Concurrent Programming in Java

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Concurrent Programming in Java

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Topics

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 ...

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.

None of this material should be construed as official Sun information.

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Concurrency

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

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:

Operate across multiple CPUs symmetric multiprocessor (SMPs), clusters, special-purpose architectures, ...	**Share access to resources** objects, memory, displays, file descriptors, sockets, ...
Parallel programming mainly deals with mapping software to multiple CPUs to improve performance.	**Distributed** programming mainly deals with concurrent programs that do *NOT* share system resources.

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

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 occuring 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**

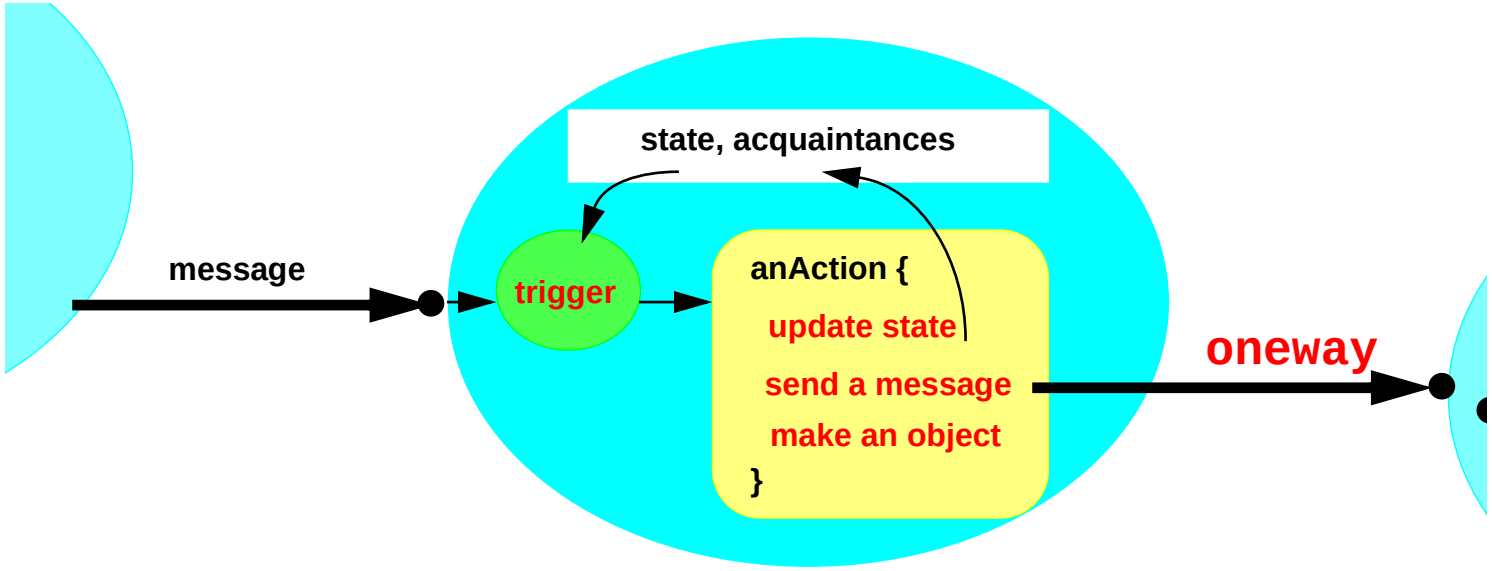
Four basic computational operations

- **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.

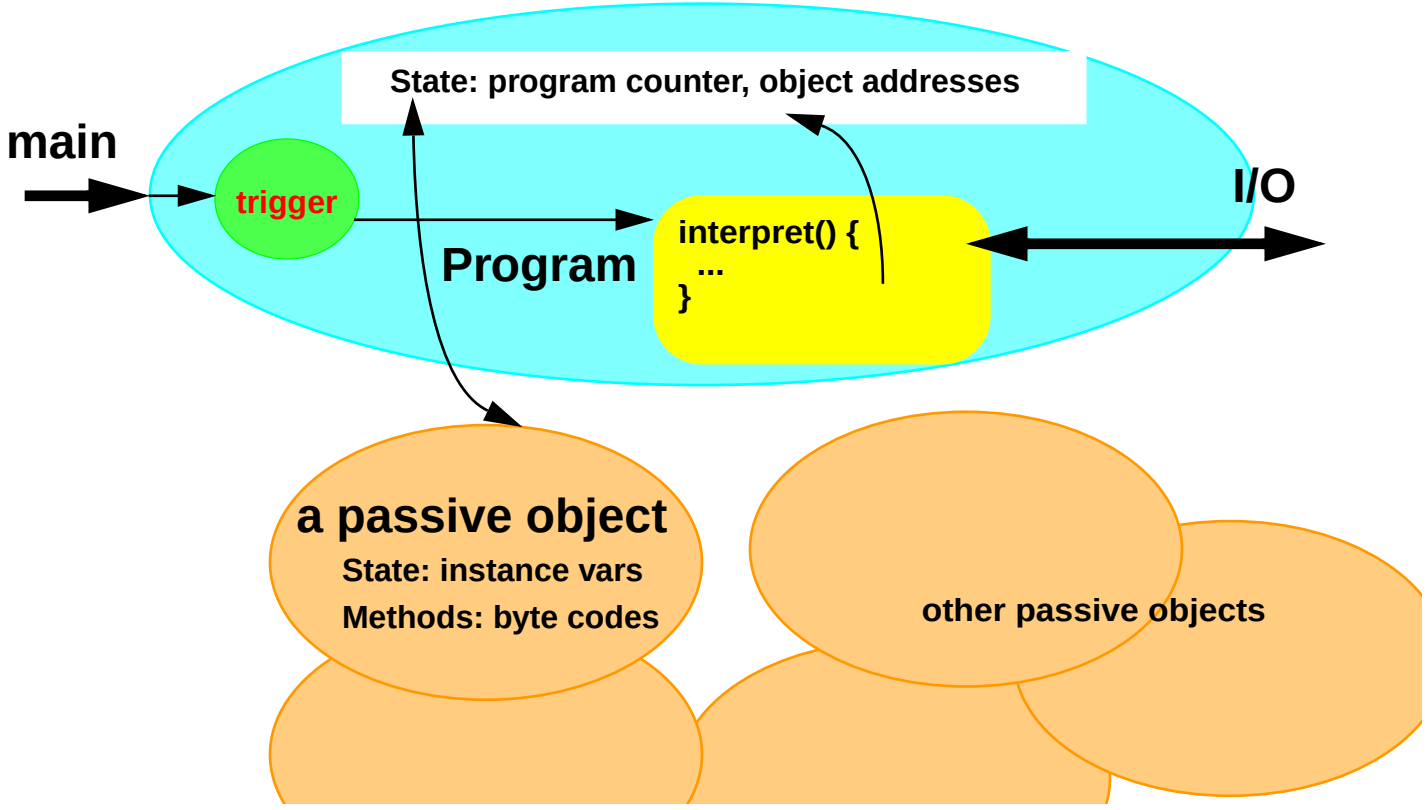
Many extensions and choices of detailed semantics

- 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 (interpretor)

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

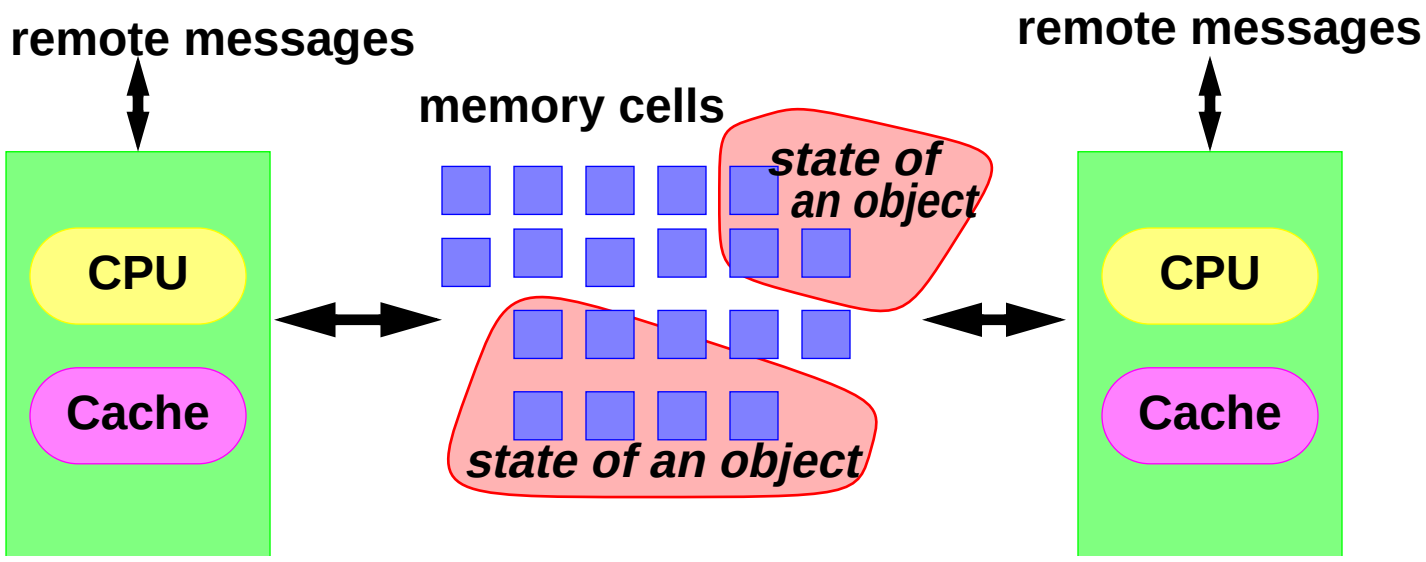
Concurrent Object Models

Mixtures of active and passive objects

Normally many fewer threads than passive objects

Dumber Active Objects	Smarter Passive Objects
• Can perform only one activity — in Java, '`run()`' • Share most resources with other threads • Require scheduling in order to coexist	• 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

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

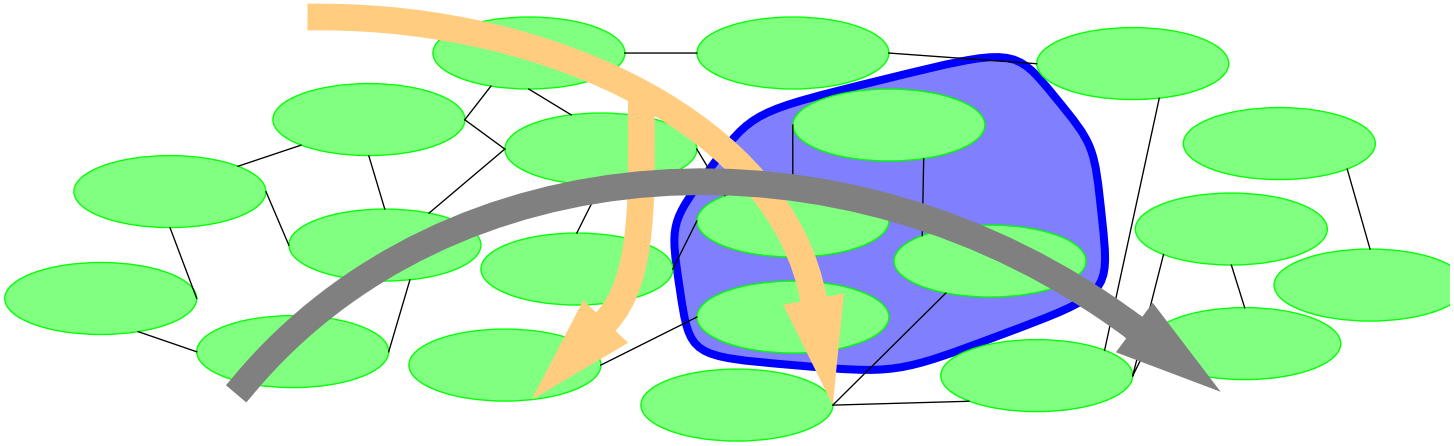
Three main aspects of concurrent OO design

Policies & Protocol	Object structures	Coding techniques
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

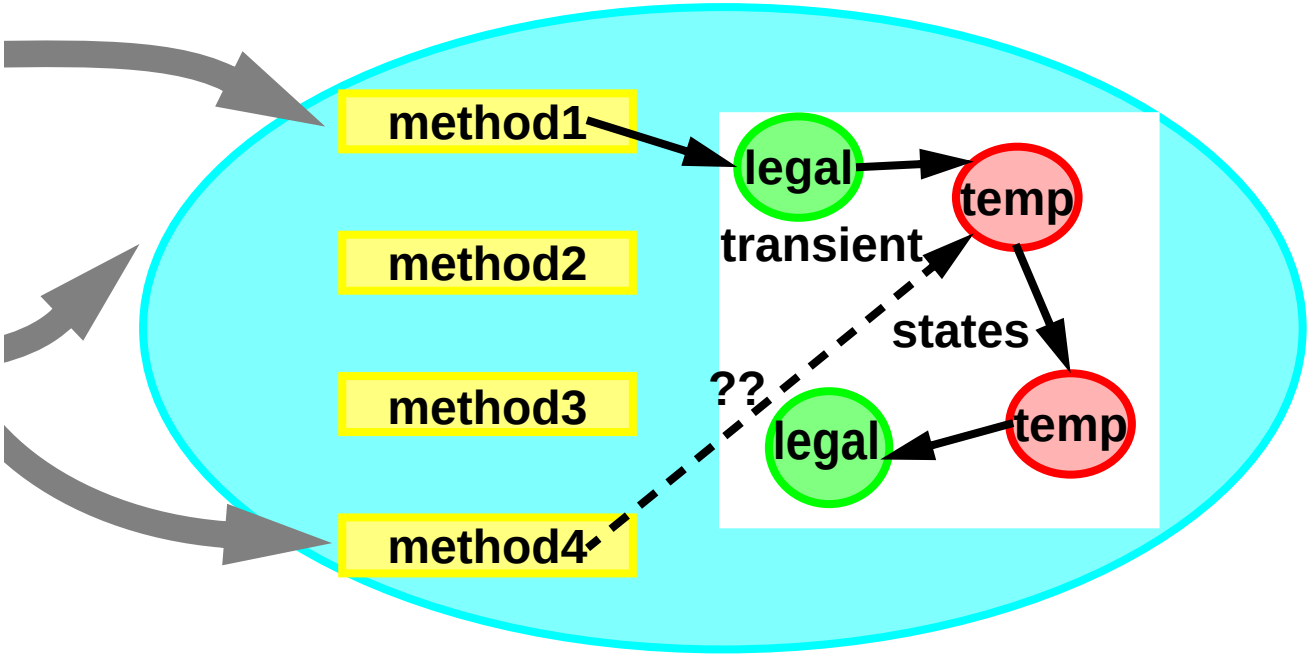
- ADTs, aggregate components, JavaBeans, monitors, business objects, remote RMI objects, subsystems, ...
- May be grouped according to structure, role, ...
- Usable across multiple activities — focus on SAFETY

