Principles of Software Construction: Objects, Design, and Concurrency (Part 1: Designing Classes)

Design for Change (class level)

Christian Kästner Charlie Garrod

Tradeoffs?

```
void sort(int[] list, String order) {
  …
  boolean mustswap;
  if (order.equals("up")) {
    mustswap = list[i] < list[j];
  } else if (order.equals("down")) {
    mustswap = list[i] > list[j];
  }
  …
}
```

```
void sort(int[] list, Comparator cmp) {
  …
  boolean mustswap;
  mustswap = cmp.compare(list[i], list[j]);
  …
}
interface Comparator {
  boolean compare(int i, int j);
}
class UpComparator implements Comparator {
  boolean compare(int I, int j) { return i<j; }}

class DownComparator implements Comparator {
  boolean compare(int I, int j) { return i>j; }}
```


Source: BC Forestry website

Case Study: Pines and Beetles

Lodgepole Pine

Mountain Pine Beetle

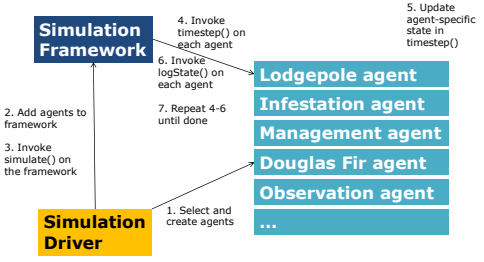
Galleries carved in inner bark

Widespread tree death

Photo by Walter Siegmund

Further reading: Liliana Pérezo and Suzana Dragićević. Exploring Forest Management Practices Using an Agent-Based Model of Forest Insect Infestations. International Congress on Environmental Modelling and Software Modelling for Environment's Sake, 2010.

Simulation Framework Behavior Model



Today: How Objects Respond to Messages

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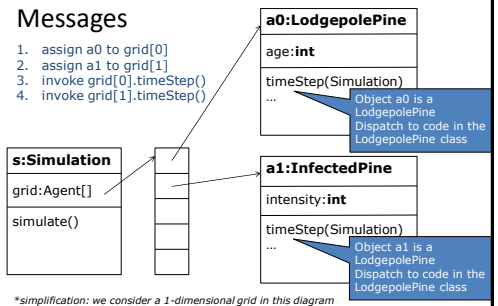


*simplification: we consider a 1-dimensional grid in this diagram

Learning Goals

- Explain the need to design for change and design for division of labor
- Understand subtype polymorphism and dynamic dispatch
  - Distinguish between static and runtime type
  - Explain *static* and *instanceof* and their limitations
- Use encapsulation to achieve information hiding
- Define method contracts beyond type signatures
- Explain the concept of design patterns, their ingredients and applications
- Identify applicability of and apply the strategy design pattern
- Write and automate unit tests

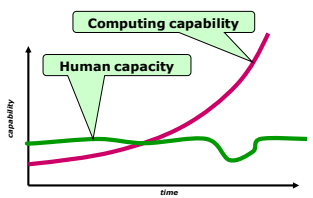
Design Goals, Principles, and Patterns

- Design Goals
  - Design for Change
  - Design for Division of Labor
- Design Principles
  - Explicit Interfaces (clear boundaries)
  - Information Hiding (hide likely changes)
- Design Patterns
  - Strategy Design Pattern
  - Composite Design Pattern
- Supporting Language Features
  - Subtype Polymorphism
  - Encapuslation

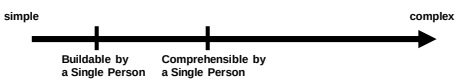
Software Change

- …accept the fact of change as a way of life, rather than an untoward and annoying exception.
  —Brooks, 1974
- Software that does not change becomes useless over time.
  —Belady and Lehman
- For successful software projects, most of the cost is spent evolving the system, not in initial development
  - Therefore, reducing the cost of change is one of the most important principles of software design

The limits of exponentials



Building Complex Systems



- Division of Labor
- Division of Knowledge and Design Effort
- Reuse of Existing Implementations

Goal of Software Design

- For each desired program behavior there are infinitely many programs that have this behavior
  - What are the differences between the variants?
  - Which variant should we choose?
- Since we usually have to synthesize rather than choose the solution…
  - How can we design a variant that has the desired properties?

