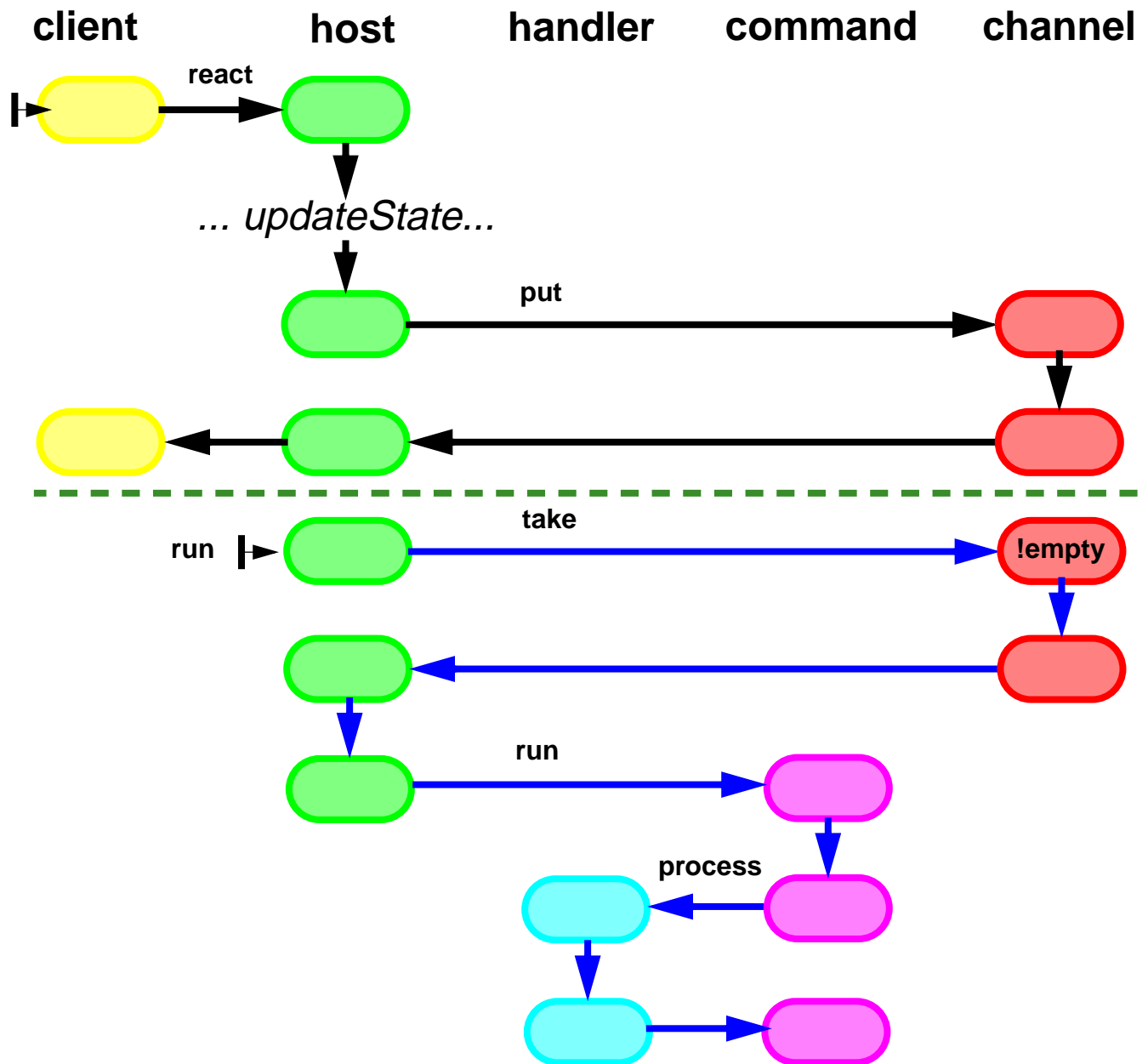
# Worker Thread Example

```
interface Channel { // buffer, queue, stream, etc
    void put(Object x);
    Object take();
}

class Host { //...
    Channel channel_ = ...;
    void sendMessage(...) {
        channel_.put(new Runnable() { // enqueue
            public void run(){
                handler_.process(...);
            }
        });
    }

    Host() { // Set up worker thread in constructor
        // ...
        new Thread(new Runnable() {
            public void run() {
                while (!Thread.interrupted())
                    ((Runnable)(channel_.take())).run();
            }
        }).start();
    }
}
```

# Worker Thread Protocol



# Channel Options

---

## Unbounded queues

- Can exhaust resources if clients faster than handlers

## Bounded buffers

- Can cause clients to block when full

## Synchronous channels

- Force client to wait for handler to complete previous task

## Leaky bounded buffers

- For example, drop oldest if full

## Priority queues

- Run more important tasks first

## Streams or sockets

- Enable persistence, remote execution

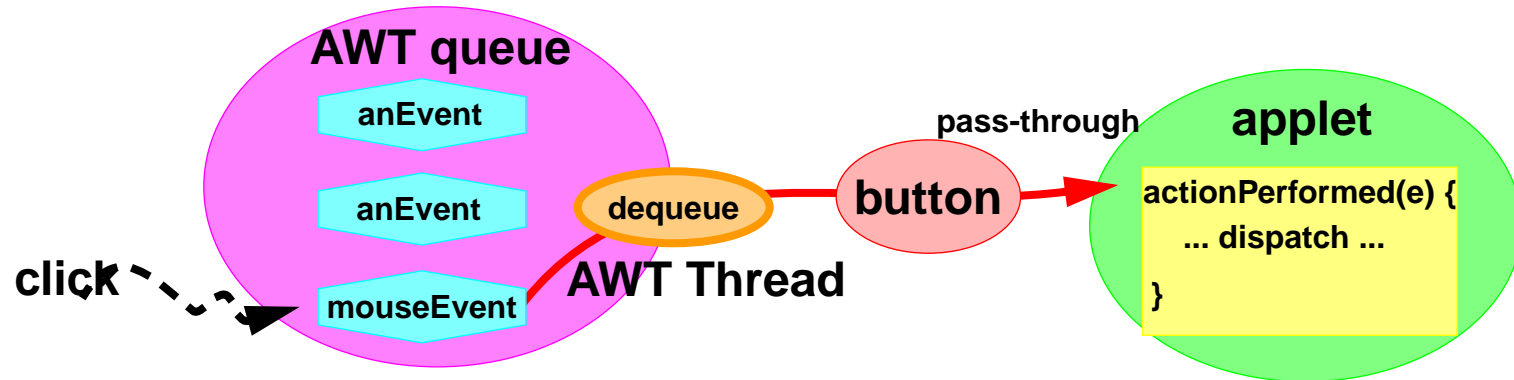
## Non-blocking channels

- Must take evasive action if `put` or `take` fail or time out

# Example: The AWT Event Queue Thread

AWT uses **one** thread and a single `java.awt.EventQueue`

- Single thread makes visual updates appear more coherent
- Browsers *may* add per-Applet threads and queues



Events implement `java.util.EventObject`

- Include both “Low-level” and “Semantic” events

Event dequeuing performed **by AWT thread**

`repaint()` places drawing request event in queue.

- The request may be optimized away if one already there
- `update/paint` is called when request dequeued
  - Drawing is done **by AWT thread**, not your threads

# AWT Example

```
class MyApplet extends Applet
    implements ActionListener {

    Button button = new Button("Push me");
    boolean onOff = false;

    public void init() {
        button.addActionListener(this); // attach
        add(button);                    // add to layout
    }

    public void actionPerformed(ActionEvent evt) {
        if (evt.getSource() == button) // dispatch
            toggle(); // update state
        repaint(); // issue event(not necessary here)
    }

    synchronized void toggle() {
        onOff = !onOff;
    }
}
```

# Using AWT in Concurrent Programs

Most conservative policy is to perform **all** GUI-related state updates in event handling methods

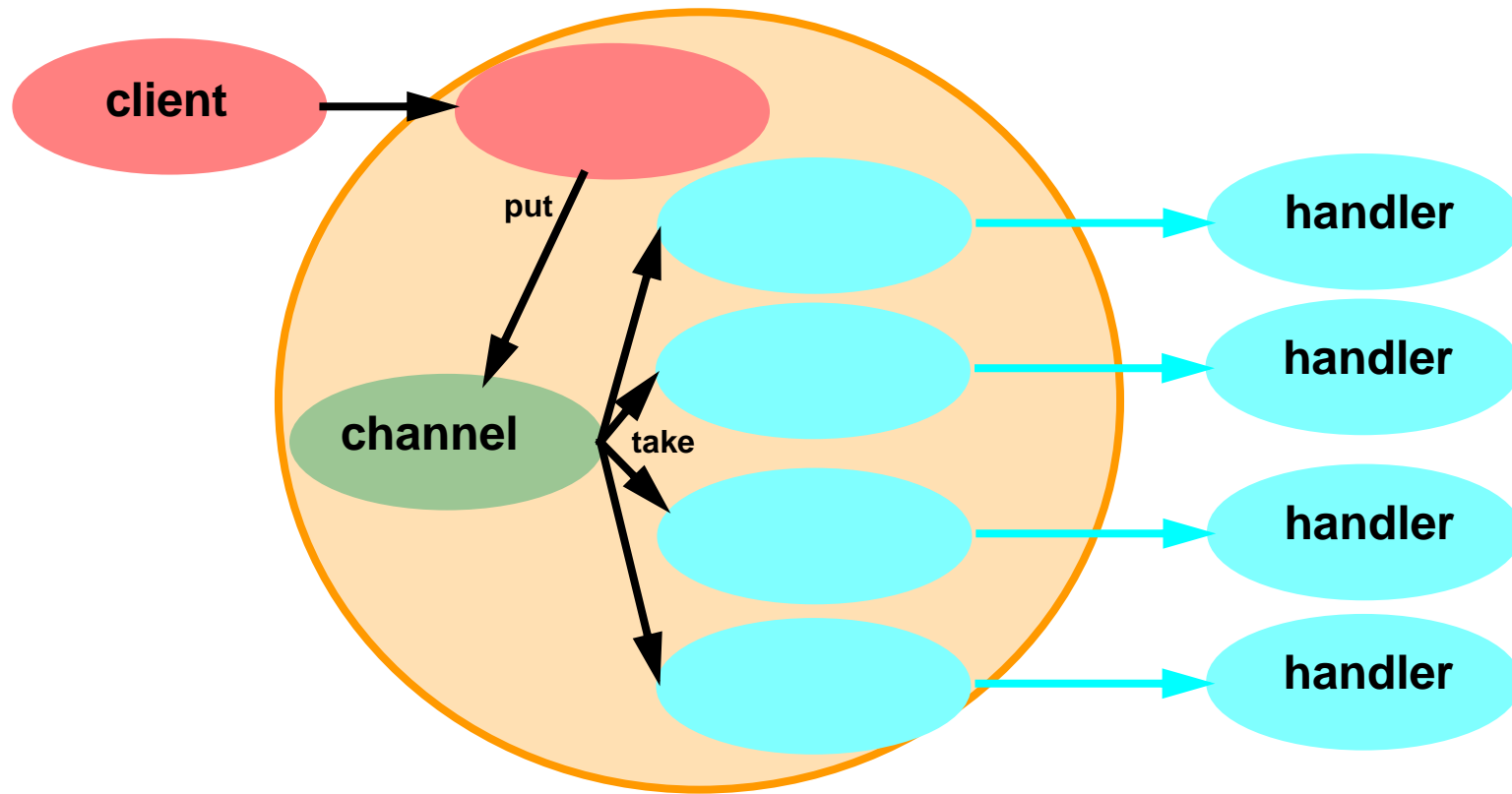
- Define and generate new `EventObjects` if necessary
- Consider **splitting** GUI-related state into separate classes
- Do not rely on thread-safety of GUI components

Define drawing and event handling methods in reactive form

- Do not hold locks when sending messages
- Do not block or delay caller thread (the AWT thread)
- Generate threads to arrange **GUI-unrelated** processing
  - Explicitly set their `ThreadGroups`
- Generate events to arrange **GUI-related** asynch processing
  - *Swing* includes some utility classes to make this easier