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 simultanous access to services**

State Inconsistency Examples

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

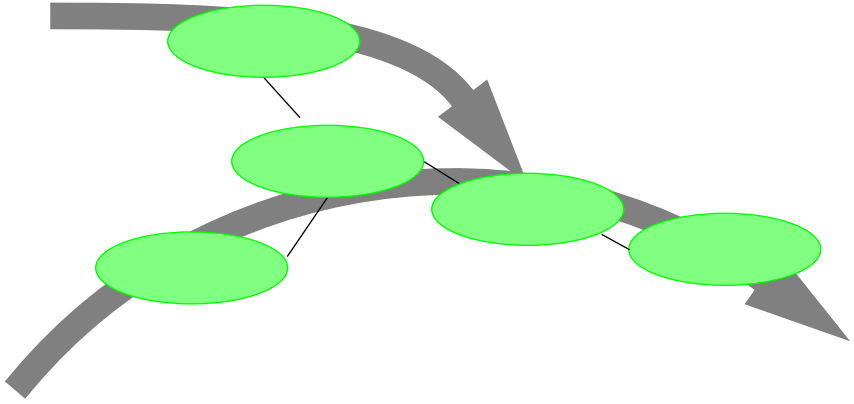
A storage location is read in the midst of being written

- 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	Liveness-first
Ensure that each class is safe, then try to improve liveness as optimization measure.	**Design live ground-level code, then try to layer on safety features such as locking and guarding.**
• **Characteristic of top-down OO Design**	• **Characteristic of multithreaded systems programming**
• **Can result in slow, deadlock-prone code**	• **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	High-level view
• Bits are never misinterpreted • Protect against storage conflicts on memory cells — read/write and — write/write conflicts	• Objects are accessible only when in consistent states • Objects must maintain state and representation invariants • Presents subclass obligations

Guaranteeing Liveness

"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

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

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

State-dependence	Service availability	Flow constraints
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

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

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

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

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

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

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

Static methods that can only be applied to current thread

`currentThread()`	reveals current thread
`sleep(ms)`	suspends for (at least) `ms` milliseconds
`interrupted()`	returns and clears interruption status

Designing Objects for Concurrency

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

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) `finals` enforce most senses of immutablity

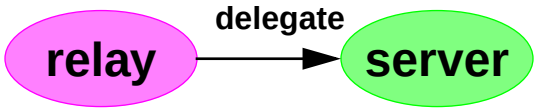
- Don't cover cases where objects eventually latch into values that they never change from

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?)

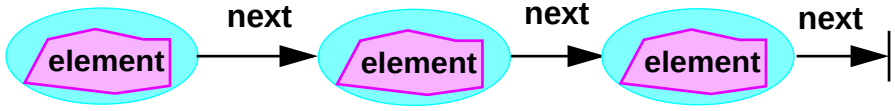
Applications of Immutability

Immutable references to mutable objects




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

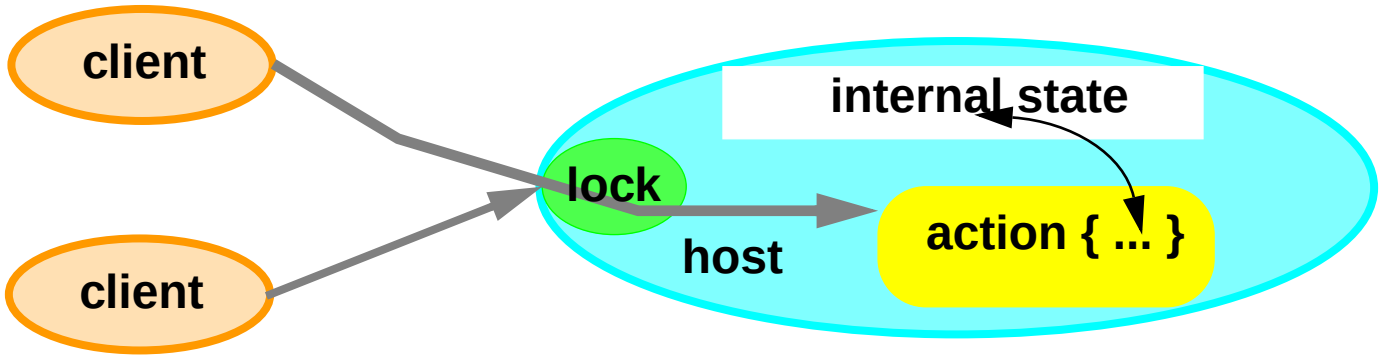
Partial immutability



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:

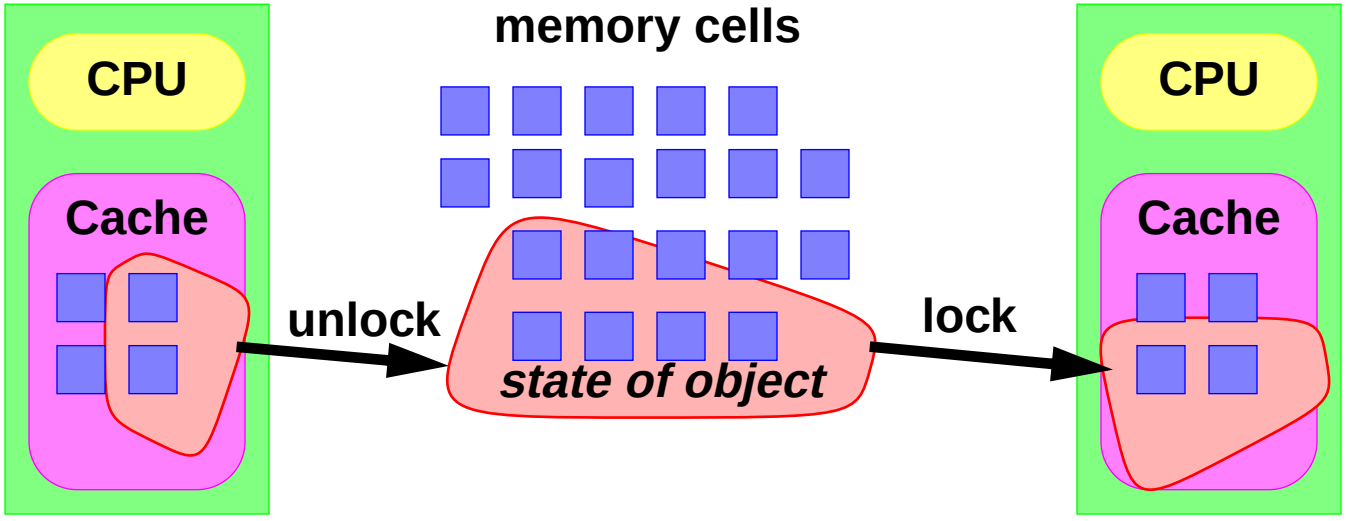
Thread 1		Thread 2	
read	0		
write	1		
		read	1
		write	2
read	2	read	2
		write	3
		return	3
write	3		
return	3		

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`

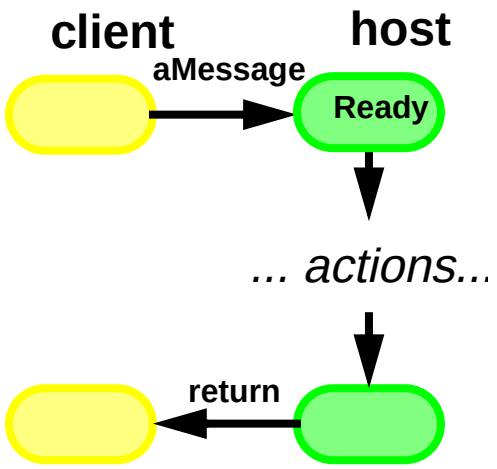
- **Always safe, but not always live or efficient**

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)**



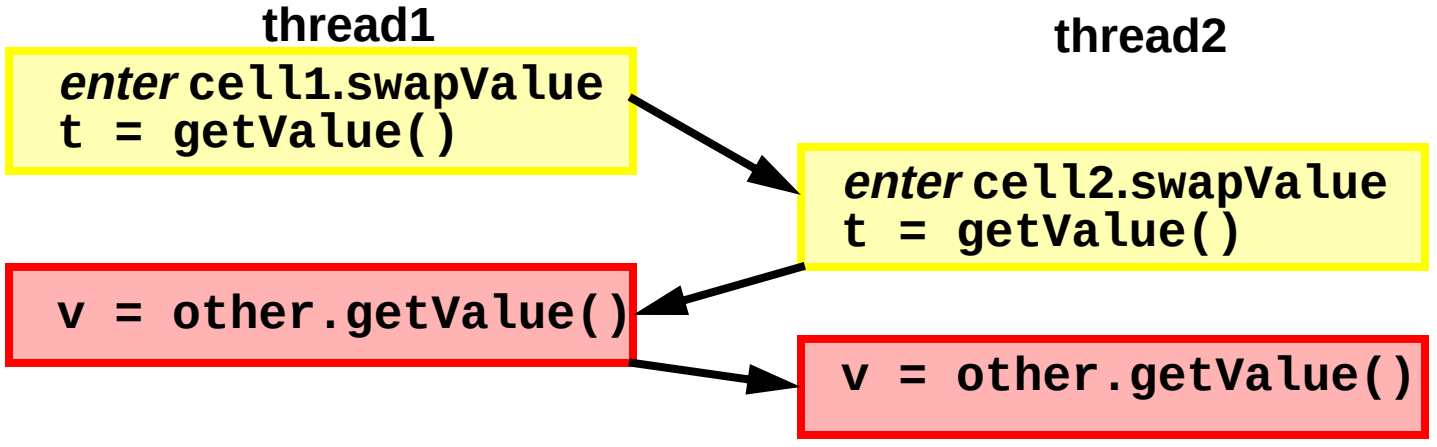
Constraints

- **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; }
  }
}
```

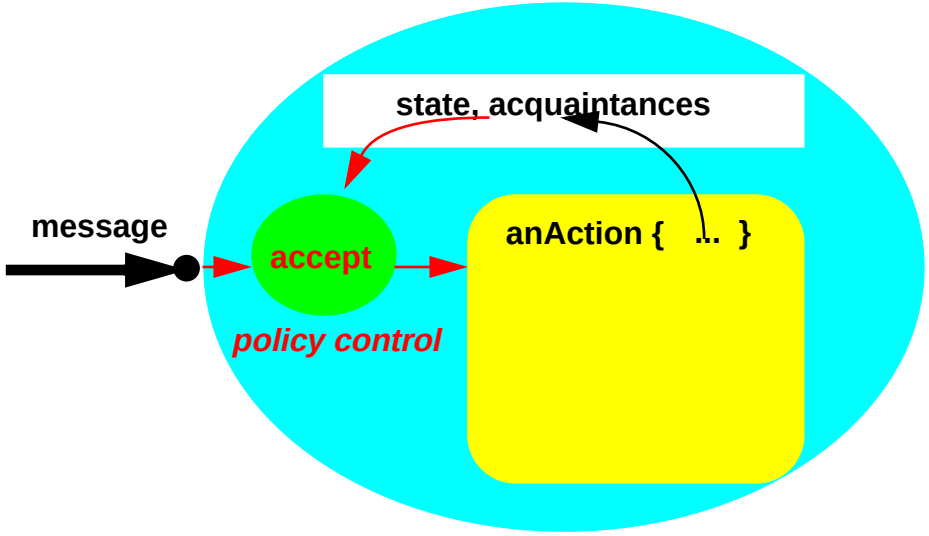
State Dependence

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

Blind action	**Proceed anyway; no guarantee of outcome**
Inaction	**Ignore request if not in right state**
Balking	**Fail (throw exception) if not in right state**
Guarding	**Suspend until in right state**
Trying	**Proceed, check if succeeded; if not, roll back**
Retrying	**Keep trying until success**
Timing out	**Wait or retry for a while; then fail**
Planning	**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
}
```