Sorting with configurable order, variant B

```
void sort(int[] list, Comparator cmp) {
   …
  boolean mustswap;
  mustswap = cmp.compare(list[i], list[j]);
  …
}
interface Comparator {
  boolean compare(int i,
}
class UpComparator imple
  boolean compare(int I,                    }

class DownComparator imp
  boolean compare(int I, int j) { return i>j; }}
```

Uses Polymorphism for Extensibility

Programming against an Interface

Strategy Design Pattern

Design Goals for Today

- **Design for Change** (flexibility, extensibility, modifiability)

also

- Design for Division of Labor
- Design for Understandability

SUBTYPE POLYMORPHISM / DYNAMIC DISPATCH
(OBJECT-ORIENTED LANGUAGE FEATURE ENABLING FLEXIBILITY)

Objects

- A package of state (data) and behavior (actions)
- Can interact with objects by sending messages
  - perform an action (e.g., move)
  - request some information (e.g., getSize)

```
Point p = ...
int x = p.getX();
```

```
IntSet a = ...; IntSet b = ...
boolean s = a.isSubsetOf(b);
```

- Possible messages described through an interface

```
interface Point {
   int getX();
   int getY();
   void moveUp(int y);
   Point copy();
}
```

```
interface IntSet {
   boolean contains(int element);
   boolean isSubsetOf(
                IntSet otherSet);
}
```


Subtype Polymorphism

- There may be multiple implementations of an interface
- Multiple implementations coexist in the same program
- May not even be distinguishable

- Every object has its own data and behavior

Creating Objects

```
interface Point {
   int getX();
   int getY();
}
Point p = new Point() {
   int getX() { return 3; }
   int getY() { return -10; }
}
```

Creating Objects

```
interface IntSet {
   boolean contains(int element);
   boolean isSubsetOf(IntSet otherSet);
}
IntSet emptySet = new IntSet() {
   boolean contains(int element) { return false; }
   boolean isSubsetOf(IntSet otherSet) { return
   true; }
}
```


Creating Objects

```
interface IntSet {
   boolean contains(int element);
   boolean isSubsetOf(IntSet otherSet);
}
IntSet threeSet = new IntSet() {
   boolean contains(int element) {
      return element == 3;
   }
   boolean isSubsetOf(IntSet otherSet) {
      return otherSet.contains(3);
   }
}
```


Classes as Object Templates

```
interface Point {
   int getX();
   int getY();
}
Class CartesianPoint implements Point {
   int x,y;
   Point(int x, int y) {this.x=x; this.y=y;}
   int getX() { return this.x; }
   int getY() { return this.y; }
}
Point p = new CartesianPoint(3, -10);
```


More Classes

```
interface Point {
   int getX();
   int getY();
}
class SkewedPoint implements Point {
   int x,y;
   SkewedPoint(int x, int y) {this.x=x + 10; this.y=y * 2;}
   int getX() { return this.x -  10; }
   int getY() { return this.y / 2; }
}
Point p = new SkewedPoint(3, -10);
```


Polar Points

```
interface Point {
   int getX();
   int getY();
}
class PolarPoint implements Point {
   double len, angle;
   PolarPoint(double len, double angle)
         {this.len=len; this.angle=angle;}
   int getX() { return this.len * cos(this.angle);}
   int getY() { return this.len * sin(this.angle); }
  double getAngle() {…}
}
Point p = new PolarPoint(5, .245);
```


Implementation of interfaces

- Classes can *implement* one or more interfaces.

public class PolarPoint implements Point, IPolarPoint {…}

- **Semantics**
  - **Must provide code** for all methods in the interface(s)

Polar Points

```
interface Point {
    int getX();
    int getY();
}
class PolarPointImpl implements Point, PolarPoint {
    double len, angle;
    PolarPoint(double len, double angle)
          {this.len=len; this.angle=angle;}
    int getX() { return this.len * cos(this.angle);}
    int getY() { return this.len * sin(this.angle); }
    double getAngle() {…}
    double getLength() {… }
}
PolarPoint p = new PolarPointImpl(5, .245);
Point q = new PolarPointImpl(5, .245);
```

```
interface PolarPoint {
    double getAngle() ;
    double getLength();
}
```