# Thread Pools



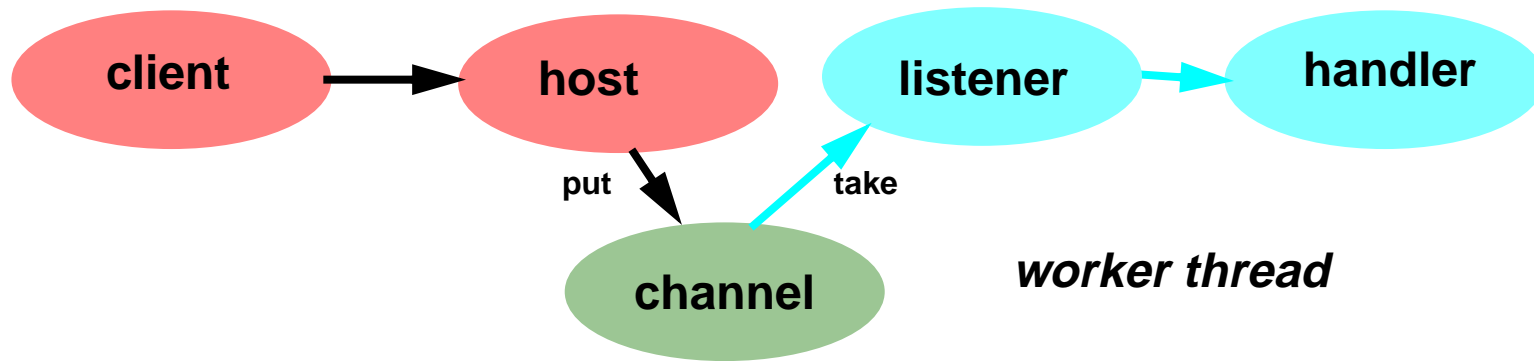
Use a collection of worker threads, not just one

- Can limit maximum number and priorities of threads

Often faster than thread-per-message

- But slower than single thread working off a multislot buffer unless handler actions permit parallelism
- Often works well for I/O-bound actions

# Listeners



House worker thread in a different object

- Even in a different process, connected via socket

But full support for **remote** listeners requires frameworks for

- Naming remote acquaintances (via registries, `jndi` etc)
- Failure, reliability, fault tolerance
- Security, protocol conformance, ...

Can make more transparent via **Proxies**

- Channels/Listeners that duplicate interface of Handler, but wrap each message as queued command for later execution

# Remote Worker Threads

```
class Host { // ...
    ObjectOutputStream c;    // connected to a Socket
    void sendMessage(...) {
        c.writeObject(new SerializableRunnable() {
            public void run(){
                new Handler().process(...);
            }
        });
    }
}

class Listener { // instantiate on remote machine
    ObjectInputStream c; // connected to a Socket
    Listener() {
        c = new ...
        Thread me = new Thread(new Runnable() {
            public void run() {
                for (;;) {
                    ((Runnable)(c.readObject())).run();
                }
            }
        });
        me.start();
    }
}
```

# Synchronous Channels

Synchronous oneway messages same as asynchronous, except:

- Caller must wait at least until message is **accepted**

Simplest option is to use synchronized methods

- Caller must wait out **all** downstream processing

Increase concurrency via synchronous channel to worker thread

- **Every put must wait for take**
- **Every take must wait for put**

Basis for synchronous message passing frameworks (CSP etc)

- Enables more precise, deterministic, analyzable, but expensive flow control measures.
- Relied on in part because CSP-inspired systems did not allow dynamic construction of new threads, so required more careful management of existing ones.

Variants

- **Barrier**: Threads wait but do not exchange information
- **Rendezvous**: Bidirectional message exchange at wait

# Synchronous Channel Example

```
class SynchronousChannel {
    Object item_ = null;
    boolean putting_ = false; //disable multiple puts

    synchronized void put(Object e) {
        if (e == null) return;
        while (putting_) try { wait(); } catch ...
        putting_ = true;
        item_ = e;
        notifyAll();
        while (item_ != null) try { wait(); } catch ...
        putting_ = false;
        notifyAll();
    }

    synchronized Object take() {
        while (item_ == null) try { wait(); } catch ...
        Object e = item_;
        item_ = null;
        notifyAll();
        return e;
    }
}
```

# Some Pattern Trade-Offs

Thread-per-Message	Pass-Through	Worker Threads
<ul style="list-style-type: none"> <li>+ Simple semantics: When in doubt, make a new thread</li> <li>- Can be hard to limit resource usage</li> <li>- Thread start-up overhead</li> </ul>	<ul style="list-style-type: none"> <li>+ Low overhead</li> <li>- Fragile</li> <li>- No within-activity concurrency</li> </ul>	<ul style="list-style-type: none"> <li>+ Tunable semantics and structure</li> <li>+ Can bound resource usage</li> <li>- Higher overhead</li> <li>- Can waste threads</li> <li>- May block caller (if buffer full etc)</li> </ul>

# Interactive Messages

## Synopsis

- Client activates Server with a oneway message



- Server later invokes a **callback** method on client



Callback can be either oneway or procedural

Callback can instead be sent to a helper object of client

Degenerate case: inform only of task completion

## Applications

- Observer designs
- Completion indications from file and network I/O
- Threads performing computations that yield results

# Observer Designs

The oneway calls are change notifications

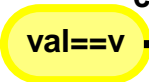

The callbacks are state queries

Examples



- Screen updates
- Constraint frameworks
- Publish/subscribe
- Hand-built variants of `wait` and `notifyAll`

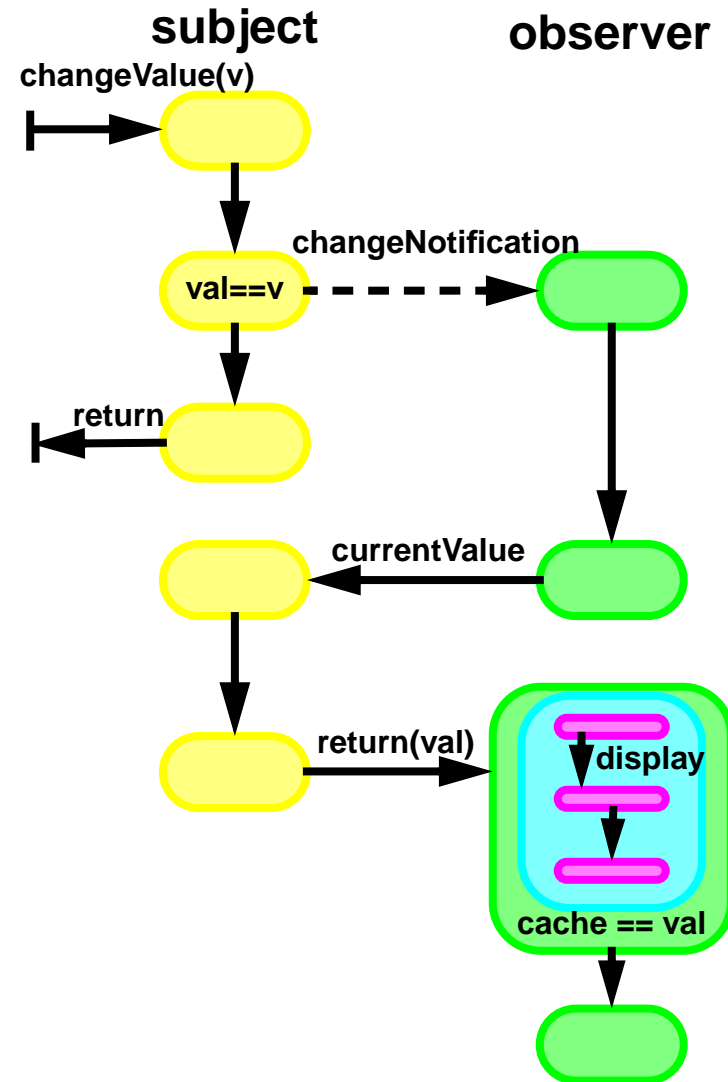
Notifications must use oneway design pattern

Otherwise:

*thread1*  **changeNotification** 

*can deadlock against:*

*thread2*  **currentValue** 





# Observer Example

```
class Subject {
    protected double val_ = 0.0; // modeled state
    public synchronized double getValue(){
        return val_;}
    protected synchronized void setValue(double d){
        val_ = d;}

    protected CopyOnWriteSet obs_ = new COWImpl();
    public void attach(Observer o) { obs_.add(o); }

    public void changeValue(double newstate) {
        setValue(newstate);
        Iterator it = obs_.iterator();
        while (it.hasNext()){
            final Observer o = (Observer)(it.next());
            new Thread(new Runnable() {
                public void run() {
                    o.changeNotification(this);
                }
            }).start();
        }
    }
} // More common to use pass-through calls instead of threads
```

## Observer Example (Continued)

```
class Observer {
    protected double cachedState_;//last known state
    protected Subject subj_;          // only one here

    Observer(Subject s) {
        subj_ = s; cachedState_ = s.getValue();
        display();
    }

    synchronized void changeNotification(Subject s){
        if (s != subj_) return;          // only one subject

        double oldState = cachedState_;
        cachedState_ = subj_.getValue(); // probe

        if (oldState != cachedState_) display();
    }

    synchronized void display() { // default version
        System.out.println(cachedState_);
    }
}
```

# Completion Callbacks

The asynch messages are service activations

The callbacks are **continuation** calls that transmit results

- May contain a message ID or completion token to tell client which task has completed

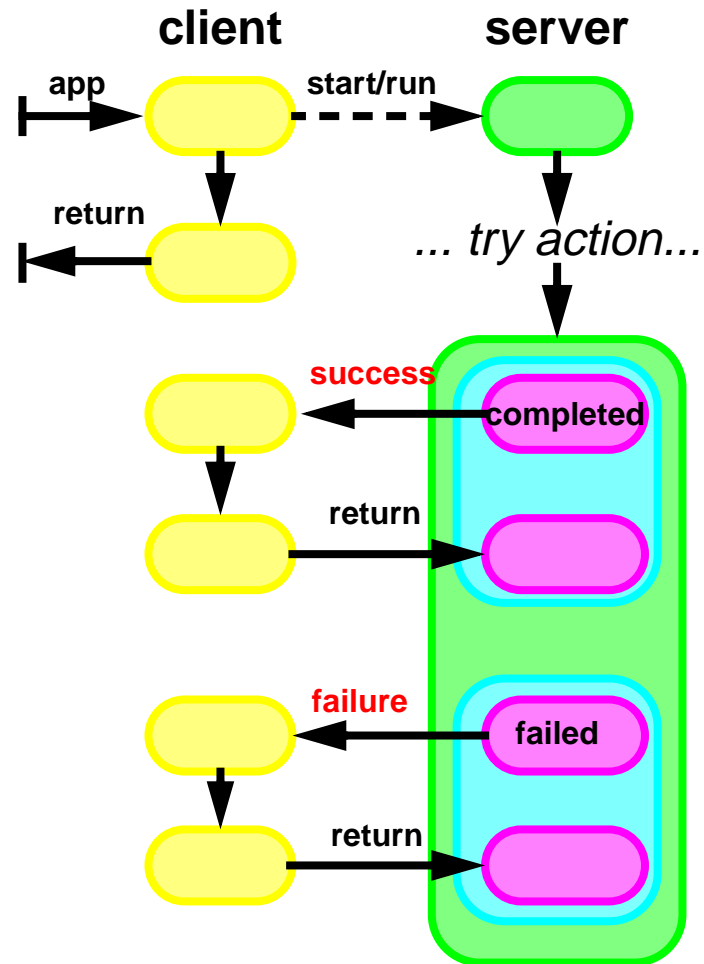
Typically two kinds of callbacks

**Success** – analog of return

**Failure** – analog of throw

Client readiness to accept callbacks may be state-dependent

- For example, if client can only process callbacks in a certain order



# Completion Callback Example

## Callback interface

```
interface FileReaderClient {  
    void readCompleted(String filename);  
    void readFailed(String filename, IOException ex);  
}
```

## Sample Client

```
class FileReaderApp implements FileReaderClient {  
    private byte[] data_;  
  
    void readCompleted(String filename) {  
        // ... use data ...  
    }  
    void readFailed(String fn, IOException e){  
        // ... deal with failure ...  
    }  
  
    void app() {  
        new Thread(new FileReader("file",  
                                   data_,this)).start();  
    }  
}
```