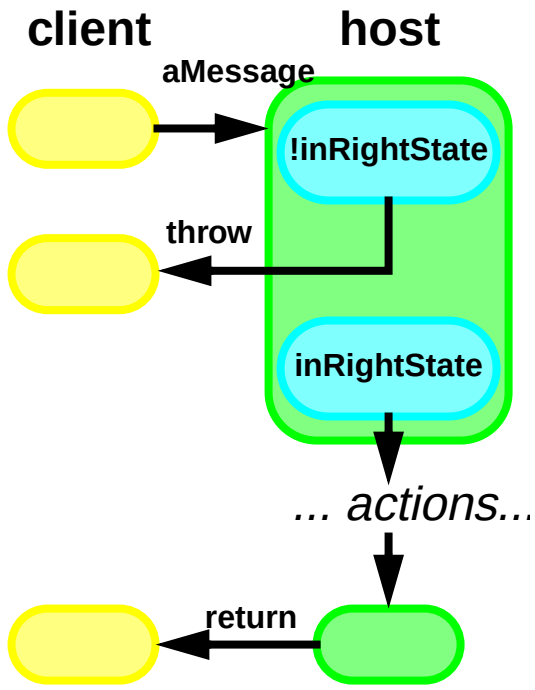
Interfaces alone cannot convey policy

- 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));
    }
  }
}
```

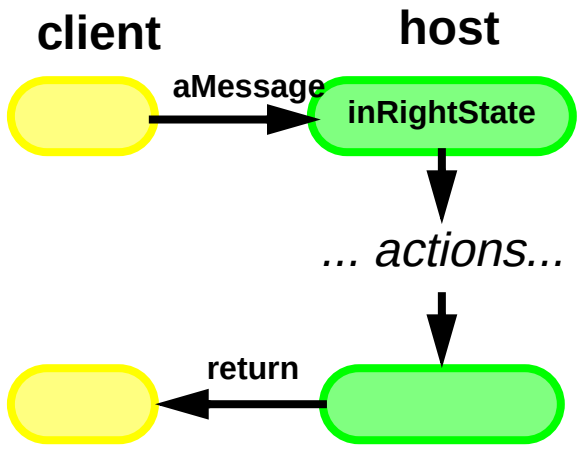
Guarding

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

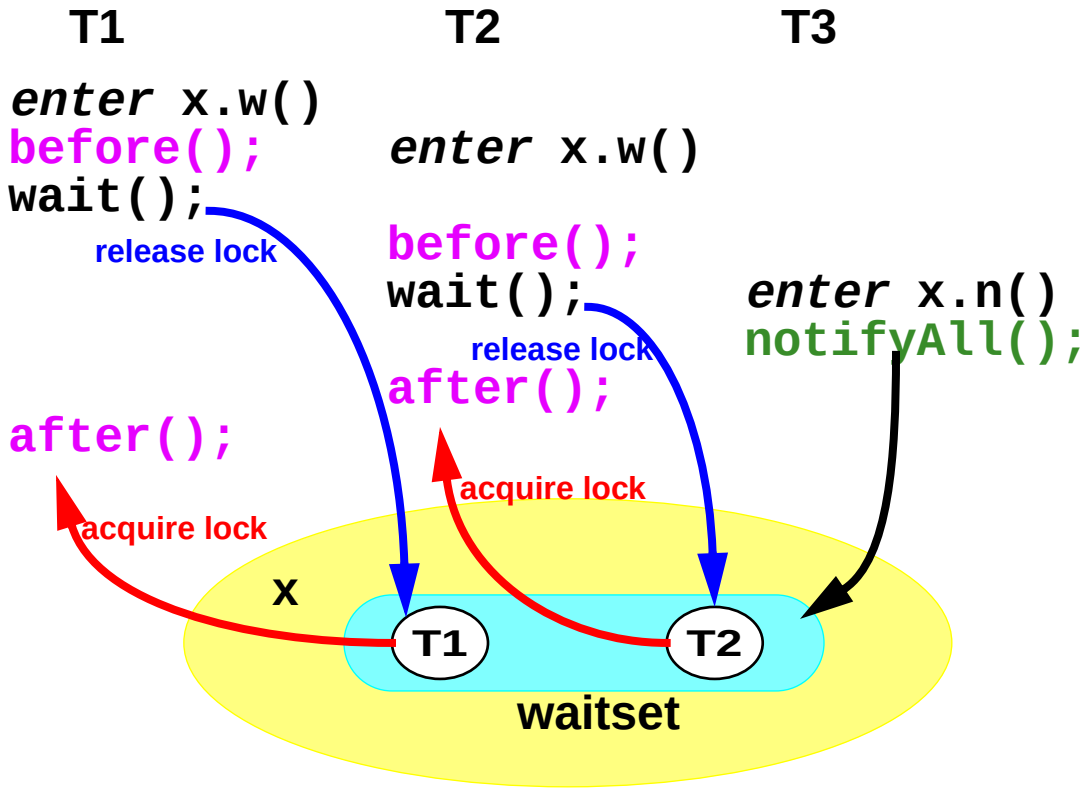
`wait(ms)` is same as `wait()` except thread is automatically notified after `ms` milliseconds if not already notified

`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(); }
}
```

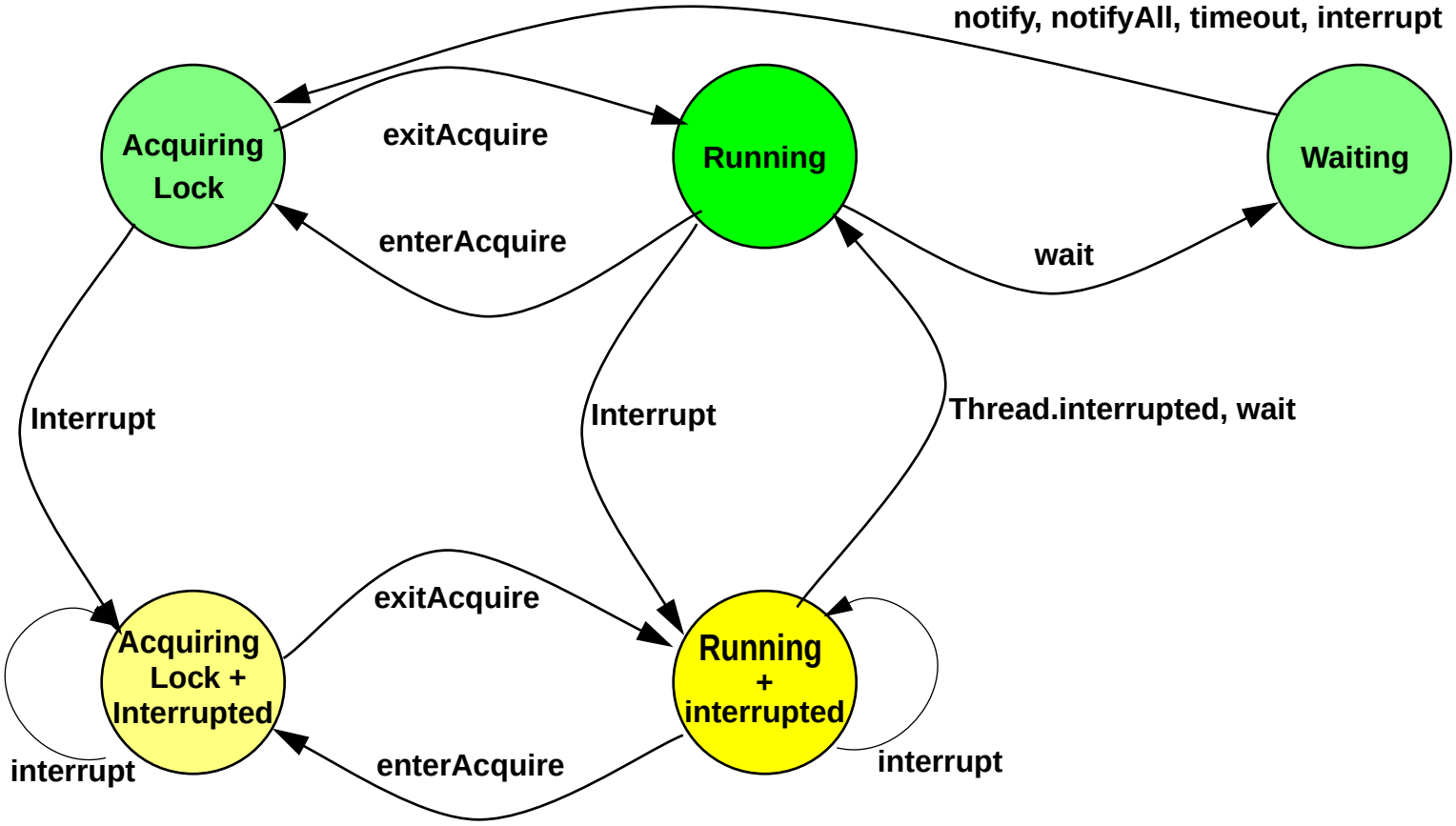
One possible trace for three threads accessing instance x:



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; }
```

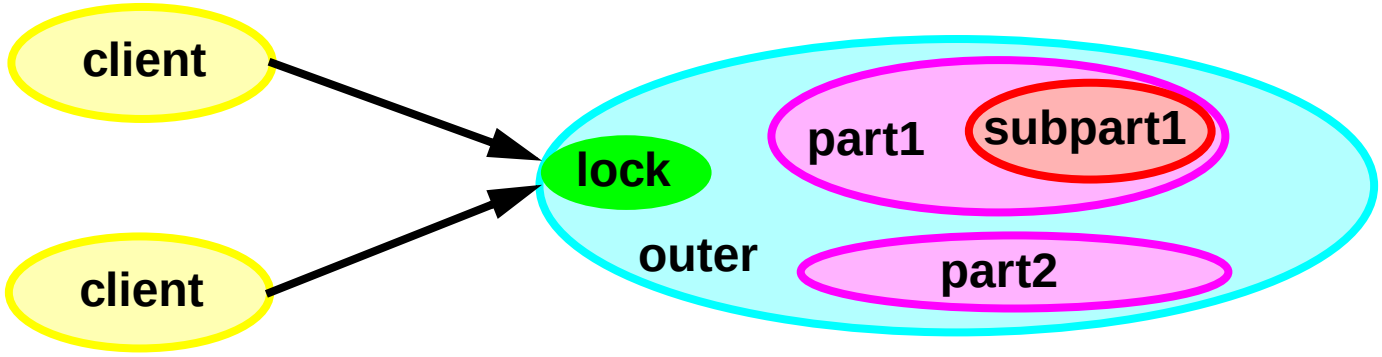
Buffer (continued)

```
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

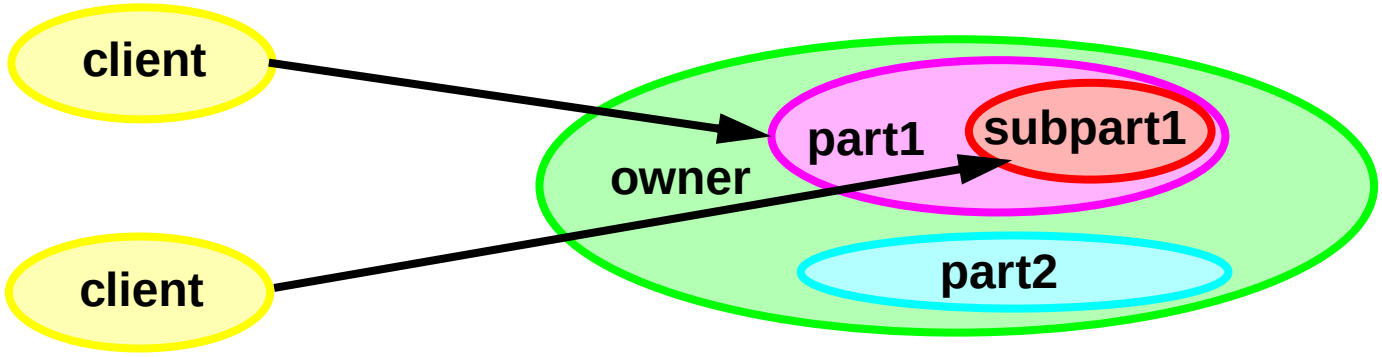
- **Otherwise, possible thread-caching problems**

Seen in concurrent versions of many delegation-based patterns

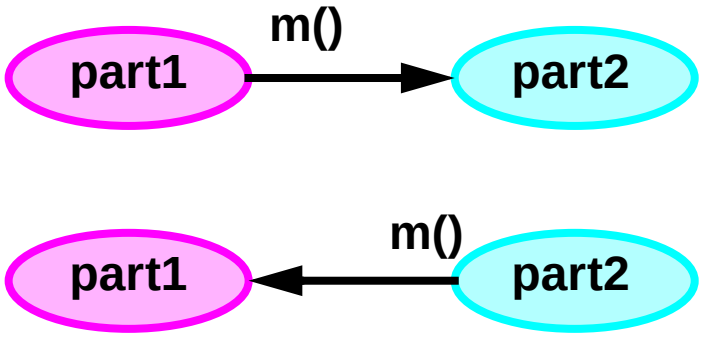
- **Adapters, decorators, proxies**

Hierarchical Locking

Applies when logically contained parts are not hidden from clients



Avoids deadlocks that could occur if parts fully synchronized



`part1` holds self lock
needs `part2` lock

`part2` holds self lock
needs `part1` lock

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

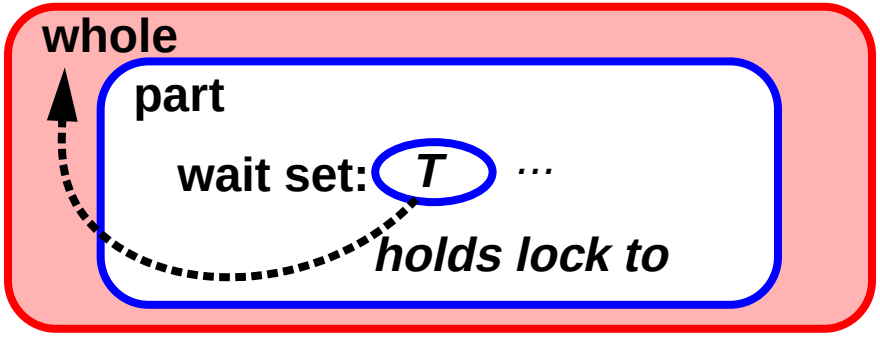
- Can manually minimize use of `synchronized`
- Requires that all callers obey conventions
- Effectiveness is context dependent
  - — Breaks encapsulation
  - — Doesn't work with fancier schemes that do not directly rely on `synchronized` blocks or methods for locking