Middle Points

```
interface Point {
    int getX();
    int getY();
}
class MiddlePoint implements Point {
    Point a, b;
    MiddlePoint(Point a, Point b) {this.a = a; this.b = b; }
    int getX() { return (this.a.getX() + this.b.getX()) / 2;}
    int getY() { return (this.a.getY() + this.b.getY()) / 2; }
}
Point p = new MiddlePoint(new PolarPoint(5, .245),
                          new CartesianPoint(3, 3));
```


Example: Points and Rectangles

Subtype Polymorphism

```
interface Point {
    int getX();
    int getY();
}
… = new Rectangle() {
    Point origin;
    int width, height;
    Point getOrigin() { return this.origin; }
    int getWidth() { return this.width; }
    void draw() {
        this.drawLine(this.origin.getX(), this.origin.getY(),    // first line
                      this.origin.getX()+this.width, this.origin.getY());
        … // more lines here
    }
};
```


Points and Rectangles: Interface

```
interface Point {
    int getX();
    int getY();
}
interface Rectangle {
    Point getOrigin();
    int getWidth();
    int getHeight();
    void draw();
}
```

What are possible implementations of the IRectangle interface?

Java interfaces and classes

- Organize program functionality around kinds of abstract "objects"
  - For each object kind, offer a specific set of operations on the objects
  - Objects are otherwise opaque: Details of representation are hidden
  - "Messages to the receiving object"
- Distinguish interface from class
  - Interface: expectations
  - Class: delivery on expectations (the implementation)
  - Anonymous class: special Java construct to create objects without explicit classes: Point x = new Point() { /* implementation */ };
- Explicitly represent the taxonomy of object types
  - This is the type hierarchy (!= inheritance, more on that later): A CartesianPoint is a Point

Discussion Subtype Polymorphism

- A user of an object does not need to know the object's implementation, only its interface
- All objects implementing the interface can be used interchangably
- Allows flexible **change** (modifications, extensions, reuse) later without changing the client implementation, even in unanticipated contexts

Design for Change!

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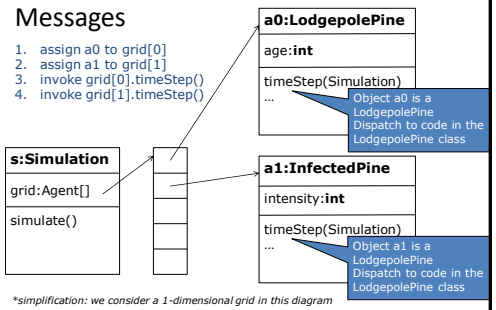


*simplification: we consider a 1-dimensional grid in this diagram

Check your Understanding

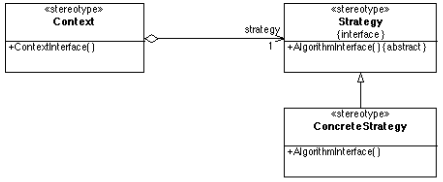
```
interface Animal {
   void makeSound();
}
class Dog implements Animal {
   public void makeSound() { System.out.println("bark!"); }
}
class Cow implements Animal {
   public void makeSound() { mew(); }
   public void mew() {System.out.println("Mew!"); }
}
0 Animal x = new Animal() {
        public void makeSound() { System.out.println("chirp!"); }}
  x.makeSound():
1 Animal a = new Animal();
2 a.makeSound();
3 Dog d = new Dog();
4 d.makeSound();
5 Animal b = new Cow();
6 b.makeSound();
7 b.mew();
```

- What happens?