# Completion Callbacks (continued)

## Sample Server

```
class FileReader implements Runnable {
    final String nm_;
    final byte[] d_;
    final FileReaderClient client_; // allow null

    public FileReader(String name, byte[] data,
                      FileReaderClient c) {
        nm_ = name; d_ = data; client_ = c;
    }

    void run() {
        try {
            // ... read...
            if (client_ != null)
                client_.readCompleted(nm_);
        }
        catch (IOException ex) {
            if (client_ != null)
                client_.readFailed(nm_, ex);
        }
    }
}
```

# Threads and I/O

## Java I/O calls generally block

- `Thread.interrupt` causes them to unblock
  - (This is broken in many Java implementations)
- Time-outs are available for some Socket operations
  - `Socket.setSoTimeout`
- Can manually set up classes to arrange time-out interrupts for other kinds of I/O

## Common variants of I/O completion callbacks

- Issue callback whenever there is enough data to process, rather than all at once
- Send a `Runnable` completion action instead of callback
- Use thread pools for either I/O or completion actions

## Alternatives

- Place the I/O and the subsequent actions all in same method, run in same thread.
- Read into a buffer serviced by a worker thread

# Rerouting Exceptions

Callbacks can be used instead of exceptions in any asynchronous messaging context, not just those directly constructing threads

Variants seen in Adaptors that call methods throwing exceptions that clients do not know how to handle:

```
interface Server { void svc() throws SException; }
interface EHandler { void handle(Exception e); }

class SvcAdapter {
    Server server = new ServerImpl();
    EHandler handler;
    void attachHandler(EHandler h) { handler = h; }
    public void svc() { // no throw clause
        try { server.svc(); }
        catch (SException e) {
            if (handler != null) handler.handle(e); }
    }
}
```

Pluggable Handlers can do anything that a normal catch clause can

- Including cancelling all remaining processing in any thread
- But are less structured and sometimes more error-prone

# Joining Threads

`Thread.join()` may be used instead of callbacks when

- Server does not need to call back client with results
- But client cannot continue until service completion

Usually the easiest way to express **termination dependence**

- No need to define callback interface or send client ref as argument
- No need for server to explicitly notify or call client
- Internally implemented in java by
  - `t.join()` calls `t.wait()`
  - terminating threads call `notifyAll()`

Can use to simulate **futures** and **deferred calls** found in other concurrent OO languages

- But no syntactic support for futures



# Join Example

```
public class PictureDisplay {
    private final PictureRenderer myRenderer_;
    // ...

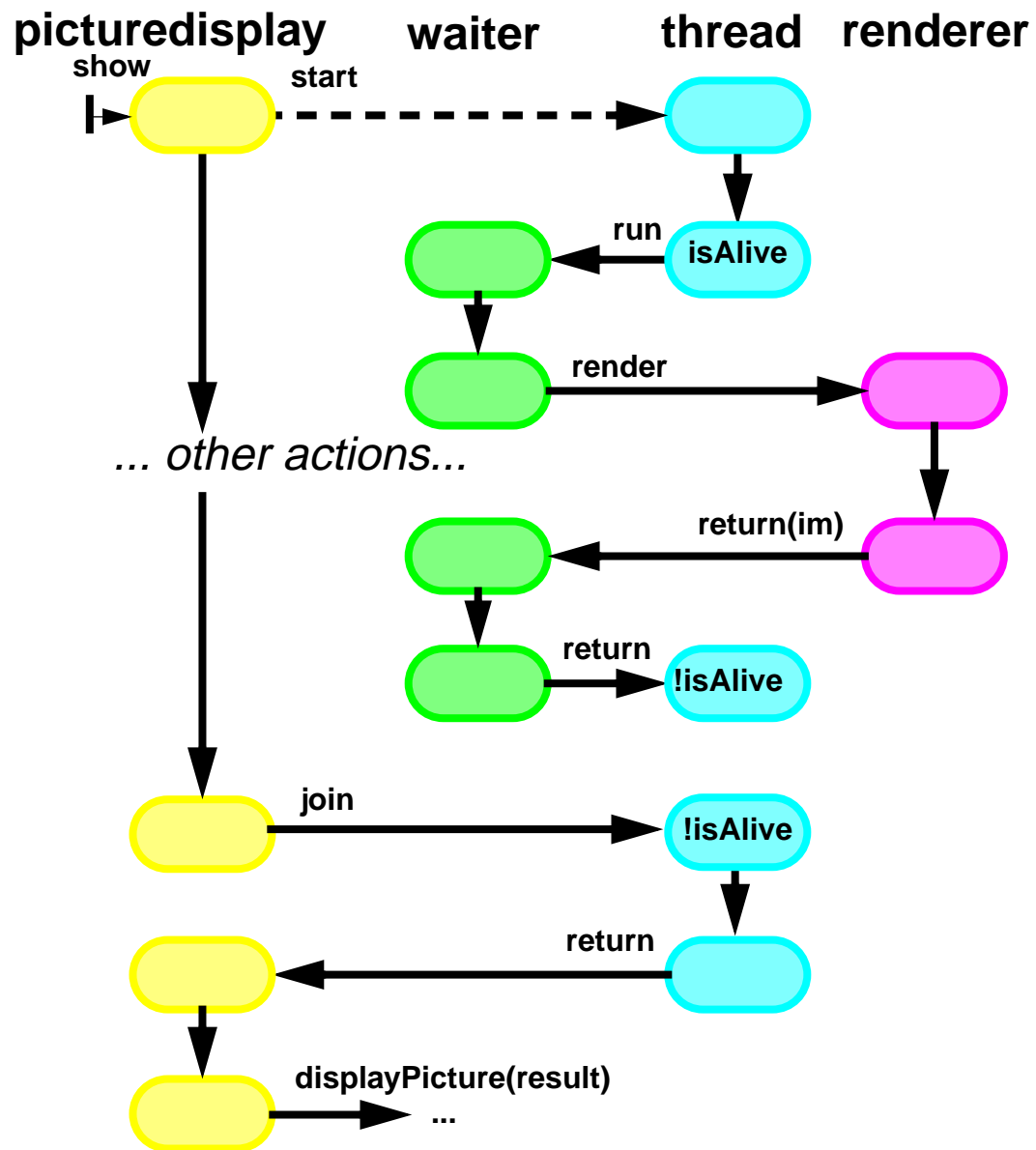
    public void show(final byte[] rawPic) {
        class Waiter implements Runnable {
            Picture result = null;
            public void run() {
                result = myRenderer_.render(rawPic); }
        };
        Waiter waiter = new Waiter();
        Thread t = new Thread(waiter);
        t.start();

        displayBorders(); // do other things
        displayCaption(); // while rendering

        try { t.join(); }
        catch (InterruptedException e) { return; }

        displayPicture(waiter.result);
    }
}
```

# Join Protocol



# Futures

Encapsulate waits for results of operations performed in threads

- Futures are “data” types that wait until results ready
  - Normally requires use of interfaces for types

Clients wait only upon trying to use results

```
interface Pic { byte[] getImage(); }
interface Renderer { Pic render(byte[] raw); }

class AsyncRenderer implements Renderer {
    static class FuturePic implements Pic { //inner
        byte[] img_ = null;
        synchronized void setImage(byte[] img) {
            img_ = img;
            notifyAll();
        }
        public synchronized byte[] getImage() {
            while (img_ == null)
                try { wait(); }
                catch (InterruptedException e) { ... }
            return img_;
        }
    } // continued
}
```

## Futures (continued)

```
// class AsyncRender, continued

    public Pic render(final byte[] raw) {
        final FuturePic p = new FuturePic();
        new Thread(new Runnable() {
            public void run() {
                p.setImage(doRender(raw));
            }
        }).start();
        return p;
    }

    private Pic doRender(byte[] r); // ...
}

class App { // sample usage
    void app(byte[] r) {
        Pic p = new AsyncRenderer().render(r);
        doSomethingElse();
        display(p.getImage()); // wait if not yet ready
    }
}
```

Could alternatively write `join`-based version.

# Cancellation

---

Threads normally terminate after completing their `run` methods

May need to cancel asynchronous activities before completion

- `Applet.stop()` called
- User hits a *CANCEL* button
- Threads performing computations that are not needed
- I/O or network-driven activities that encounter failures

## Options

Asynchronous cancellation: `Thread.stop`

Polling and exceptions: `Thread.interrupt`

Terminating program: `System.exit`

Minimizing contention: `setPriority(MIN_PRIORITY)`

Revoking permissions: `SecurityManager` methods

Unlinking resources known to cause failure exceptions

# Asynchronous Cancellation

**Thread.stop** stops thread by throwing ThreadDeath exception

Deprecated in JDK1.2 because it can corrupt object state:

```
class C {  
    private int v;           // invariant: v >= 0  
    synchronized void f() {  
        v = -1;             // temporarily set to illegal value  
        compute();           // call some other method  
        v = 1;               // set to legal value  
    }  
    synchronized void g() { // depend on invariant  
        while (v != 0) { --v; something(); } }  
}
```

What happens if **stop** occurs during **compute()**?

In principle, could catch(ThreadDeath)

- But this would only work well if done after just about every line of code in just about every Java class. **Impractical.**
- Most other thread systems (including POSIX) either do not support or severely restrict asynchronous cancellation

# Interruption

Safety can be maintained by each object checking cancellation status only when in an appropriate state to do so, relying on:

## `thread.isInterrupted`

- Returns current interruption status.

## `(static) Thread.interrupted`

- *Clears* status for current thread, returning previous status.

## `thread.interrupt`

- Sets interrupted status, and also causes applicable methods to throw `InterruptedException`
- Threads that are blocked waiting for synchronized method or block entry are NOT awakened by `interrupt`

## `InterruptedException`

- Thrown by `Thread.sleep`, `Thread.join`, `Object.wait` if blocked during interruption, **also clearing status**
- Blocking IO methods in the `java.io` package respond to `interrupt` by throwing `InterruptedIOException`

# Implementing a Cancellation Policy

Best-supported policy is:

`Thread.isInterrupted()` means cancelled

Any method sensing interruption should

- Assume current task is cancelled.
- Exit as quickly and cleanly as possible.
- Ensure that callers are aware of cancellation. Options:

`Thread.currentThread().interrupt()`

`throw new InterruptedException()`

Alternatives

- Local recovery and continuation
- Centralized error recovery objects
- Always ignoring/resetting status



# Detecting Cancellation

Cancellation can be checked as a precondition for any method

```
if (Thread.currentThread().isInterrupted())  
    cancellationCode();
```

- Also in loop headers of looping methods, etc

Can be caught, thrown, or rethrown as an exception

```
try { somethingThrowingInterruptedException(); }  
catch (InterruptedException ex) {  
    cancellationCode();  
}
```

- Or as a subclass of a general failure exception, as in `InterruptedException`

Placement, style, and poll frequency require engineering tradeoffs

- How important is it to stop **now**?
- How hard is it to stop now?
- Will another object detect and deal with at a better time?
- Is it too late to stop an irreversable action?
- Does it really matter if the thread is stopped?

# Responses to Cancellation

## Early return

- Clean up and exit without producing or signalling errors — May require rollback or recovery
- Callers can poll status if necessary to find out why action was not carried out.
- Reset (if necessary) interruption status before return:  
`Thread.currentThread().interrupt()`

## Continuation (ignoring cancellation status)

- When it is too dangerous to stop
- When partial actions cannot be backed out
- When it doesn't matter (but consider lowering priority)

## Throwing `InterruptedException`

- When callers must be alerted on method return

## Throwing a general failure `Exception`

- When interruption is one of many reasons method can fail

# Multiphase Cancellation

Foreign code running in thread might not respond to cancellation.