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;
  }
}
```

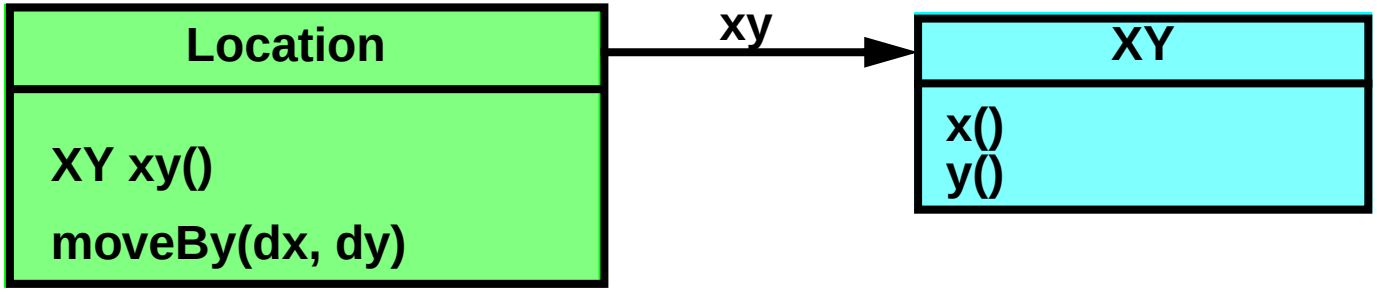
No protection from interleaving problems such as:

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 reversable

  — **Ensures that failures are clean (no side effects)**

  — **No I/O or thread construction unless safely cancellable**

  — **All internally called methods must also be reversable**

- **`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

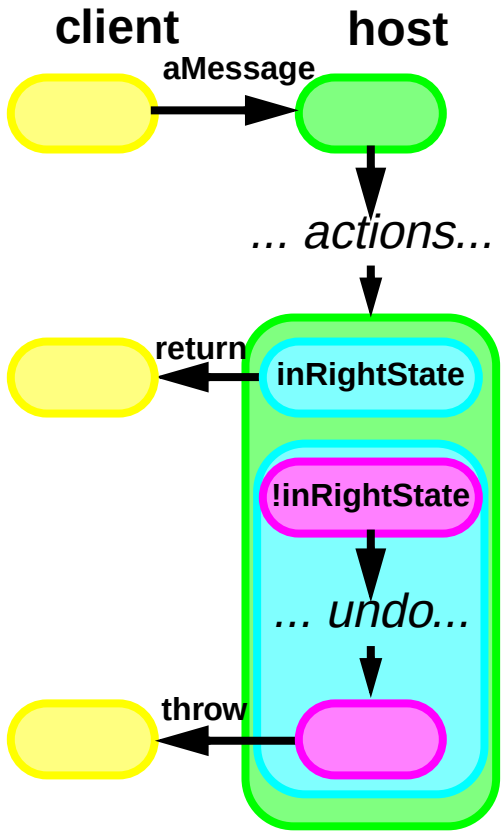
As with optimistic updates, isolate state into versions, and isolate state changes to `commit` method

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

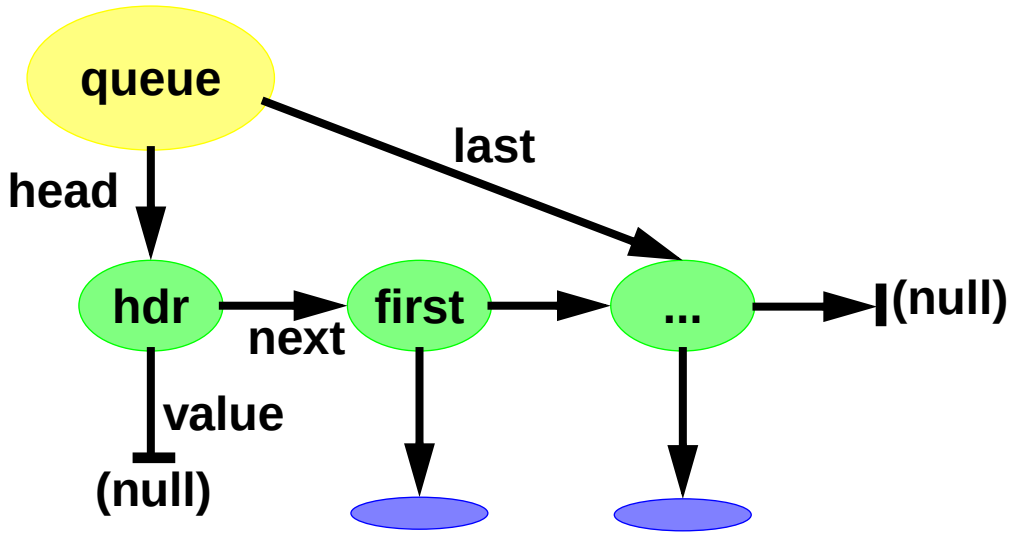
When there is no existing object to delegate independent actions:

- 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

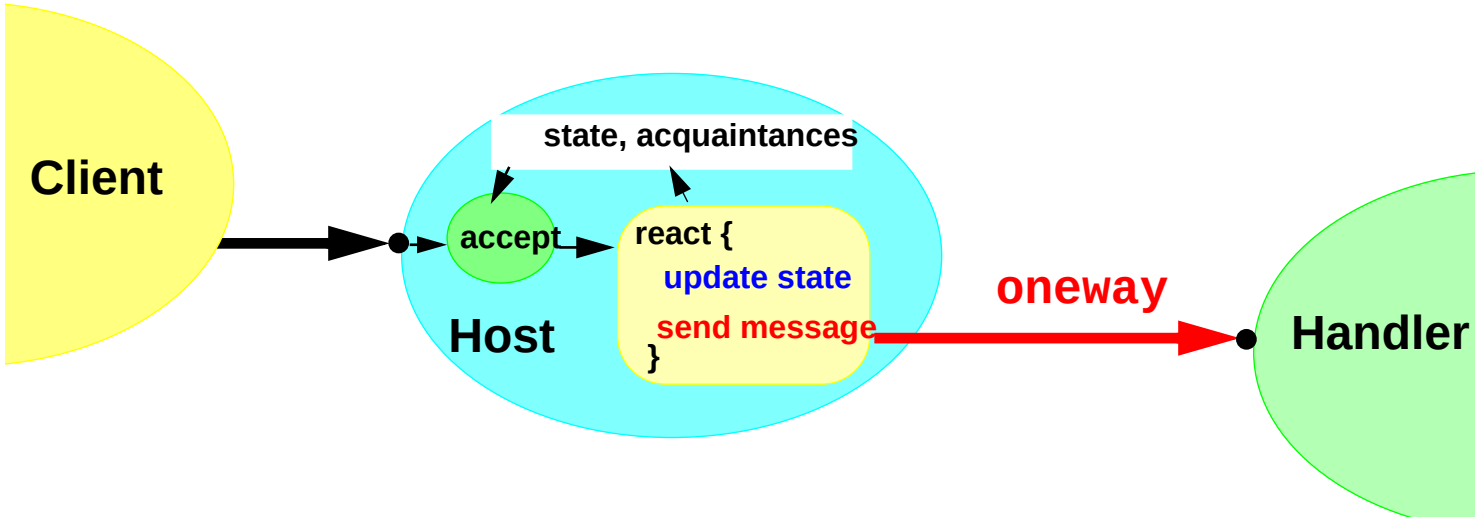
Autonomous Particle Class

```
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

Events	Mouse clicks, etc
Notifications	Status change alerts, etc
Postings	Mail messages, stock quotes, etc
Activations	Applet creation, etc
Commands	Print requests, repaint requests, etc
Relays	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

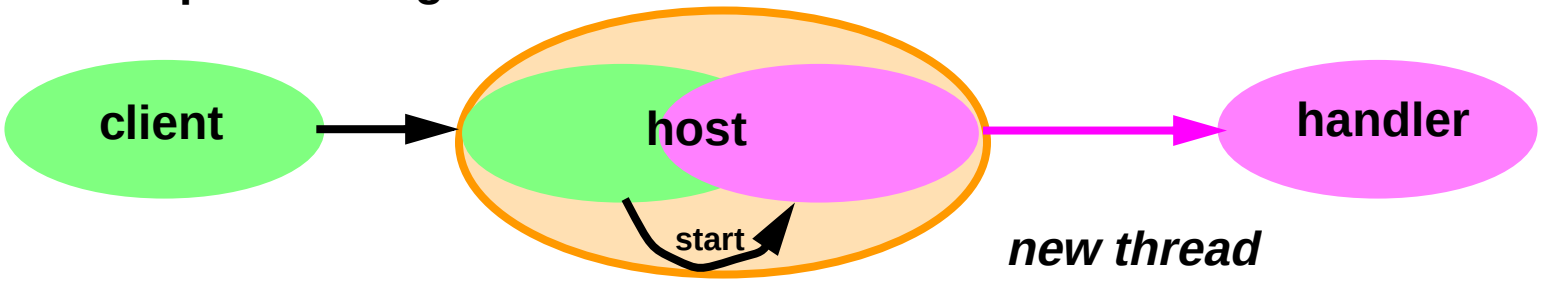
- **The activity should progress with minimal contention**

Performance

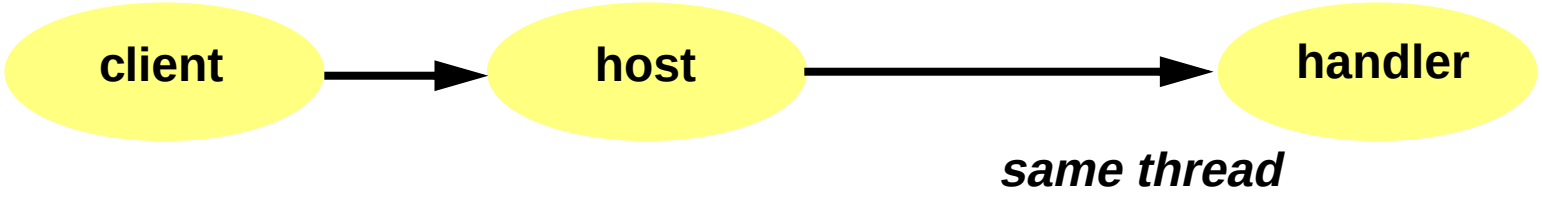
- **Minimize overhead and resource usage**

Design Patterns for Oneway Messages

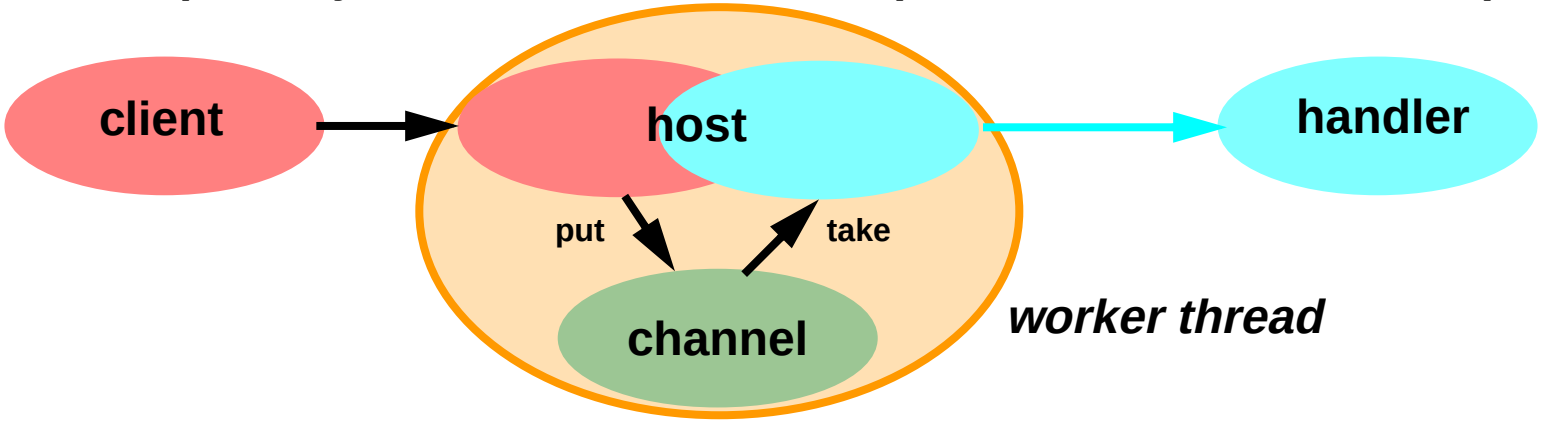
Thread-per-Message



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

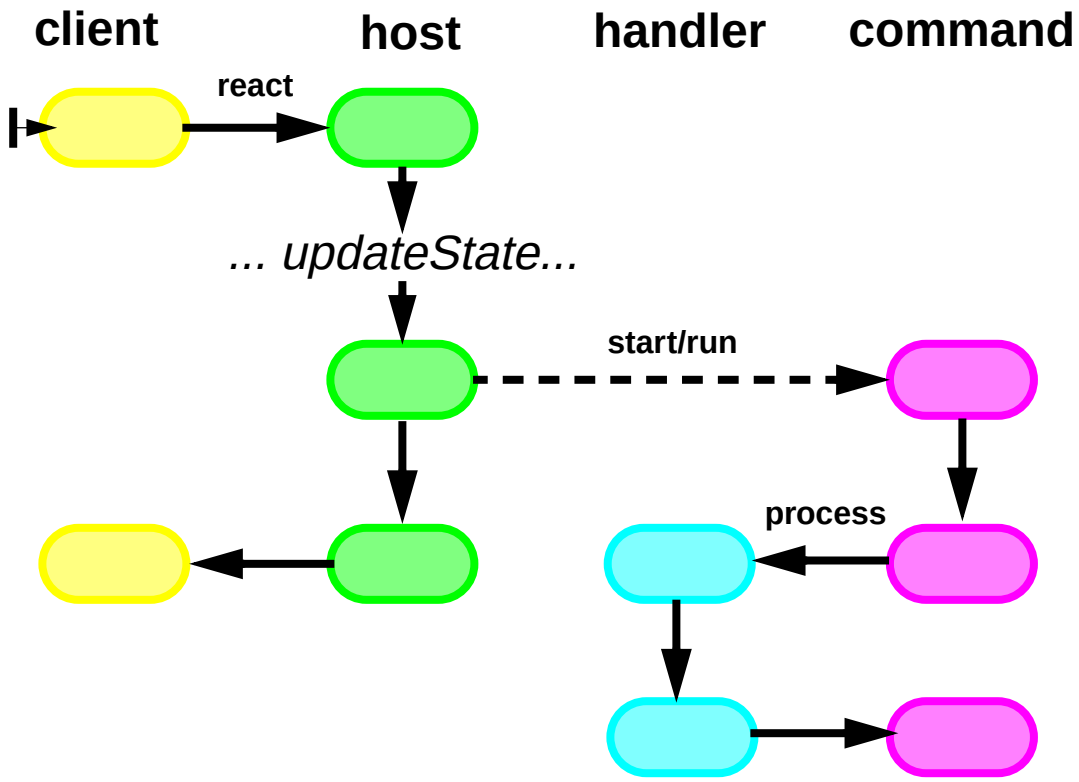
```
class Host { //...
  public void react(...) {
    updateState(...);
    sendMessage(...);
  }

  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*)

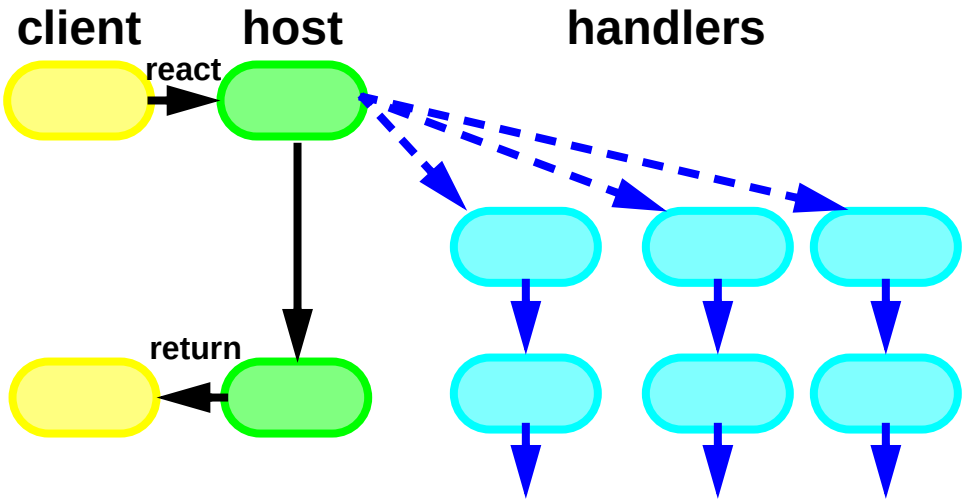
Synchronization of `sendMessage` desirable if `handler_` or `process()` arguments not fixed/final

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

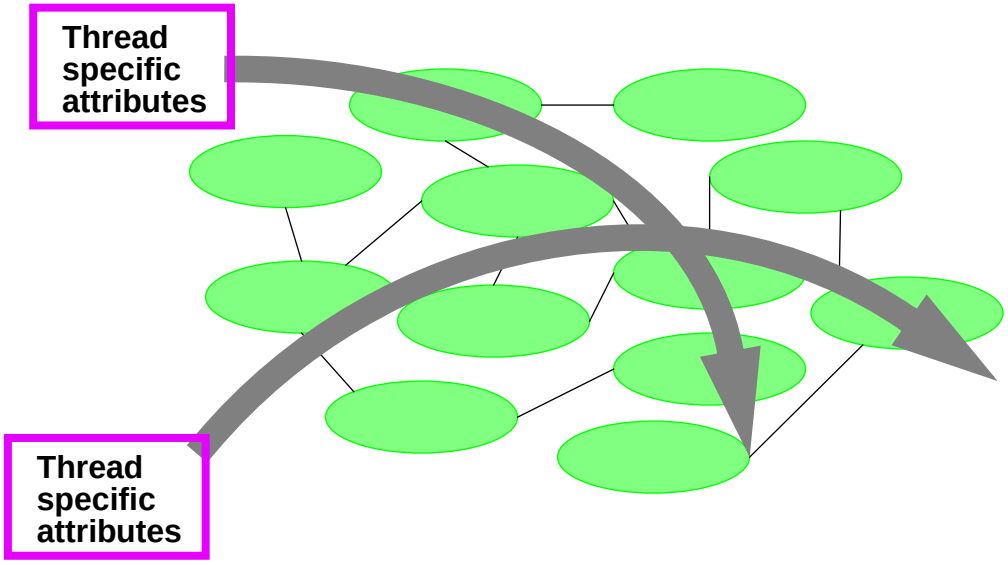
JVM schedulers give preference to threads with higher priority

- 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

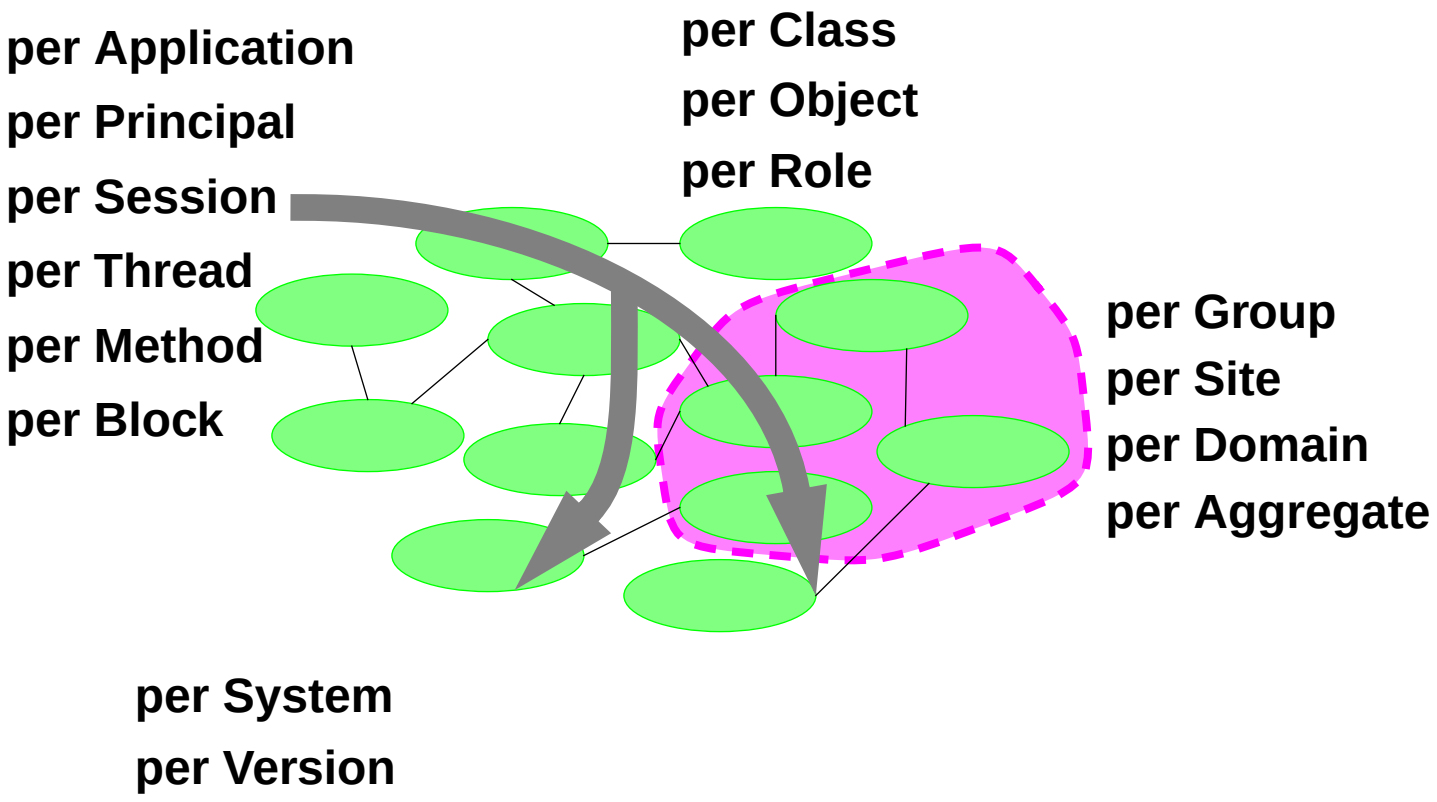
```
class Ball {
  static ThreadLocal delay = new ThreadLocal();
  void move() { // ...
    if (delay.get()==null) delay.set(new Long(3));
    long d = ((Long)(delay.get())).longValue();
    Thread.sleep(d);
  }
}
```

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

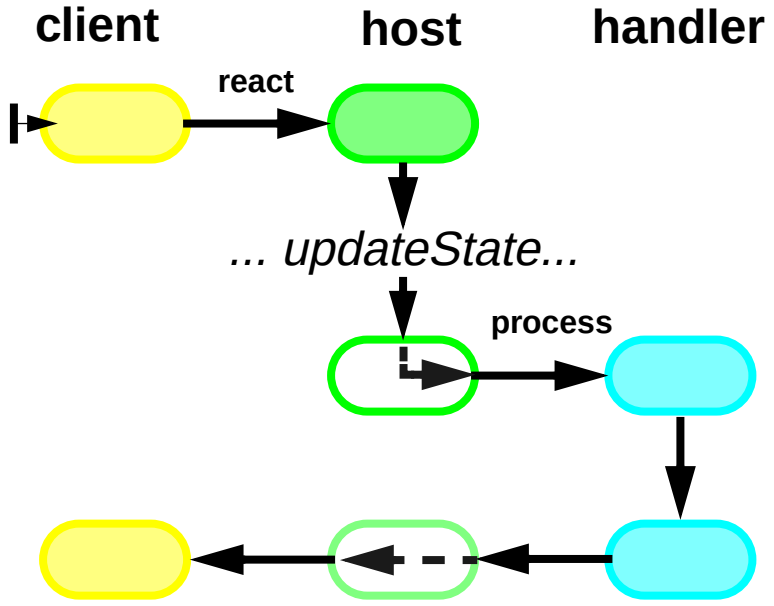
Thread-per-Activity via Pass-Throughs

```
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);
}
```

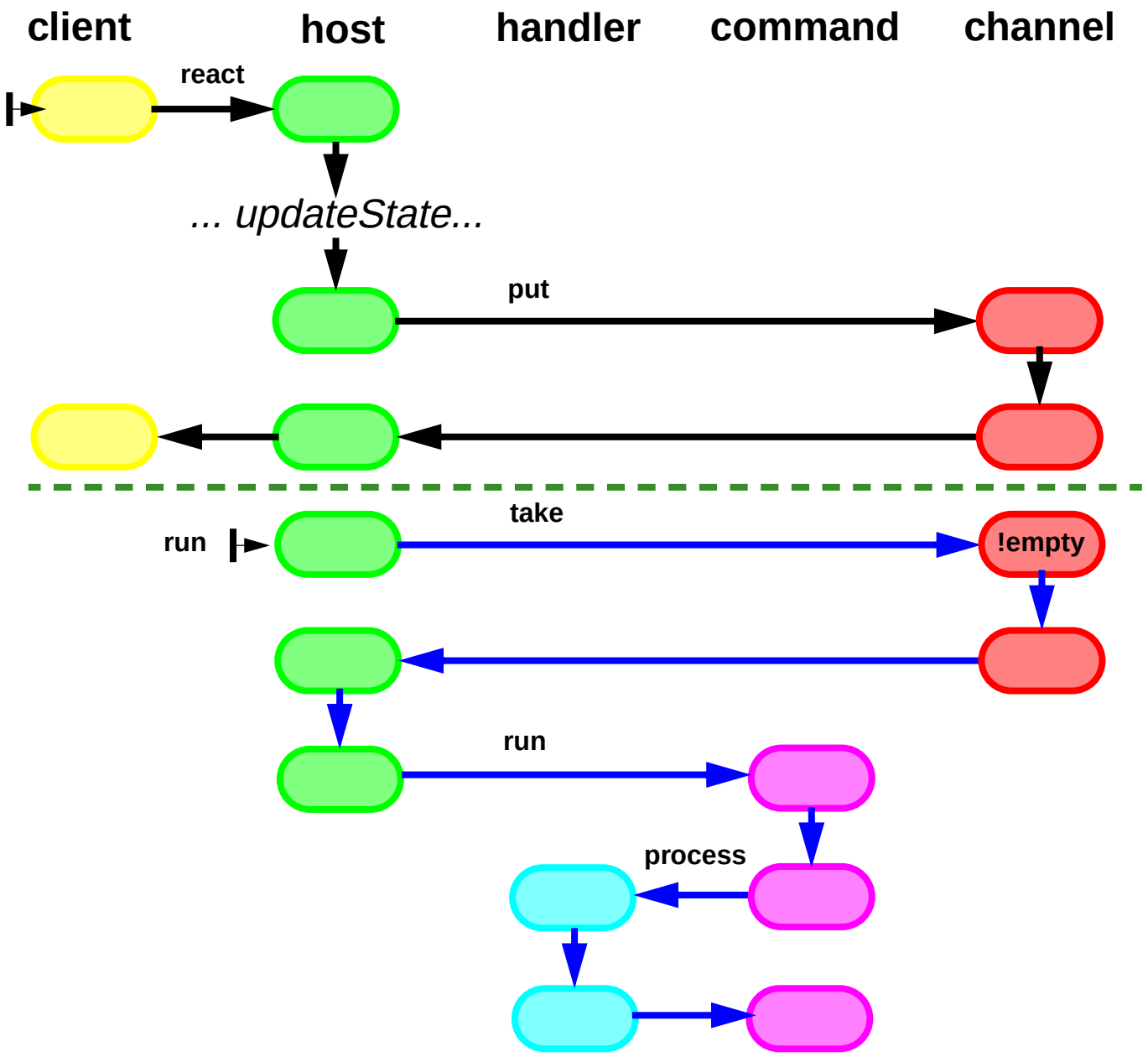
Common variants

- **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

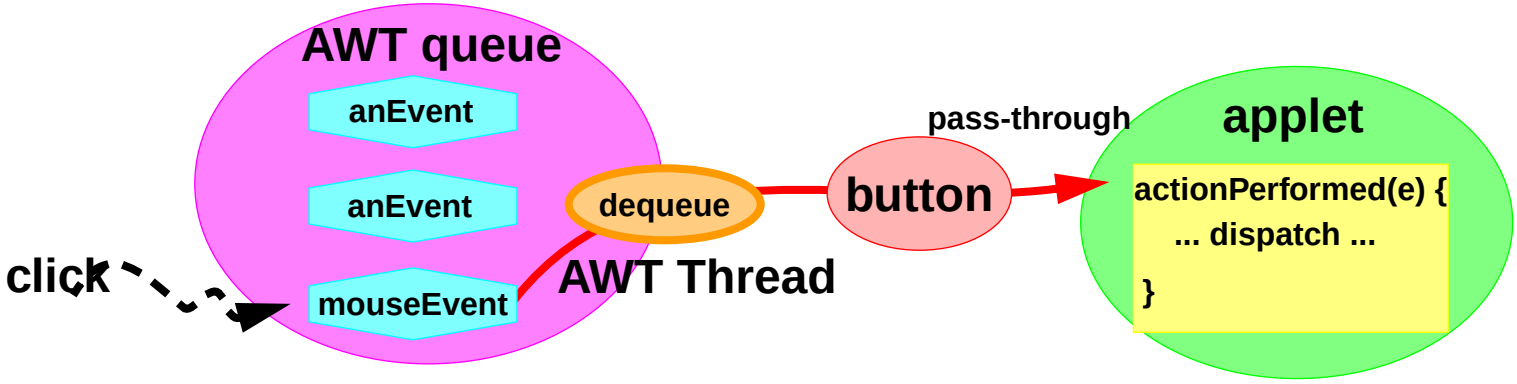
Non-blocking channels

- 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 beoptimized 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

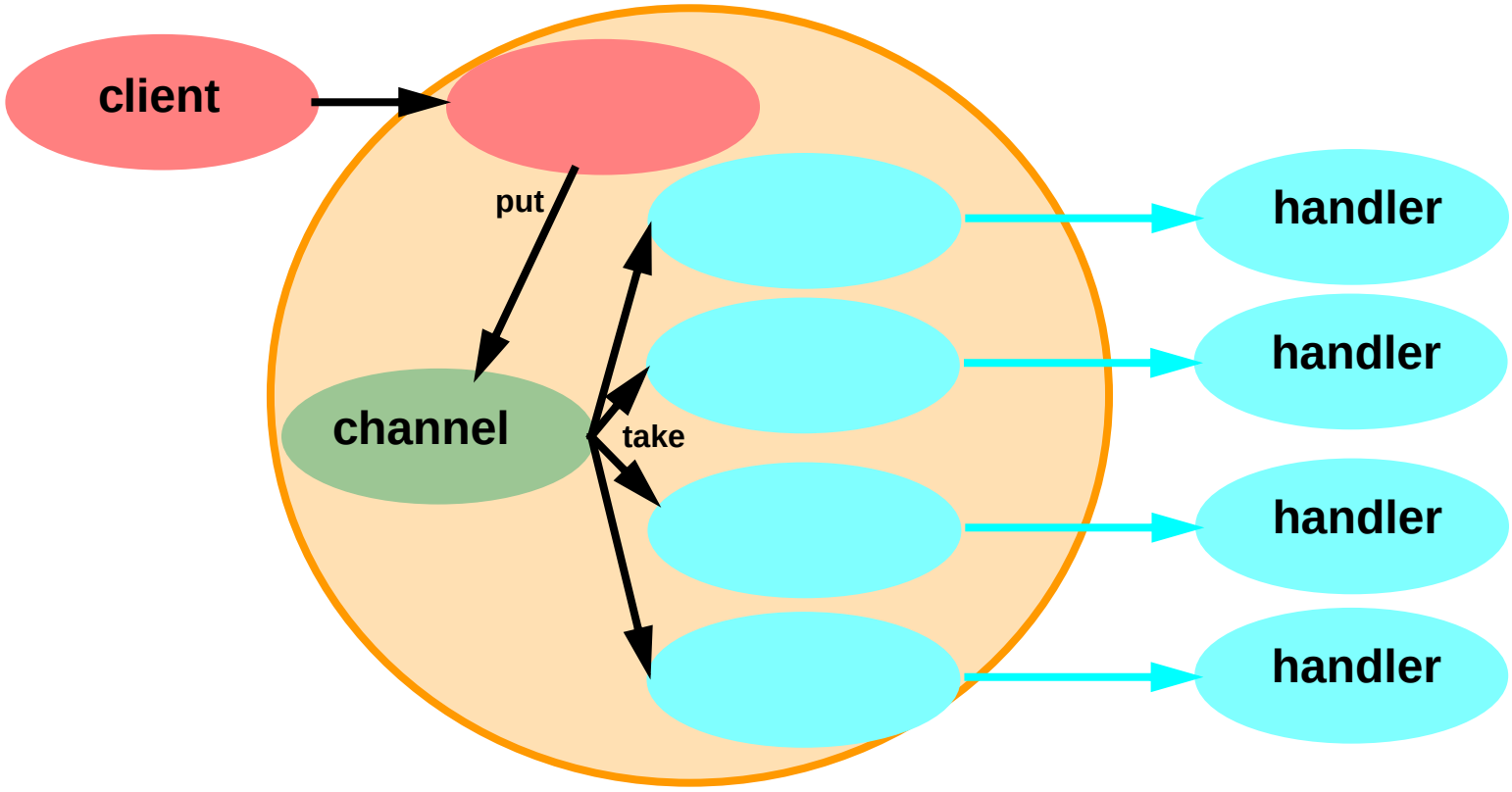
Most conservative policy is to perform all GUI-related state updates in event handling methods

- **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



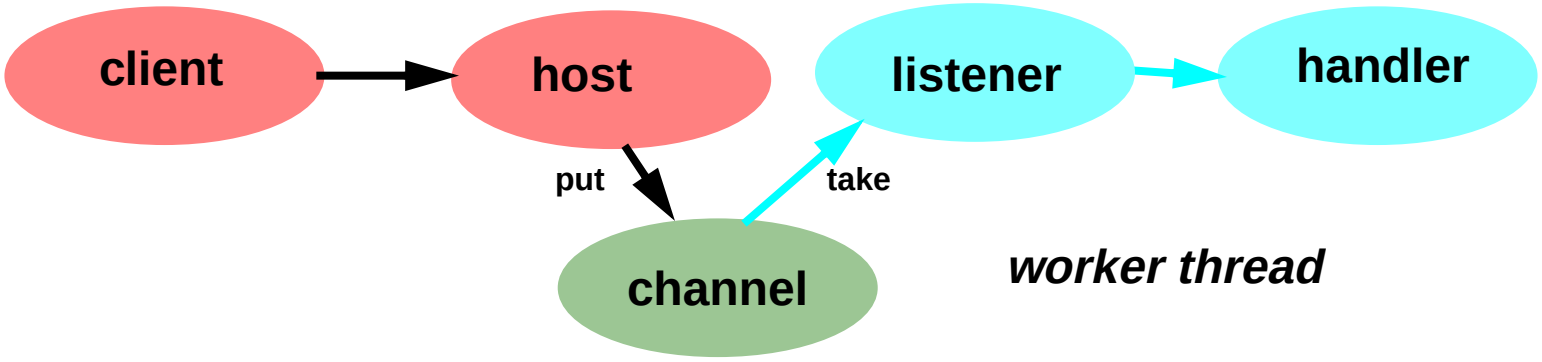
Use a collection of worker threads, not just one

- 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;
  }
}
```