Dealing with this forms part of any security framework. Example:

```
static boolean terminate(Thread t) {  
    if (!t.isAlive()) return true;    // already dead  
  
    // phase 1 -- graceful cancellation  
    t.interrupt();  
    try { t.join(maxWaitToDie); }  
    catch (InterruptedException e) {} // ignore  
    if (!t.isAlive()) return true;    // success  
  
    // phase 2 -- trap all security checks  
    theSecurityMgr.denyAllChecksFor(t); // made-up  
    try { t.join(maxWaitToDie); }  
    catch (InterruptedException ex) {}  
    if (!t.isAlive()) return true;  
  
    // phase 3 -- minimize damage  
    t.setPriority(Thread.MIN_PRIORITY);  
    // or even unsafe last-resort t.stop()  
    return false;  
}
```

# Shutting Down Applets

Applets can create threads

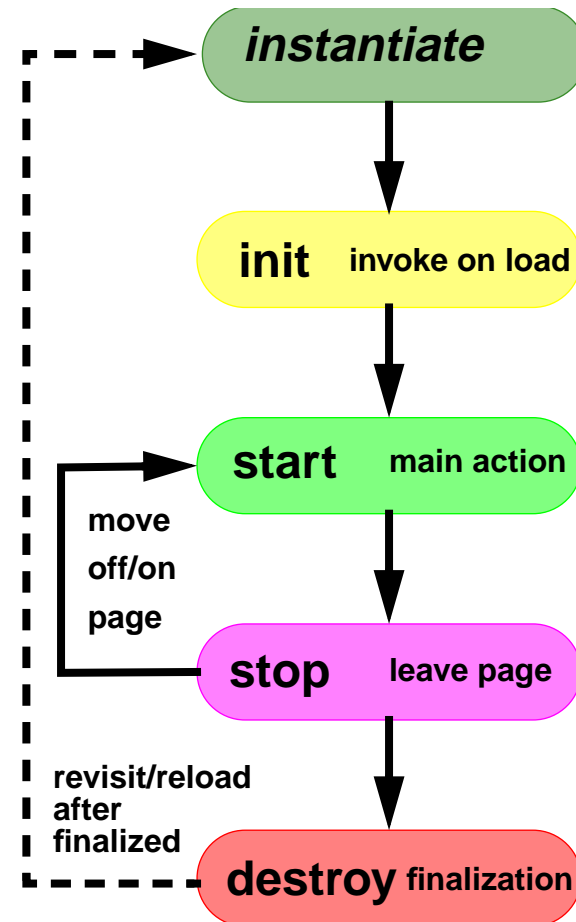
- usually in `Applet.start` and terminate them
- usually in `Applet.stop`

These threads should be cancellable

- Otherwise, it is impossible to predict lifecycle
- No guarantees about when browsers will destroy, or whether threads automatically killed when unloading

Guidelines

- Explicitly cancel threads (normally in `Applet.stop`)
- Ensure that activities check cancellation often enough
- Consider last-resort `Thread.stop` in `Applet.destroy`



# Concurrent Application Architectures

---

Establishing application- (or subsystem-) wide Policies

- Communication directionality, synchronization
- Avoid inconsistent case-by-case decisions

Samplings from three styles

## Flow systems

Wiring together processing stages

- Illustrated with **Push Flow designs**

## Parallel execution

Partitioning independent tasks

- Illustrated with **Group-based designs**

## Layered services

Synchronization and control of ground objects

- Illustrated with **Before/After designs**

# Push Flow Systems

Systems in which (nearly) all activities are performed by objects issuing oneway messages along paths from **sources** to **sinks**

- Each message **transfers** information and/or objects

## Examples

Control systems

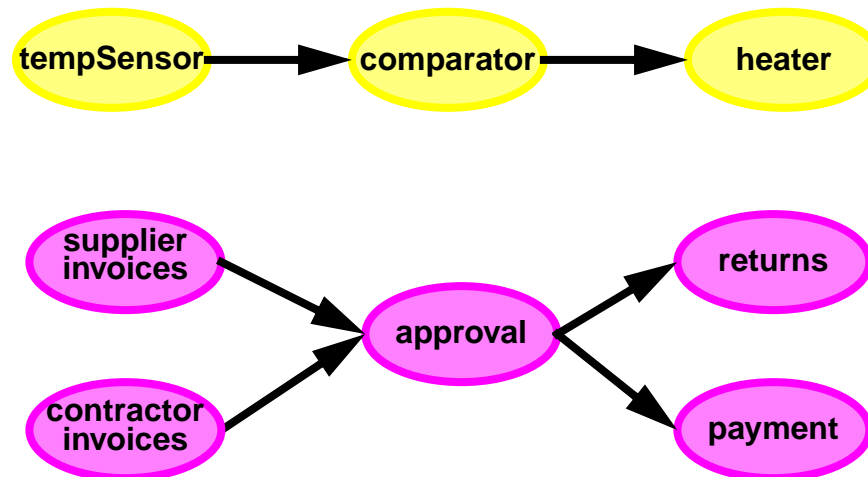
Assembly systems

Workflow systems

Event processing

Chain of command

Pipeline algorithms



Requires common directionality and locality constraints

- Precludes many safety and liveness problems
- Success relies on adherence to design rules  
— potentially formally checkable

The simplest and sometimes best open systems protocol

# Stages in Flow Systems

Every stage is a producer and/or consumer

Stages implement common interface  
with method of form

```
void put(Object item)
```

May have multiple successors

Outgoing elements may be

- **multicast**ed or
- **route**d

May have multiple predecessors

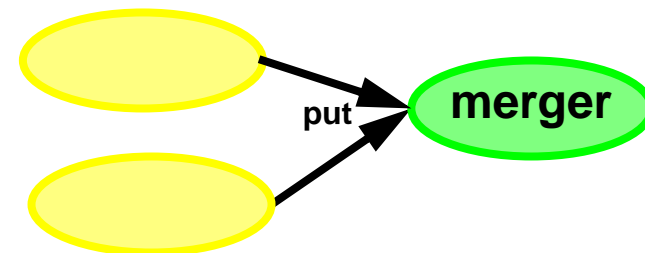
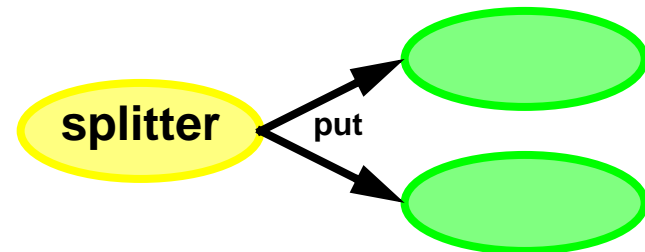
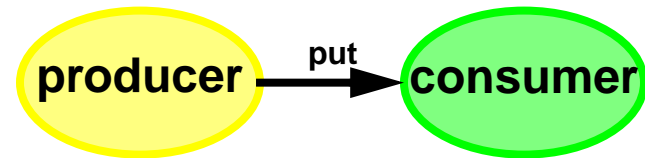
Incoming elements may be

- **combine**d or
- **collect**ed

Normally require **explicit** linkages

- only one stage per connection

Each stage can define `put` using any appropriate oneway message implementation pattern — may differ across stages



# Exclusive Ownership of Resources

Elements in most flow systems act like physical **resources** in that

- If you have one, then you can do something (with it) that you couldn't do otherwise.
- If you have one, then no one else has it.
- If you give it to someone else, then you no longer have it.
- If you destroy it, then no one will ever have it.

## Examples

- Invoices
- Network packets
- File and socket handles
- Tokens
- Mail messages
- Money



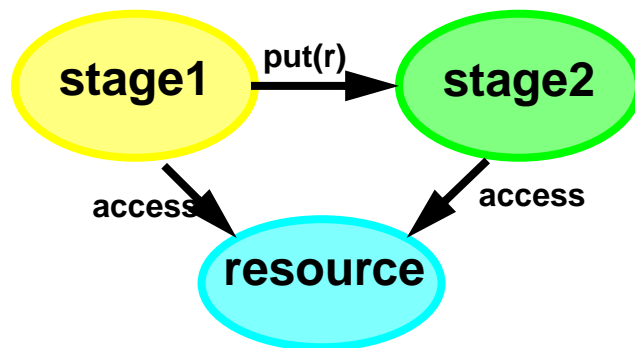
# Accessing Resources

How should stages manage resource objects?

```
class Stage {  
    Resource res;  
    void put(Resource r) { /* ... */ }  
}
```

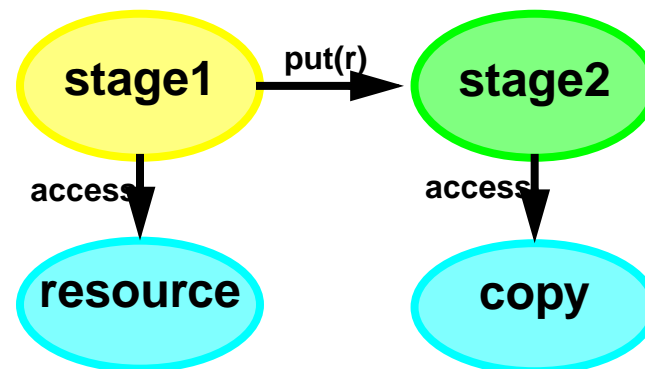
Both reference-passing “shared memory” and copy-based “message passing” policies can encounter problems:

Shared memory



Synchronize access to resource

Message passing



Deal with identity differences

# Ownership Transfer

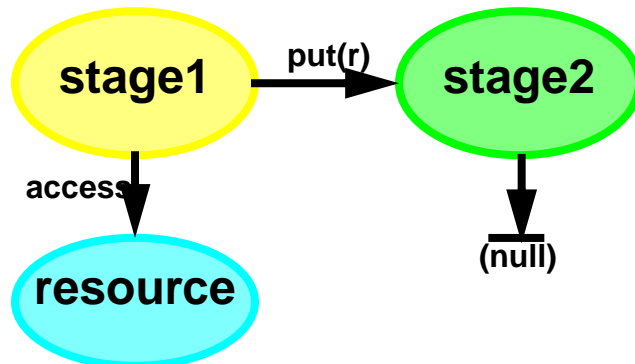
## Transfer policy

**At most one stage refers to any resource at any time**

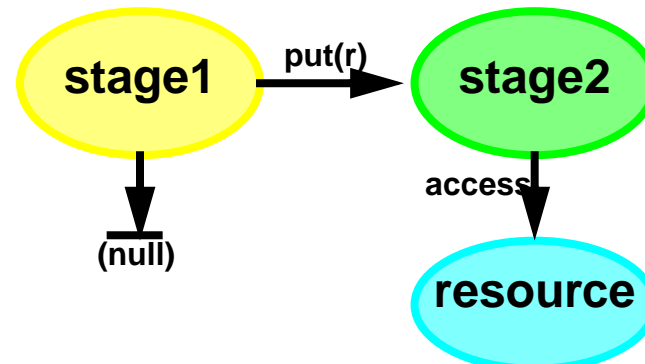
Require each owner to **forget** about each resource after revealing it to any other owner as message argument or return value

- Implement by nulling out instance variables referring to resources after hand-off
  - Or avoiding such variables
- Resource Pools can be used to hold unused resources
  - Or just let them be garbage collected

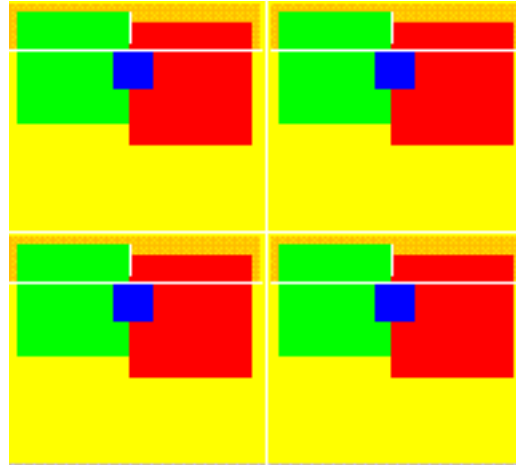
Before message



After message



# Assembly Line Example



**Boxes are flow elements**

- Have adjustable dimension and color
- Can clone and draw themselves

**Sources produce continuous stream of BasicBoxes**

**Boxes are pushed through stages**

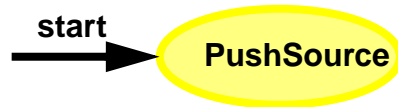
- Stages paint, transform, combine into composite boxes

**A viewer applet serves as the sink**

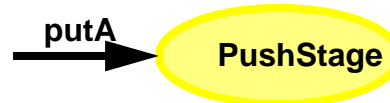
**See CPJ p233-248 for most code omitted here**