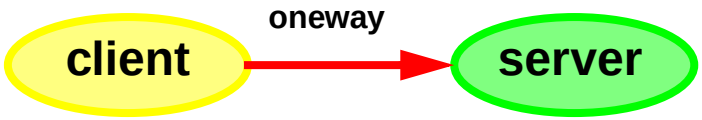
Some Pattern Trade-Offs

Thread-per-Message	Pass-Through	Worker Threads
+ Simple semantics: When in doubt, make a new thread - Can be hard to limit resource usage - Thread start-up overhead	+ Low overhead - Fragile - No within-activity concurrency	+ Tunable semantics and structure + Can bound resource usage - Higher overhead - Can waste threads - May block caller (if buffer full etc)

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

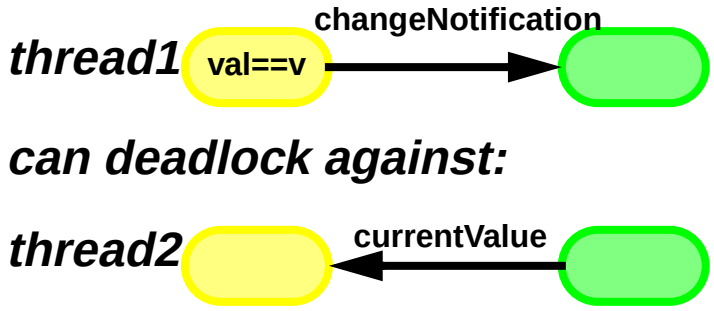
The callbacks are state queries

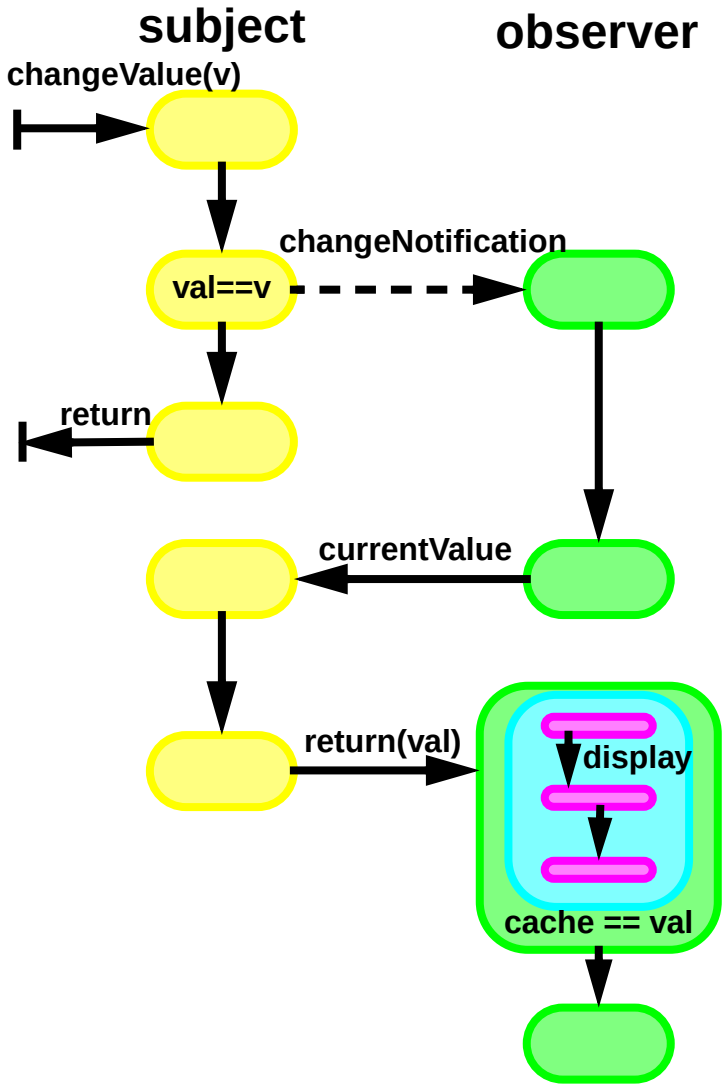
Examples

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

Notifications must use oneway design pattern

Otherwise:





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

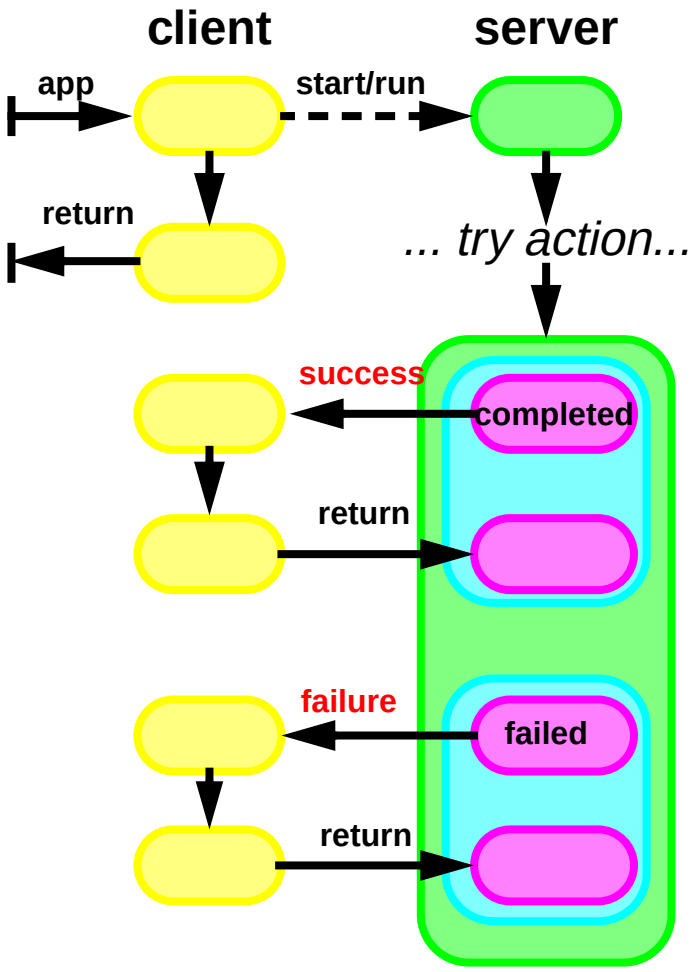
Typically two kinds of callbacks

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 filenm) {
    // ... 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()`**

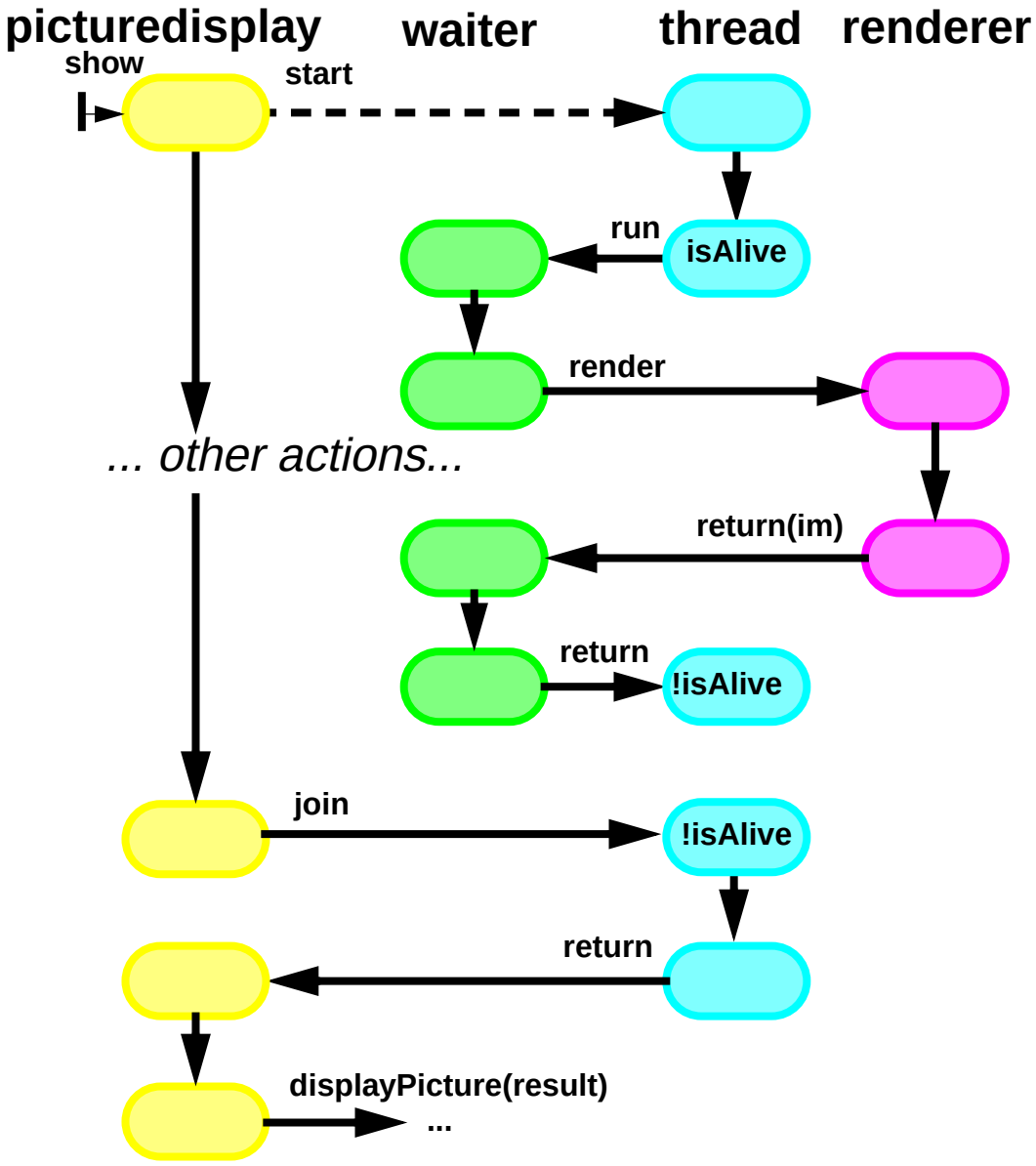
Can use to simulate futures and deferred calls found in other concurrent OO languages

- **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 AsynchRenderer 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 AsynchRender, 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 AsynchRenderer().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 activites 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 `InterruptedIOException`

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

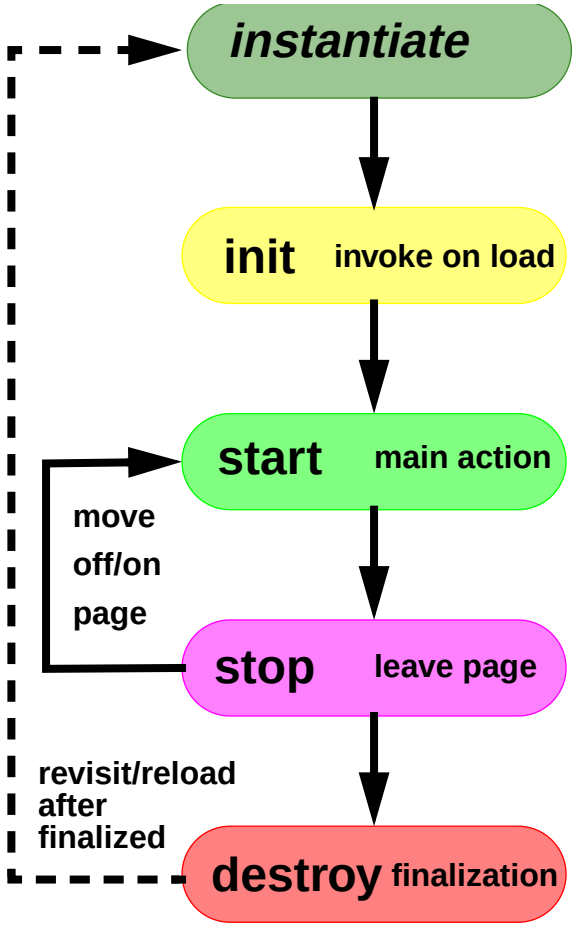
— usually in `Applet.start`

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

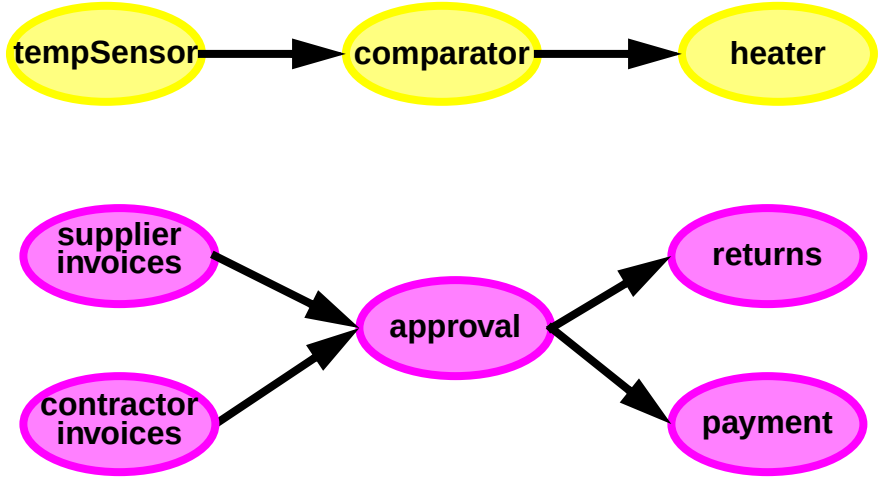
Assembly systems

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

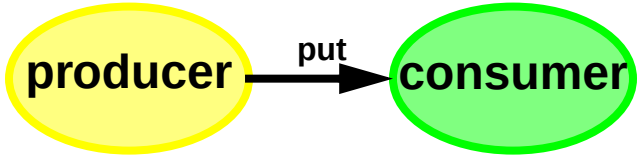
The simplest and sometimes best open systems protocol

Stages in Flow Systems

Every stage is a producer and/or consumer

Stages implement common interface
with method of form

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

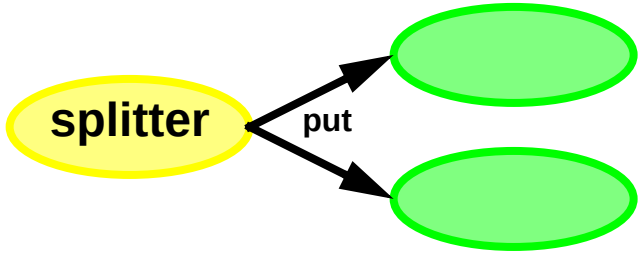


May have multiple successors

Outgoing elements may be

— multicasted or

— routed

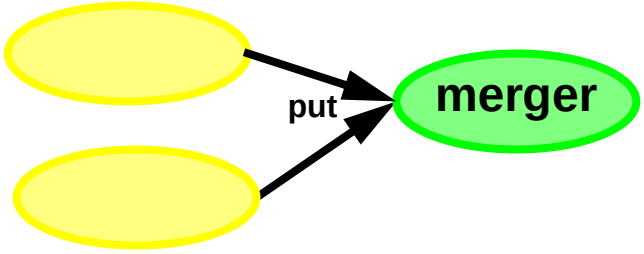


May have multiple predecessors

Incoming elements may be

— combined or

— collected



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**

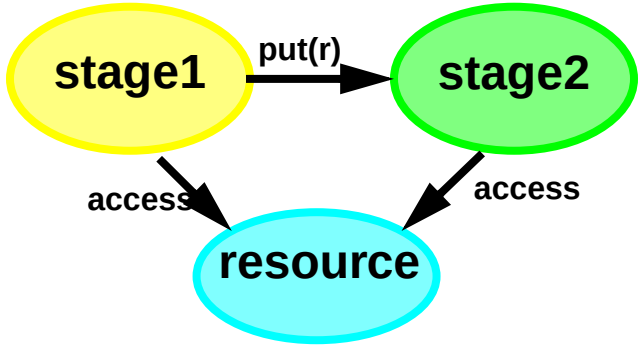
Accessing Resources

How should stages manage resource objects?

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

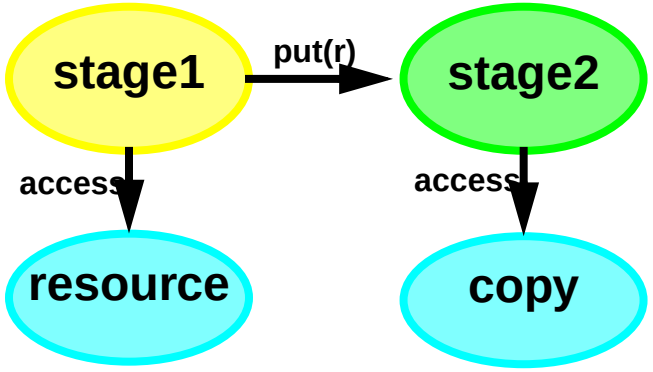
Both reference-passing “shared memory” and copy-based “message passing” policies can encounter problems:

Shared memory



Synchronize access to resource

Message passing



Deal with identity differences

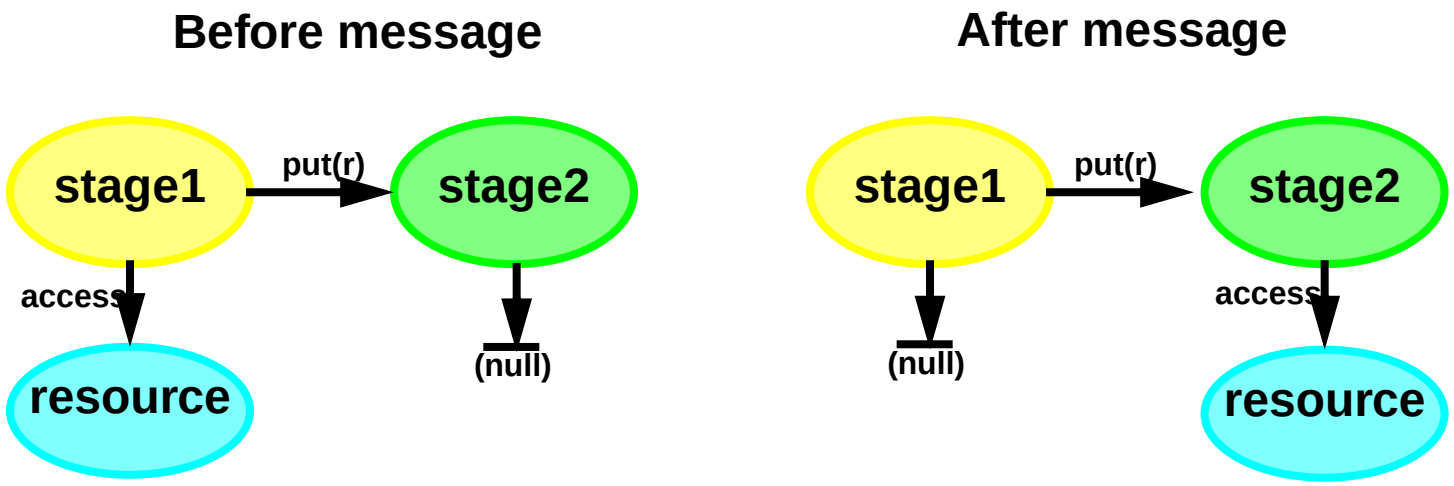
Ownership Transfer

Transfer policy

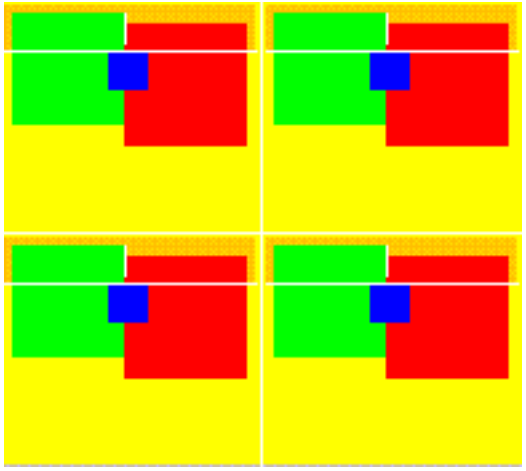
At most one stage refers to any resource at any time

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 refering 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**



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

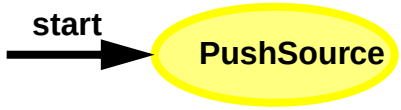
- **Stages paint, transform, combine into composite boxes**

A viewer applet serves as the sink

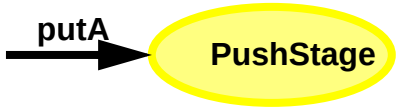
See CPJ p233-248 for most code omitted here

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

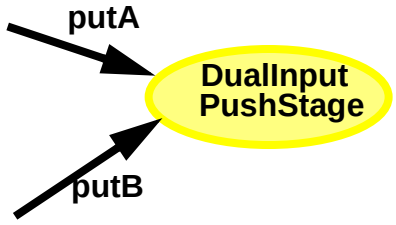
Interfaces




```
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`

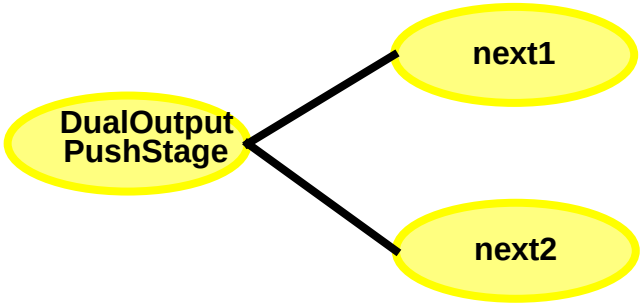
- Use adapter when necessary to convert to `putB`
- Simplifies composition

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; }
}
```

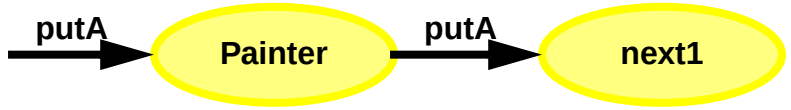



```
class DualOutputPushStage
                    extends SingleOutputPushStage {
  protected PushStage next2_ = null;
  void attach2(PushStage s) { next2_ = s; }
}
```

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

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

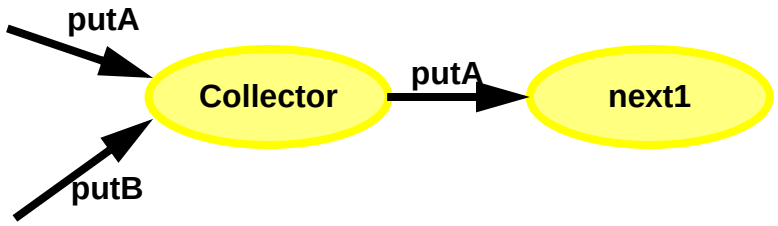
Linear Stages




```
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



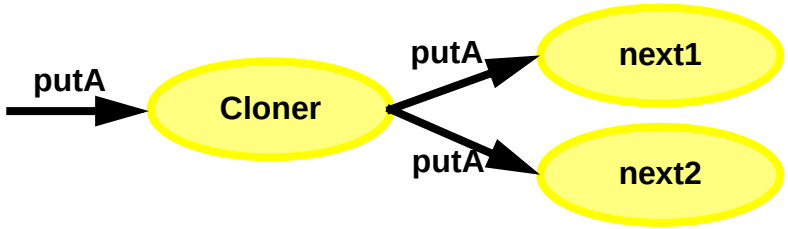

```
public class Collector
                    extends SingleOutputPushStage
                    implements DualInputPushStage {

  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)
```

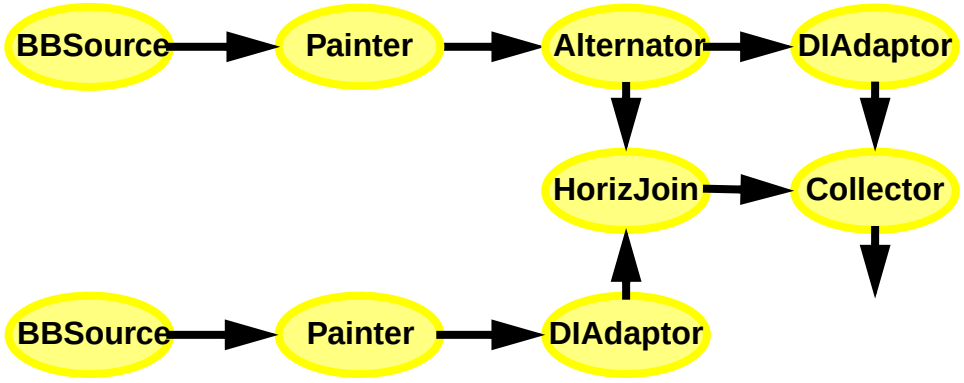
Dual Output Stages




```
class Cloner extends DualOutputPushStage
             implements PushStage {

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

  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

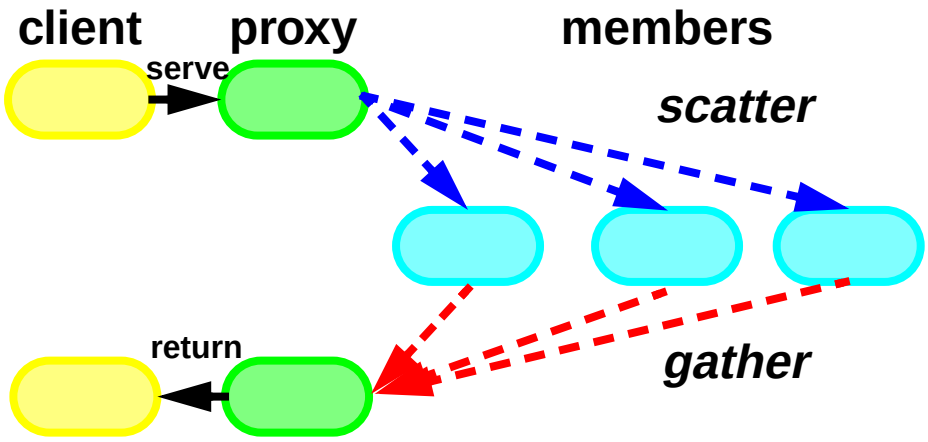
- Minimize thread communication and synchronization
- Minimize sharing of resource objects