- Some code here differs in minor ways for sake of illustration

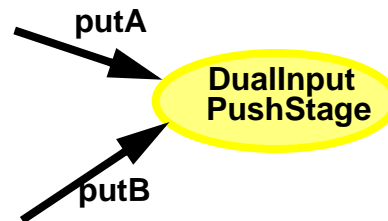
# Interfaces



```
interface PushSource { void start(); }
```



```
interface PushStage { void putA(Box p); }
```



```
interface DualInputPushStage extends PushStage {  
    public void putB(Box p);  
}
```

# Adapters



```
class DualInputAdapter implements PushStage {  
    protected final DualInputPushStage stage_;  
  
    DualInputAdapter(DualInputPushStage stage) {  
        stage_ = stage;  
    }  
  
    void putA(Box p) { stage_.putB(p); }  
}
```

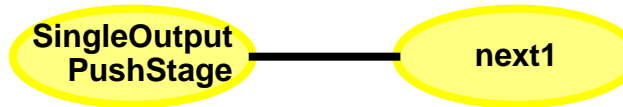
Allows all other stages to issue `putA`

- Use adapter when necessary to convert to `putB`
- Simplifies composition

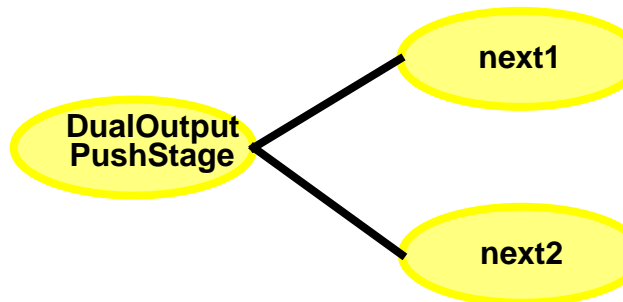
Alternatively, could have used a single `put(command)` interface

- Would require each stage to decode type/sense of command

# Connections



```
class SingleOutputPushStage {  
    protected PushStage next1_ = null;  
    void attach1(PushStage s) { next1_ = s; }  
}
```

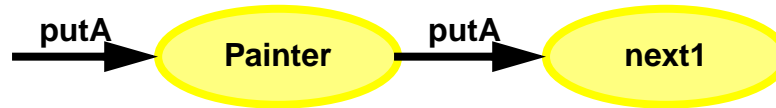


```
class DualOutputPushStage  
    extends SingleOutputPushStage {  
    protected PushStage next2_ = null;  
    void attach2(PushStage s) { next2_ = s; }  
}
```

Alternatively, could have used a collection (Vector etc) of nexts

We assume/require all attaches to be performed before any puts

# Linear Stages



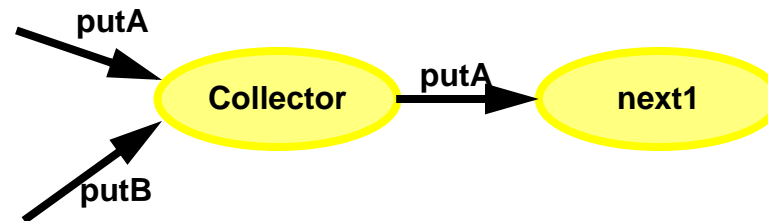
```
class Painter extends SingleOutputPushStage
    implements PushStage {
    protected final Color color_;

    public Painter(Color c) {
        super();
        color_ = c;
    }

    public void putA(Box p) {
        p.color(color_);
        next1_.putA(p);
    }
}
```

**Painter is immutable after initialization**

# Dual Input Stages



```
public class Collector
    extends SingleOutputPushStage
    implements DualInputPushStage {

    public synchronized void putA(Box p) {
        next1_.putA(p);
    }

    public synchronized void putB(Box p) {
        next1_.putA(p);
    }

}
```

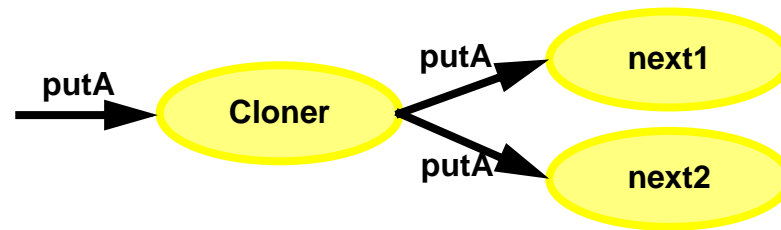
Synchronization used here to illustrate flow control, not safety



# Joiners

```
class Joiner extends SingleOutputPushStage
    implements DualInputPushStage {
    protected Box a_ = null; // incoming from putA
    protected Box b_ = null; // incoming from putB
    protected abstract Box join(Box p, Box q);
    protected synchronized Box joinFromA(Box p) {
        while (a_ != null) // wait until last consumed
            try { wait(); }
            catch (InterruptedException e){return null;}
        a_ = p;
        return tryJoin();
    }
    protected synchronized Box tryJoin() {
        if (a_ == null || b_ == null) return null;
        Box joined = join(a_, b_); // make combined box
        a_ = b_ = null;           // forget old boxes
        notifyAll();              // allow new puts
        return joined;
    }
    void putA(Box p) {
        Box j = joinFromA(p);
        if (j != null) next1_.putA(j);
    }
} // (mechanics for putB are symmetrical)
```

# Dual Output Stages



```

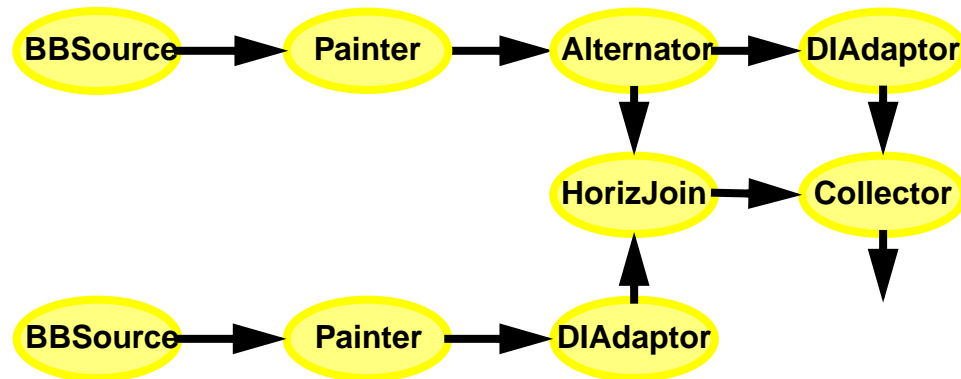
class Cloner extends DualOutputPushStage
    implements PushStage {

    protected synchronized Box dup(Box p) {
        return p.clone();
    }

    public void putA(final Box p) {
        Box p2 = dup(p); // synched update (not nec.)
        Runnable r = new Runnable() {
            public void run() { next1_.putA(p); }
        };
        new Thread(r).start(); // use new thread for A
        next2_.putA(p2);      // current thread for B
    }
}
  
```

Using second thread for second output maintains liveness

# Configuration



All setup code is of form

```
Stage aStage = new Stage();  
aStage.attach(anotherStage);
```

Would be nicer with a visual scripting tool

# Parallel Execution

---

Classic parallel programming deals with

- Tightly coupled, fine-grained multiprocessors

- Large scientific and engineering problems

Speed-ups from parallelism are possible in less exotic settings

- SMPs, Overlapped I/O

Key to speed-up is **independence** of tasks

- Minimize thread communication and synchronization

- Minimize sharing of resource objects

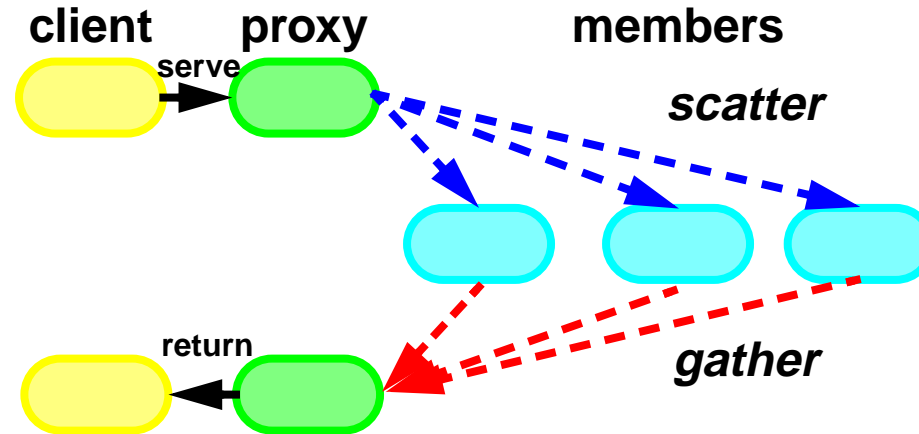
Rely on **groups** of thread-based objects

- Worker thread designs

- Scatter/gather designs

# Interacting with Groups

Group Proxies encapsulate a group of workers and protocol



```

class GroupProxy implements Service {
    public Result serve(Data data) {
        split the data into parts;

        for each part p
            start up a thread to process p;

        for each thread t {
            collect results from t; //via callback or join
            if (have enough results) // one, all, or some
                return aggregate result;
        }
    }
}
  
```

# Group Service Example

```
public class GroupPictureRenderer {

    public Picture[] render(final byte[][] data)
        throws InterruptedException {

        int n = data.length;
        Thread threads[] = new Thread[n];
        final Picture results[] = new Picture[n];

        for (int k = 0; k < n; k++) {
            final int i = k;    // inner vars must be final
            threads[i] = new Thread(new Runnable() {
                public void run() {
                    PictureRenderer r = new PictureRenderer();
                    results[i] = r.render(data[i]);
                }
            });
            threads[i].start();
        }
        // block until all are finished
        for (int k = 0; k < n; k++) threads[k].join();
        return results;
    }
}
```

# Iteration using Cyclic Barriers

CyclicBarrier is synchronization tool for **iterative** group algorithms

- Initialize count with number of members
- `synch()` waits for zero, then resets to initial count

```
class PictureProcessor { // ...
    public void processPicture(final byte[][] data){

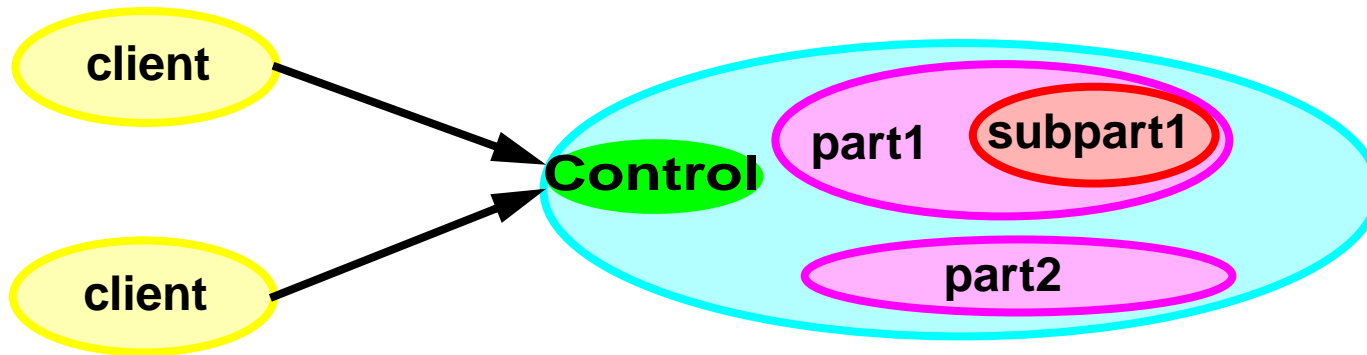
        final CyclicBarrier barrier =
            new CyclicBarrier(NWORKERS);
        for (int ii = 0; ii < NWORKERS; ++ii) {
            final int i = ii;
            Runnable worker = new Runnable() {
                public void run() {
                    while (!done()) {
                        transform(data[i]);
                        try { barrier.barrier(); }
                        catch (InterruptedException e){return;}
                        combine(data[i],data[(i+1)%NWORKERS]);
                    } } };
            new Thread(worker).start();
        }
    }
}
```

# Implementing Cyclic Barriers

```
class CyclicBarrier {  
  
    private int count_  
    private int initial_  
    private int resets_ = 0;  
  
    CyclicBarrier(int c) { count_ = initial_ = c; }  
  
    synchronized boolean barrier() throws Inte...{  
        if (--count_ > 0) { // not yet tripped  
            int r = resets_; // wait until next reset  
            do { wait(); } while (resets_ == r);  
            return false;  
        }  
        else {  
            count_ = initial_  
            ++resets_  
            notifyAll();  
            return true; // return true if caller tripped  
        }  
    }  
}
```



# Layered Services



Providing concurrency control for methods of **internal** objects

- Applying special synchronization policies
- Applying different policies to the same mechanisms

Requires visibility control (containment)

- Inner code must be **communication-closed**
- No unprotected calls in to or out from island
- Outer objects **must never leak identities** of inner objects
- Can be difficult to enforce and check

Usually based on before/after methods

# Three-Layered Application Designs

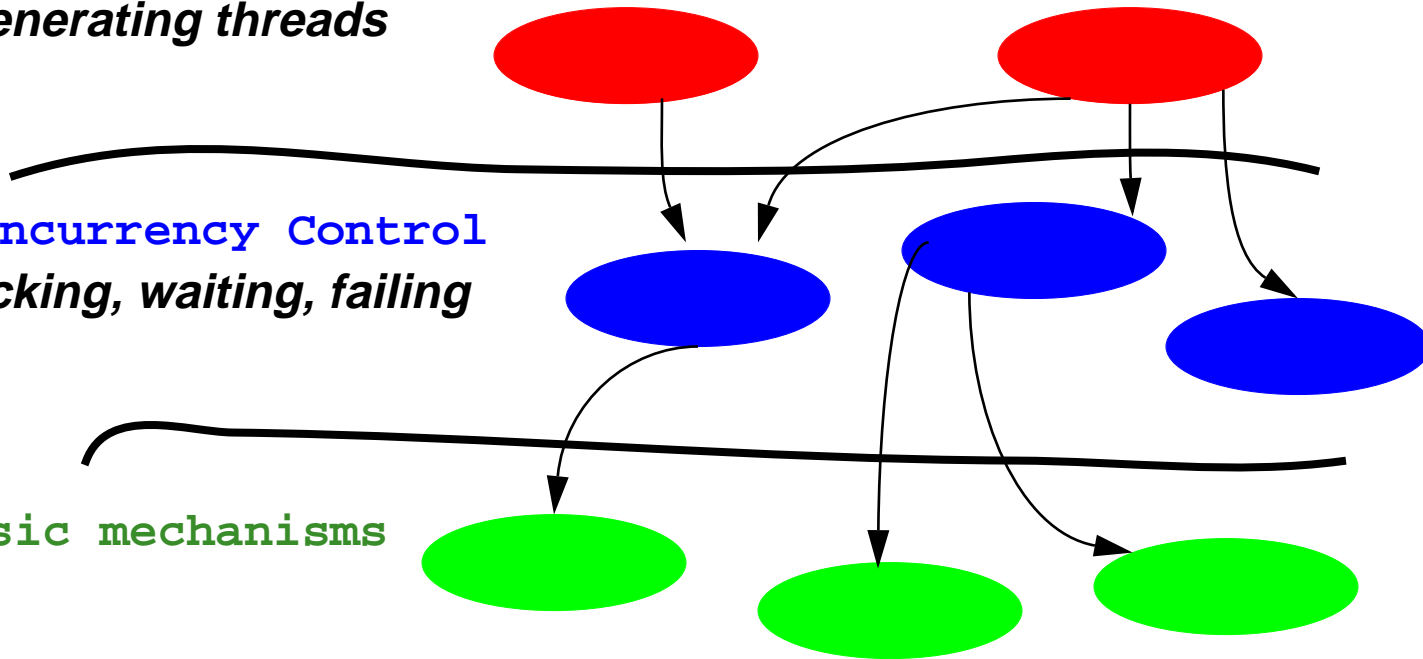
Interaction with external world

*generating threads*

Concurrency Control

*locking, waiting, failing*

Basic mechanisms



Common across many concurrent applications

Generally easy to design and implement

Maintain directionality of control and locking

# Before/After Control

Control access to contained object/action via a method of the form

```
void controlled() {  
    pre();  
    try { action(); }  
    finally { post(); }  
}
```

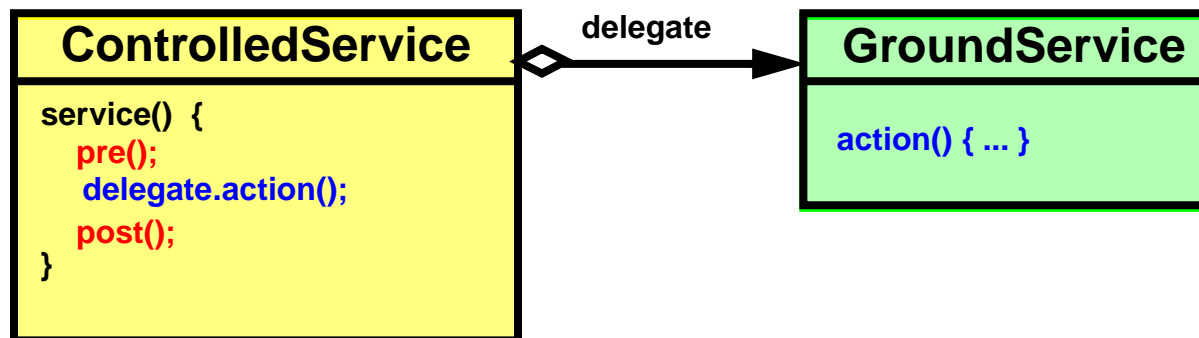
Used by built-in Java `synchronized(obj) { action(); }`

Pre: '{' obtains lock ... Post: '}' releases lock

Control code must be separable from ground action code

- Control code deals only with **execution state**
- Ground code deals only with **intrinsic state**

Basis for many delegation-based designs



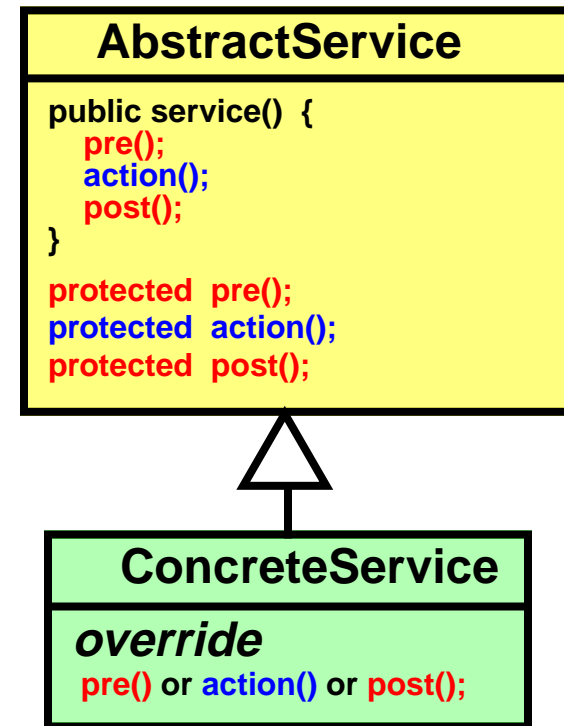
# Template Method Before/After Designs

**Subclassing** is one way to implement before/after containment designs

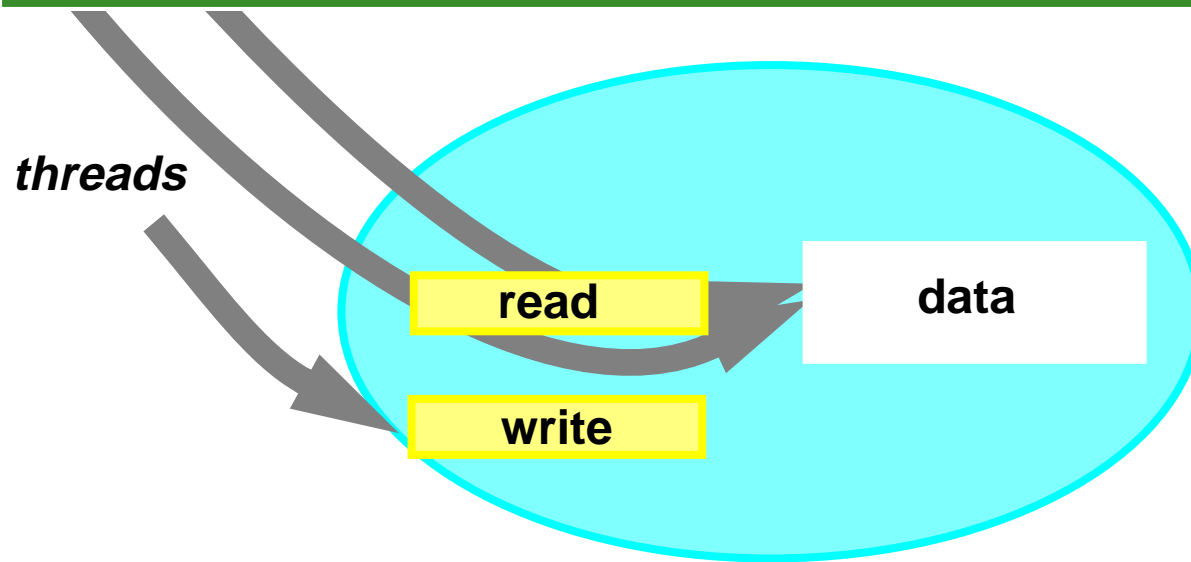
- Superclass instance variables and methods are “contained” in subclass instances

## Template methods

- Isolate ground code and control code in overridable **protected** methods
- **Public** methods call control and ground code in an established fashion
- Can provide default versions in abstract classes
- Can override the control code and/or the ground code in subclasses



# Readers & Writers Policies



## Apply when

- Methods of ground class can be separated into readers (accessors) vs writers (mutators)
  - For example, controlling access to data repository
- Any number of reader threads can run simultaneously, but writers require exclusive access

## Many policy variants possible

- Mainly surrounding precedence of waiting threads
  - Readers first? Writers first? FIFO?

# Readers & Writers via Template Methods

```
public abstract class RW {
    protected int activeReaders_ = 0; // exec state
    protected int activeWriters_ = 0;
    protected int waitingReaders_ = 0;
    protected int waitingWriters_ = 0;

    public void read() {
        beforeRead();
        try { doRead(); } finally { afterRead(); }
    }
    public void write(){
        beforeWrite();
        try { doWrite(); } finally { afterWrite(); }
    }

    protected boolean allowReader() {
        return waitingWriters_ == 0 &&
               activeWriters_ == 0;
    }
    protected boolean allowWriter() {
        return activeReaders_ == 0 &&
               activeWriters_ == 0;
    }
}
```

## Readers & Writers (continued)

```
protected synchronized void beforeRead() {  
    ++waitingReaders_;  
    while (!allowReader())  
        try { wait(); }  
    catch (InterruptedException ex) { ... }  
    --waitingReaders_;  
    ++activeReaders_;  
}
```

```
protected abstract void doRead();
```

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

## Readers & Writers (continued)

```
protected synchronized void beforeWrite() {  
    ++waitingWriters_;  
    while (!allowWriter())  
        try { wait(); }  
        catch (InterruptedException ex) { ... }  
    --waitingWriters_;  
    ++activeWriters_;  
}
```

```
protected abstract void doWrite();
```

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



# Using Concurrency Libraries

---

Library classes can help separate responsibilities for

**Choosing** a policy; for example

- Exclusive versus shared access
- Waiting versus failing
- Use of privileged resources