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 aggegrate 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

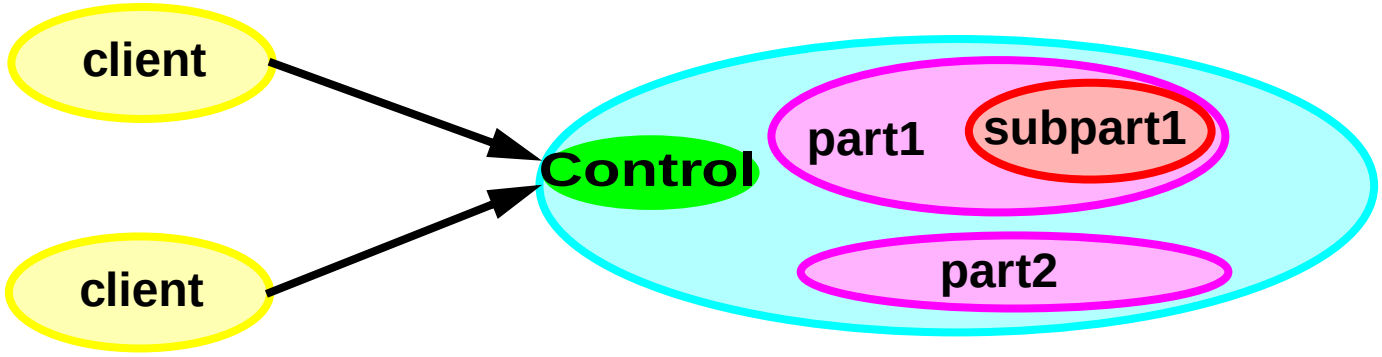
- Initialize count with number of members
- synch( ) waits for zero, then resets to initial count

```
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

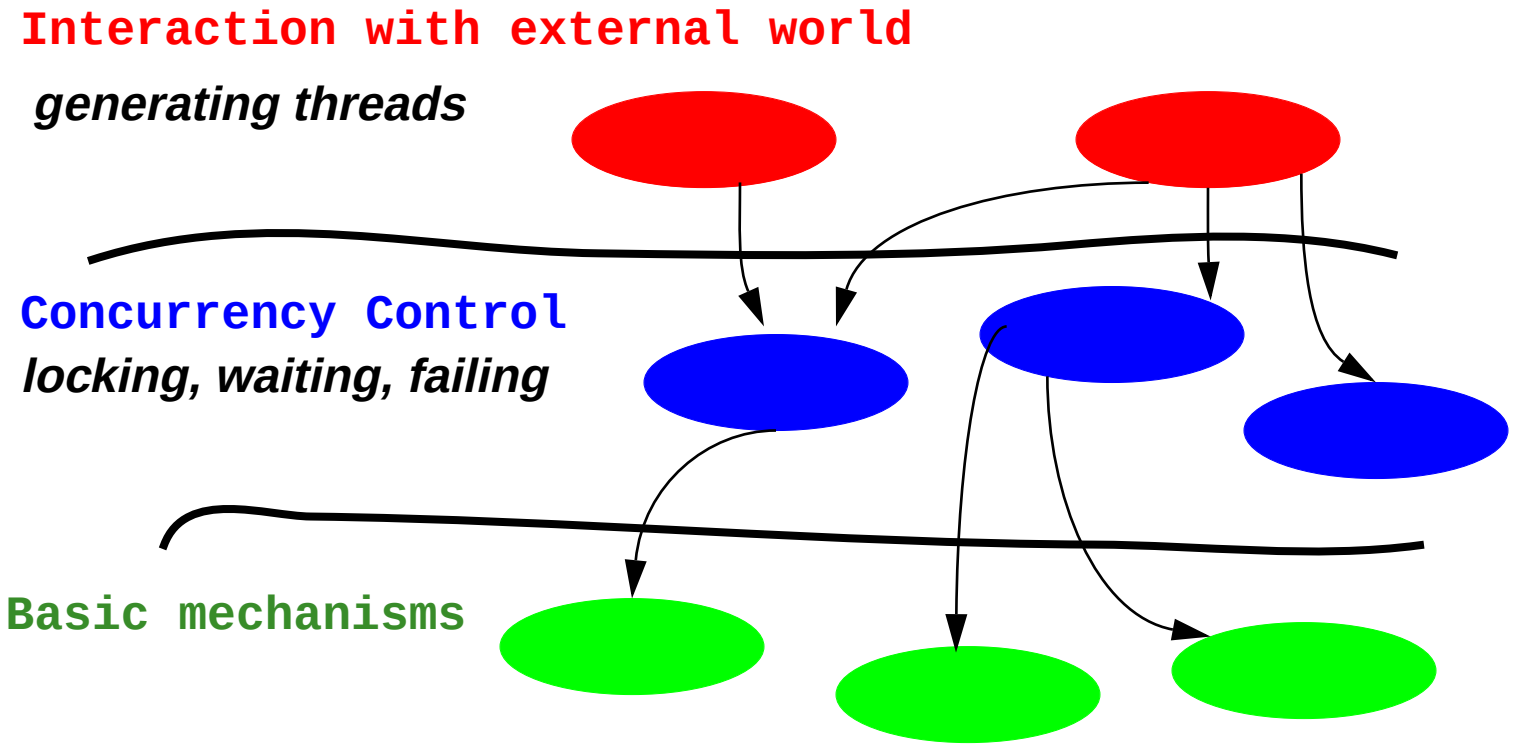
- **Applying special synchronization policies**
- **Applying different policies to the same mechanisms**

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



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(); }
}
```

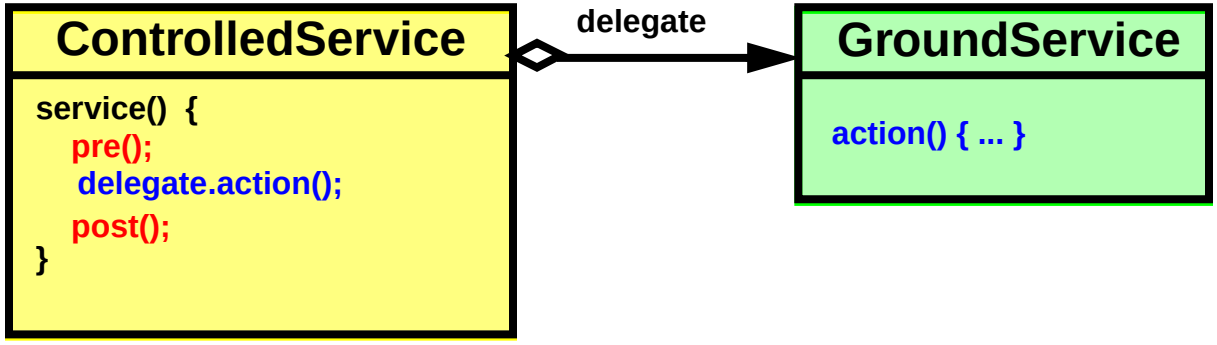
Used by built-in Java `synchronized(obj) { action(); }`

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

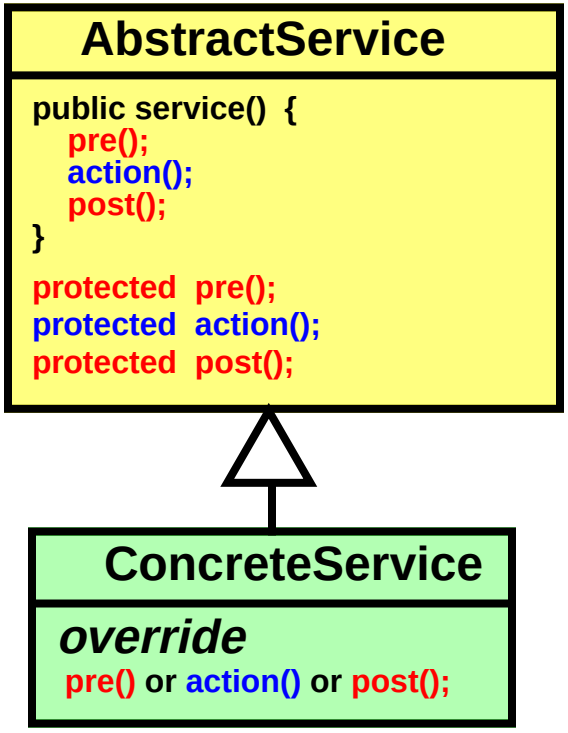
Basis for many delegation-based designs



Template Method Before/After Designs

Subclassing is one way to implement before/after containment designs

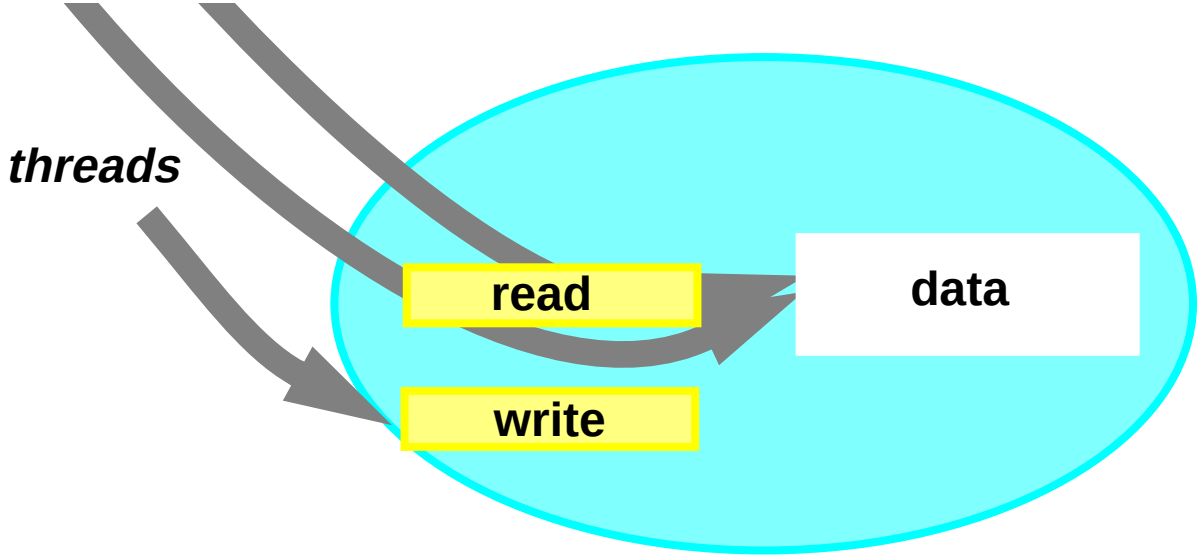
- Superclass instance variables and methods are "contained" in subclass instances



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 simultanously, 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

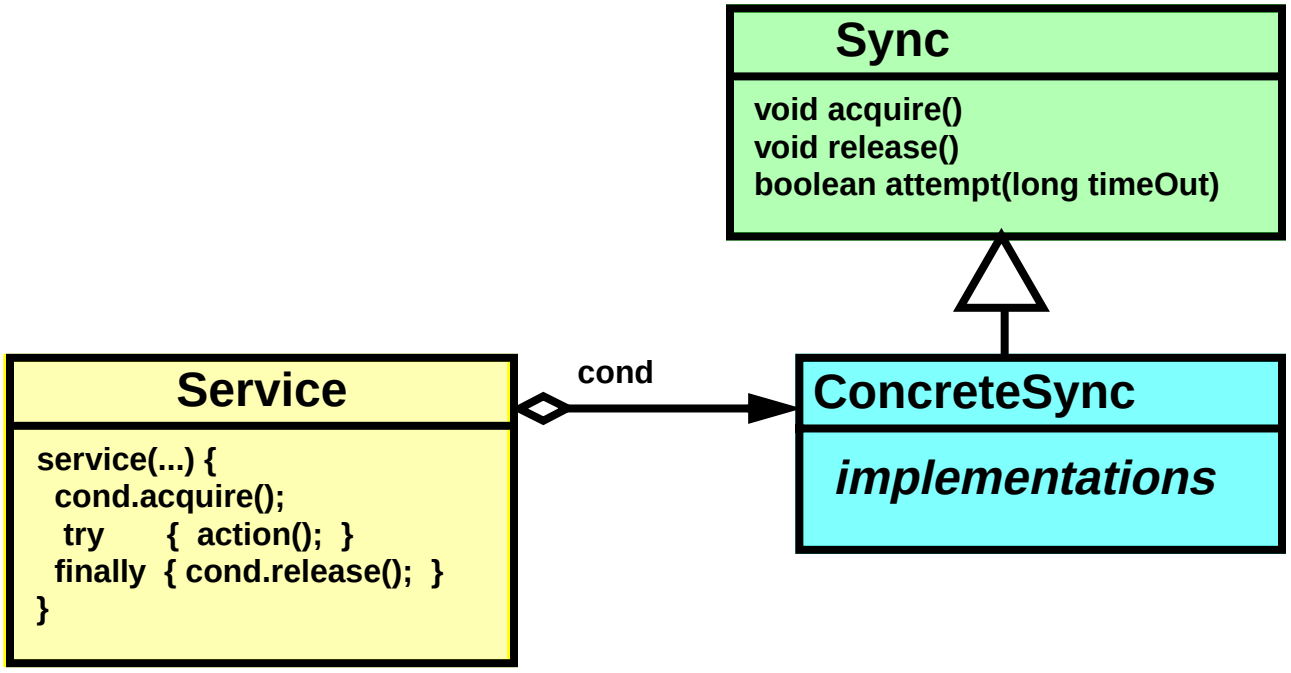
- Correctness relies on all objects obeying usage policy
- Cannot automatically enforce

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

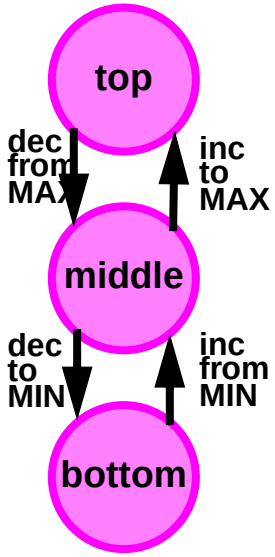
- **Don’t lock if can be sure won’t wait**

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	`value == MAX`	no	yes
middle	`MIN < value < MAX`	yes	yes
bottom	`value == MIN`	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 Interrup.. {
    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