**Applying** a policy in the course of a service or transaction

- These decisions can occur many times within a method

Standard libraries can encapsulate intricate synchronization code

But can add programming obligations

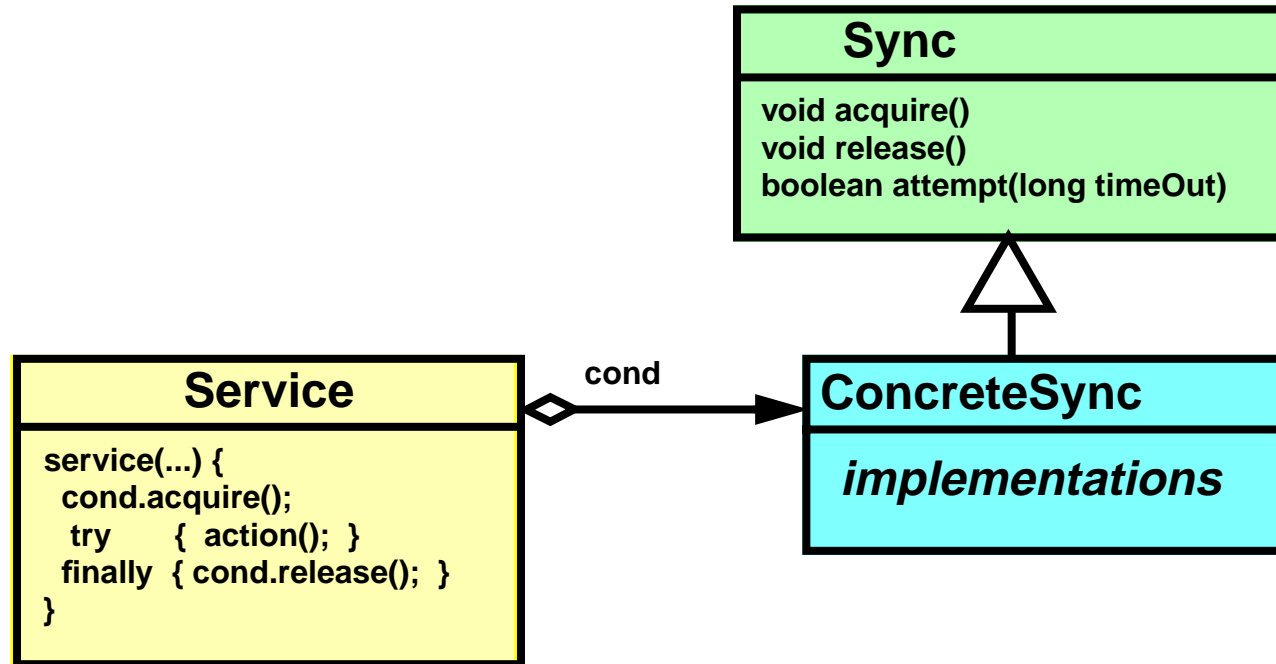
- Correctness relies on all objects obeying usage policy
- Cannot automatically enforce

Examples

- Synchronization, Channels, Transactions

# Interfaces

Sync encompasses many concurrency control policies



```
public interface Sync {
    // Serve as a gate, fail only if interrupted
    void acquire() throws InterruptedException;
    // Possibly allow other threads to pass the gate
    void release();
    // Try to pass for at most timeout msecs,
    // return false if fail
    boolean attempt(long timeout);
}
```

# Synchronization Libraries

---

## Semaphores

- Maintain count of the number of threads allowed to pass

## Latches

- Boolean conditions that are set once, ever

## Barriers

- Counters that cause all threads to wait until all have finished

## Reentrant Locks

- Java-style locks allowing multiple acquisition by same thread, but that may be acquired and released as needed

## Mutexes

- Non-reentrant locks

## Read/Write Locks

- Pairs of conditions in which the readLock may be shared, but the writeLock is exclusive

# Semaphores

Conceptually serve as **permit** holders

- Construct with an initial number of permits (usually 0)
- `require` waits for a permit to be available, then takes one
- `release` adds a permit

But in normal implementations, no actual permits change hands.

- The semaphore just maintains the current count.
- Enables very efficient implementation

## Applications

- Isolating wait sets in buffers, resource controllers
- Designs that would otherwise encounter **missed signals**
  - Where one thread signals before the other has even started waiting
  - Semaphores 'remember' how many times they were signalled

# Counter Using Semaphores

```
class BoundedCounterUsingSemaphores {  
  
    long count_ = MIN;  
  
    Sync decPermits_ = new Semaphore(0);  
    Sync incPermits_ = new Semaphore(MAX-MIN);  
  
    synchronized long value() { return count_; }  
  
    void inc() throws InterruptedException {  
        incPermits_.acquire();  
        synchronized(this) { ++count_; }  
        decPermits_.release();  
    }  
  
    void dec() throws InterruptedException {  
        decPermits_.acquire();  
        synchronized(this) { --count_; }  
        incPermits_.release();  
    }  
}
```

This uses native synch for update protection, but only inside permit blocks. This avoids nested monitor lockouts

# Semaphore Synchronous Channel

```
class SynchronousChannelVS {
    Object item = null;

    Semaphore putPermit = new Semaphore(1);
    Semaphore takePermit = new Semaphore(0);

    Semaphore ack = new Semaphore(0);

    void put(Object x) throws InterruptedException {
        putPermit.acquire();
        item = x;
        takePermit.release();
        ack.acquire();
    }

    Object take() throws InterruptedException {
        takePermit.acquire();
        Object x = item;
        putPermit.release();
        ack.release();
        return x;
    }
}
```

# Using Latches

Conditions starting out false, but once set true, remain true forever

- Initialization flags
- End-of-stream conditions
- Thread termination
- Event occurrences

```
class Worker implements Runnable {  
    Latch go;  
    Worker(Latch l) { go = l; }  
    public void run() {  
        go.acquire();  
        doWork();  
    }  
}  
  
class Driver { // ...  
    void main() {  
        Latch go = new Latch();  
        for (int i = 0; i < N; ++i) // make threads  
            new Thread(new Worker(go)).start();  
        doSomethingElse(); // don't let run yet  
        go.release(); // let all threads proceed  
    }  
}
```

# Using Barrier Conditions

## Count-based latches

- Initialize with a fixed count
- Each release monotonically decrements count
- All acquires pass when count reaches zero

```
class Worker implements Runnable {
    Barrier done;
    Worker(Barrier d) { done = d; }
    public void run() {
        doWork();
        done.release();
    }
}

class Driver { // ...
    void main() {
        Barrier done = new Barrier(N);
        for (int i = 0; i < N; ++i)
            new Thread(new Worker(done)).start();
        doSomethingElse();
        done.acquire(); // wait for all to finish
    }
}
```



# Using Lock Classes

```
class HandSynched {
    private double state_ = 0.0;
    private Sync lock_;

    HandSynched(Sync l) { lock_ = l; }

    void changeState(double d) {
        try {
            lock_.acquire();
            try { state_ = d; }
            finally { lock_.release(); }
        } catch (InterruptedException ex) { }
    }

    double getState() {
        double d = 0.0;
        try {
            lock_.acquire();
            try { d = state_; }
            finally { lock_.release(); }
        } catch (InterruptedException ex) {}
        return d;
    }
}
```

# Wrapper Classes

Standardize common client usages of custom locks using wrappers

- Wrapper class supports `perform` method that takes care of all before/after control surrounding a `Runnable` command sent as a parameter
- Can also standardize failure control by accepting `Runnable` action to be performed on `acquire` failure

Alternative `perform` methods can accept blocks that return results and/or throw exceptions

- But need to create new interface type for each kind of block

Similar to macros in other languages

- But implement more safely via inner classes
  - Wrappers are composable

Adds noticeable overhead for simple usages

- Most useful for controlling “heavy” actions

# Before/After Wrapper Example

```
class WithLock {
    Sync cond;
    public WithLock(Sync c) { cond = c; }

    public void perform(Runnable command)
        throws InterruptedException {
        cond.acquire();
        try { command.run(); }
        finally { cond.release(); }
    }

    public void perform(Runnable command,
        Runnable onInterrupt) {
        try { perform(command); }
        catch (InterruptedException ex) {
            if (onInterrupt != null)
                onInterrupt.run();
            else // default
                Thread.currentThread().interrupt();
        }
    }
}
```

# Using Wrappers

```
class HandSynchedV2 { // ...
    private double state_ = 0.0;
    private WithLock withlock_;

    HandSynchedV2(Sync l) {
        withlock_ = new WithLock(l);
    }

    void changeState(double d) {
        withlock_.perform(
            new Runnable() {
                public void run() { state_ = d; } },
            null); // use default interrupt action
    }

    double getState() {
        // (need to define interface & perform version)
        try {
            return withLock_.perform(new DoubleAction(){
                public void run() { return state_; } });
        }
        catch (InterruptedException ex){return 0.0;}
    }
}
```

# Using Conditional Locks

`Sync.attempt` can be used in conditional locking idioms

## Back-offs

- Escape out if a lock not available
- Can either retry or fail

## Reorderings

- Retry lock sequence in different order if first attempt fails

## Heuristic deadlock detection

- Back off on time-out

## Precise deadlock detection

- Implement `Sync` via lock manager that can detect cycles

# Back-off Example

```
class Cell {
    long value;
    Sync lock = new SyncImpl();
    void swapValue(Cell other) {
        for (;;) {
            try {
                lock.acquire();
                try {
                    if (other.lock.attempt(100)) {
                        try {
                            long t = value; value = other.value;
                            other.value = t;
                            return;
                        }
                        finally { other.lock.release(); }
                    }
                }
                finally { lock.release(); }
            }
            catch (InterruptedException ex) { return; }
        }
    }
}
```

# Lock Reordering Example

```
class Cell {
    long value;
    Sync lock = new SyncImpl();
    private static boolean trySwap(Cell a, Cell b) {
        a.lock.acquire();
        try {
            if (!b.lock.attempt(0)) return false;
            try {
                long t = a.value;
                a.value = b.value;
                b.value = t;
                return true;
            }
            finally { other.lock.release(); }
        }
        finally { lock.release(); }
        return false;
    }

    void swapValue(Cell other) {
        while (!trySwap(this, other) &&
            !tryswap(other, this)) Thread.yield();
    }
}
```

# Using Read/Write Locks

```
public interface ReadWriteLock {  
    Sync readLock();  
    Sync writeLock();  
}
```

## Sample usage using wrapper

```
class WithRWLock {  
    ReadWriteLock rw;  
  
    public WithRWLock(ReadWriteLock l) { rw = l; }  
  
    public void performRead(Runnable readCommand)  
        throws InterruptedException {  
  
        rw.readLock().acquire();  
        try { readCommand.run(); }  
        finally { rw.readlock().release(); }  
    }  
  
    public void performWrite(...) // similar  
}
```



# Transaction Locks

## Associate keys with locks

- Each key corresponds to a different transaction.
  - `Thread.currentThread()` serves as key in reentrant Java synchronization locks
- Supply keys as arguments to gating methods
- Security frameworks can use similar interfaces, adding mechanisms and protocols so keys serve as capabilities

## Sample interface

```
interface TransactionLock {  
  
    void begin(Object key); // bind key with lock  
  
    void end(Object key);    // get rid of key  
  
    void acquire(Object key)  
        throws InterruptedException;  
  
    void release(Object key);  
}
```

# Transactional Classes

Implement a common transaction control interface, for example:

```
interface Transactor {  
  
    // enter a new transaction  
    void join(Object key) throws Failure;  
  
    // return true if transaction can be committed  
    boolean canCommit(Object key);  
  
    // update state to reflect current transaction  
    void commit(Object key) throws Failure;  
  
    // roll back state  
    void abort(Object key);  
}
```

Transactors must ensure that **all** objects they communicate with are also Transactors

- Control arguments must be propagated to all participants

# Per-Method Transaction Control

Add transaction control argument to each method.

For example:

```
interface TransBankAccount extends Transactor {  
    long balance(Object key)  
        throws InterruptedException;  
  
    void deposit(Object key, long amount)  
        throws InsufficientFunds,  
            InterruptedException;  
  
    void withdraw(Object key, long amount)  
        throws InsufficientFunds,  
            InterruptedException;  
}
```

The same interfaces can apply to optimistic transactions

- Use interference detection rather than locking.
- They are generally interoperable

# Per -ThreadGroup Transaction Control

Assumes each transaction established in own ThreadGroup

```
class Context { // ...
    Object    get(Object name);
    void      bind(Object name, Object val);
}

class XTG extends ThreadGroup { // ...
    Context getContext();
}

class Account extends Transactor {
    private long balance_;
    private TransactionLock tlock_;
    // ...
    void deposit(long amount) throws ... {
        tlock_.acquire(((XTG)
            (Thread.currentThread().getThreadGroup()))
            .getContext().get("TransactionID"));
        synchronized (this) {
            if (amount >= 0) balance_ += amount; else ...
        }
    }
}
```

# Integrating Control Policies

Dealing with multiple contextual domains, including

- **Security**: Principal identities, keys, groups, etc
- **Synchronization**: Locks, conditions, transactions, ...
- **Scheduling**: Priorities, timing, checkpointing, etc
- **Environment**: Location, computational resources

Dealing with multiple outcomes

- Block, fail, proceed, save state, commit state, notify, ...

Encapsulating associated policy control information

- For example access control lists, lock dependencies

Introducing new policies in sub-actions

- New threads, conditions, rights-transfers, subtransactions
- Avoiding policy conflicts: policy compatibility matrices, ...

Avoiding excessive programming obligations for developers

Tool-based code generation, layered virtual machines

# Using Integrated Control

Methods invoke helpers to make control decisions as needed

```
class Account { // ...

    void deposit(long amount, ...) {
        authenticator.authenticate(clientID);
        accessController.checkAccess(clientID, acl);
        logger.logDeposit(clientID, transID, amount);
        replicate.shadowDeposit(...);
        db.checkpoint(this);
        lock.acquire();

        balance += amount;

        lock.release();
        db.commit(balance, ...);
        UIObservers.notifyOfChange(this);
    }
}
```

Not much fun to program.

# Implementing Library Classes

Classes based on Java monitor methods can be slow

- Involve context switch, locking, and scheduling overhead
- Relative performance varies across platforms

Some performance enhancements

## State tracking

- Only notify when state changes known to unblock waits

## Isolating wait sets

- Only wake up threads waiting for a particular state change

## Single notifications

- Only wake up a single thread rather than all waiting threads

## Avoiding locks

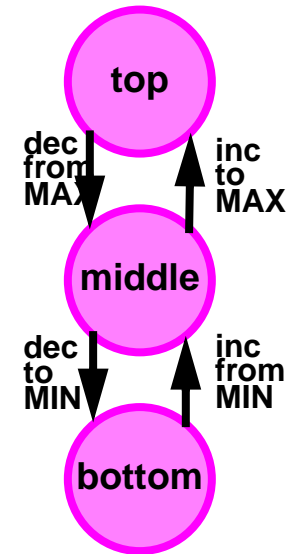
- Don't lock if can be sure won't wait

Can lead to significantly faster, but more complex and fragile code

# Tracking State in Guarded Methods

Partition action control state into categories with same enabling properties

State	Condition	inc	dec
top	<code>value == MAX</code>	no	yes
middle	<code>MIN &lt; value &lt; MAX</code>	yes	yes
bottom	<code>value == MIN</code>	yes	no



Only provide notifications when making a state transition that can ever unblock another thread

- Here, on exit from **top** or **bottom**
  - When count goes up from MIN or down from MAX
- Still need `notifyAll` unless add instrumentation

State tracking leads to faster but more fragile code

- Usually many fewer notification calls
- Harder to change guard conditions
- Harder to add subclasses with different conditions



# Counter with State Tracking

```
class FasterGuardedBoundedCounter {  
    protected long count_ = MIN;  
    synchronized long value() { return count_; }  
  
    synchronized void inc()  
        throws InterruptedException {  
        while (count_ == MAX) wait();  
        if (count_++ == MIN) notifyAll();  
    }  
  
    synchronized void dec()  
        throws InterruptedException {  
        while (count_ == MIN) wait();  
        if (count_-- == MAX) notifyAll();  
    }  
}
```

# Buffer with State Tracking

```
class BoundedBufferVST {
    Object[] data_;
    int putPtr_ = 0, takePtr_ = 0, size_ = 0;

    protected void doPut(Object x){
        data_[putPtr_] = x;
        putPtr_ = (putPtr_ + 1) % data_.length;
        if (size_++ == 0) notifyAll();
    }

    protected Object doTake() {
        Object x = data_[takePtr_];
        data_[takePtr_] = null;
        takePtr_ = (takePtr_ + 1) % data_.length;
        if (size_-- == data_.length) notifyAll();
        return x;
    }

    synchronized void put(Object x) throws Inte... {
        while (isFull()) wait();
        doPut(x);
    }
    // ...
}
```

# Inheritance Anomaly Example

```
class XBuffer extends BoundedBufferVST {
    synchronized void putPair(Object x, Object y)
        throws InterruptedException {
        put(x);
        put(y);
    }
}
```

PutPair does not guarantee that the pair is inserted contiguously

To ensure contiguity, try adding guard:

```
while (size_ > data_.length - 2) wait();
```

But doTake only performs notifyAll when the buffer transitions from full to not full

- The wait may block indefinitely even when space available
- So **must rewrite doTake** to change notification condition

Would have been better to factor out the notification conditions in a separate overridable method

- Most inheritance anomalies can be avoided by fine-grained (often tedious) factoring of methods and classes

# Isolating Waits and Notifications

## Mixed condition problems

- Threads that wait in different methods in the same object may be blocked for different reasons — for example, *not Empty* vs *not Full* for buffer
- `notifyAll` wakes up all threads, even those waiting for conditions that could not possibly hold

Can isolate waits and notifications for different conditions in different objects — an application of **splitting**

## Thundering herd problems

- `notifyAll` may wake up many threads
- Often, at most one of them will be able to continue

Can solve by using **notify** instead of `notifyAll` **only** when

- **All threads wait on same condition**
- **At most one thread could continue anyway**
- That is, when it doesn't matter which one is woken, and it doesn't matter that others aren't woken

# Implementing Reentrant Locks

```
final class ReentrantLock implements Sync {
    private Thread owner_ = null;
    private int    holds_ = 0;

    synchronized void acquire() throws Interru... {
        Thread caller = Thread.currentThread();
        if (caller == owner_) ++holds_;
        else {
            try { while (owner_ != null) wait(); }
            catch (InterruptedException e) {
                notify(); throw e;
            }
            owner_ = caller; holds_ = 1;
        }
    }

    synchronized void release() {
        Thread caller = Thread.currentThread();
        if (caller != owner_ || holds_ <= 0)
            throw new Error("Illegal Lock usage");
        if (--holds_ == 0) {
            owner_ = null;
            notify();
        }
    }
}
```

# Implementing Semaphores

```
final class Semaphore implements Sync {
    int permits_; int waits_ = 0;

    Semaphore(int p) { permits_ = p; }

    synchronized void acquire() throws Interrupt.. {
        if (permits_ <= waits_) {
            ++waits_;
            try {
                do { wait(); } while (permits_ == 0);
            }
            catch(InterruptedException ex) {
                --waits_; notify(); throw ex;
            }
            --waits_;
        }
        --permits_;
    }

    synchronized void release() {
        ++permits_;
        notify();
    }
}
```

# Implementing Latches

Exploit set-once property to avoid locking using **double-check**:

Check status without even locking

- If set, exit — no possibility of conflict or stale read
- Otherwise, enter standard locked wait

But can have surprising effects if callers expect locking for sake of memory consistency.

```
final class Latch implements Sync {
    private boolean latched_ = false;

    void acquire() throws InterruptedException {
        if (!latched_)
            synchronized(this) {
                while (!latched_) wait();
            }
    }

    synchronized void release() {
        latched_ = true;
        notifyAll();
    }
}
```

# Implementing Barrier Conditions

Double-check can be used for any **monotonic** variable that is tested only for a threshold value

CountDown Barriers monotonically decrement counts

- Tests against zero cannot encounter conflict or staleness

(This technique does not apply to Cyclic Barriers)

```
class CountDown implements Sync {
    private int count_;
    CountDown(int initialc) { count_ = initialc; }

    void acquire() throws InterruptedException {
        if (count_ > 0)
            synchronized(this) {
                while (count_ > 0) wait();
            }
    }
    synchronized void release() {
        if (--count_ == 0) notifyAll();
    }
}
```



# Implementing Read/Write Locks

```
class SemReadWriteLock implements ReadWriteLock {

    // Provide fair access to active slot
    Sync active_ = new Semaphore(1);

    // Control slot sharing by readers
    class ReaderGate implements Sync {
        int readers_ = 0;

        synchronized void acquire()
            throws InterruptedException {
            // readers pile up on lock until first passes
            if (readers_++ == 0) active_.acquire();
        }

        synchronized void release() {
            if (--readers_ == 0) active_.release();
        }
    }

    Sync rGate_ = new ReaderGate();

    public Sync writeLock() { return active_; }
    public Sync readLock()  { return rGate_; }
}
```

# Documenting Concurrency

---

Make code **understandable**

- To developers who use components
- To developers who maintain and extend components
- To developers who review and test components

**Avoid** need for extensive documentation by adopting:

- Standard policies, protocols, and interfaces
- Standard design patterns, libraries, and frameworks
- Standard coding idioms and conventions

Document **decisions**

- Use javadoc to link to more detailed descriptions
- Use naming and signature conventions as shorthand clues
- Explain deviations from standards, usage limitations, etc
- Describe necessary data invariants etc

Use **checklists** to ensure minimal sanity

# Sample Documentation Techniques

## Patlet references

```
/** ... Uses  
 * <a href="tpm.html">Thread-per-Message</a> **/  
void handleRequest(...);
```

## Default naming and signature conventions

Sample rule: Unless specified otherwise, methods that can block have signature

```
... throws InterruptedException
```

## Intentional limitations, and how to work around them

```
/** ... NOT Threadsafe, but can be used with  
 * @see XAdapter to make lockable version. **/
```

## Decisions impacting potential subclassers

```
/** ... Always maintains a legal value,  
 * so accessor method is unsynchronized **/  
protected int bufferSize;
```

## Certification

```
/** Passed safety review checklist 11Nov97 **/
```

# Semiformal Annotations

**PRE** – Precondition (normally unchecked)

```
/** PRE: Caller holds synch lock ...
```

**WHEN** – Guard condition (always checked)

```
/** WHEN not empty return oldest ...
```

**POST** – Postcondition (normally unchecked)

```
/** POST: Resource r is released...
```

**OUT** – Guaranteed message send (relays, callbacks, etc)

```
/** OUT: c.process(buff) called after read...
```

**RELY** – Required property of other objects/methods

```
/** RELY: Must be awakened by x.signal()...
```

**INV** – Object constraint true at start/end of every activity

```
/** INV: x,y are valid screen coordinates...
```

**INIT** – Object constraint that must hold upon construction

```
/** INIT: bufferCapacity greater than zero...
```

# Safety Problem Checklist

---

## Storage conflicts

- Failure to ensure exclusive access; race conditions

## Atomicity errors

- Breaking locks in the midst of logically atomic operations

## Representation inconsistencies

- Allowing dependent representations to vary independently

## Invariant failures

- Failing to re-establish invariants within atomic methods  
for example failing to clean up after exceptions

## Semantic conflicts

- Executing actions when they are logically prohibited

## Slipped Conditions

- A condition stops holding in the midst of an action  
requiring it to hold

## Memory ordering and visibility

- Using stale cached values

# Liveness Problems

---

## Lockout

- A called method never becomes available

## Deadlock

- Two or more activities endlessly wait for each other

## Livelock

- A retried action never succeeds

## Missed signals

- A thread starts waiting after it has already been signalled

## Starvation

- A thread is continually crowded out from passing gate

## Failure

- A thread that others are waiting for stops

## Resource exhaustion

- Exceeding memory, bandwidth, CPU limitations

# Efficiency Problems

---

## Too much locking

- Cost of using `synchronized`
- Cost of blocking waiting for locks
- Cost of thread cache flushes and reloads

## Too many threads

- Cost of starting up new threads
- Cost of context switching and scheduling
- Cost of inter-CPU communication, cache misses

## Too much coordination

- Cost of guarded waits and notification messages
- Cost of layered concurrency control

## Too many objects

- Cost of using objects to represent state, messages, etc

# Reusability Problems

---

## Context dependence

- Components that are not safe/live outside original context

## Policy breakdown

- Components that vary from system-wide policies

## Inflexibility

- Hardwiring control, premature optimization

## Policy clashes

- Components with incompatible concurrency control strategies

## Inheritance anomalies

- Classes that are difficult or impossible to subclass

## Programmer-hostile components

Components imposing awkward, implicit , and/or error-prone programming obligations