See textbook 26.7

STRATEGY DESIGN PATTERN (EXPLOITING POLYMORPHISM FOR FLEXIBILITY)

Behavioral: Strategy



Tradeoffs

```
void sort(int[] list, String order) {
  …
  boolean mustswap;
  if (order.equals("up")) {
    mustswap = list[i] < list[j];
  } else if (order.equals("down")) {
    mustswap = list[i] > list[j];
  }
  …
}
```

```
void sort(int[] list, Comparator cmp) {
  …
  boolean mustswap;
  mustswap = cmp.compare(list[i], list[j]);
  …
}
interface Comparator {
  boolean compare(int i, int j);
}
class UpComparator implements Comparator {
  boolean compare(int I, int j) { return i<j; }}

class DownComparator implements Comparator {
  boolean compare(int I, int j) { return i>j; }}
```


Behavioral: Strategy

- Applicability
  - Many classes differ in only their behavior
  - Client needs different variants of an algorithm
- Consequences
  - Code is more extensible with new strategies
    - compare to conditionals
  - Separates algorithm from context
    - each can vary independently
    - design for change and reuse; reduce coupling
  - Adds objects and dynamism
    - code harder to understand
  - Common strategy interface
    - may not be needed for all Strategy implementations – may be extra overhead
- Design for change
  - Find what varies and encapsulate it
  - Allows changing/adding alternative variations later
  - Class *Context* closed for modification, but open for extension
- Equivalent in functional progr. languages: Higher-order functions

Design Patterns

- "Each pattern describes a problem which occurs over and over again in our environment, and then describes the core of the solution to that problem, in such a way that you can use this solution a million times over, without ever doing it the same way twice"
  – Christopher Alexander
- Every Strategy interface has its own domain-specific interface
  – But they share a common problem and solution

Examples

- Change the sorting criteria in a list
- Change the aggregation method for computations over a list (e.g., fold)
- Compute the tax on a sale
- Compute a discount on a sale
- Change the layout of a form

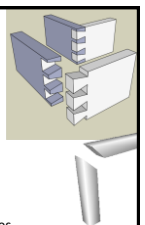
Benefits of Patterns

- Shared language of design
  – Increases communication bandwidth
  – Decreases misunderstandings
- Learn from experience
  – Becoming a good designer is hard
    - Understanding good designs is a first step
  – Tested solutions to common problems
    - Where is the solution applicable?
    - What are the tradeoffs?

Illustration [Shalloway and Trott]

- Carpenter 1: How do you think we should build these drawers?
- Carpenter 2: Well, I think we should make the joint by cutting straight down into the wood, and then cut back up 45 degrees, and then going straight back down, and then back up the other way 45 degrees, and then going straight down, and repeating…
- SE example: "I wrote this if statement to handle … followed by a while loop … with a break statement so that…"

A Better Way



- Carpenter 1: Should we use a dovetail joint or a miter joint?
- Subtext:
  – miter joint: cheap, invisible, breaks easily
  – dovetail joint: expensive, beautiful, durable
- Shared terminology and knowledge of consequences raises level of abstraction
  – CS: Should we use a Strategy?
  – Subtext
    - Is there a varying part in a stable context?
    - Might there be advantages in limiting the number of possible implementations?

Elements of a Pattern

- Name
  – Important because it becomes part of a design vocabulary
  – Raises level of communication
- Problem
  – When the pattern is applicable
- Solution
  – Design elements and their relationships
  – Abstract: must be specialized
- Consequences
  – Tradeoffs of applying the pattern
    - Each pattern has costs as well as benefits
    - Issues include flexibility, extensibility, etc.
    - There may be variations in the pattern with different consequences

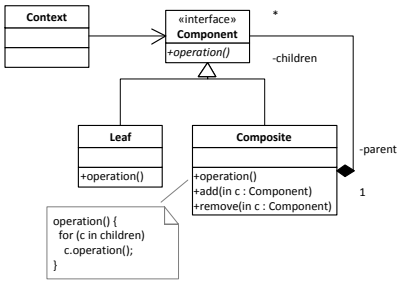
History: Design Patterns Book

- Brought Design Patterns into the mainstream
- Authors known as the Gang of Four (GoF)
- Focuses on *descriptions of communicating objects and classes that are customized to solve a general design problem in a particular context*
- Great as a reference text
- Uses C++, Smalltalk

Design Exercise (on paper)

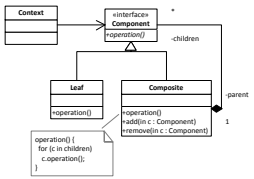
- You are designing software for a shipping company.
- There are several different kinds of items that can be shipped: letters, books, packages, fragile items, etc.
- Two important considerations are the **weight** of an item and its **insurance cost**.
  - Fragile items cost more to insure.
  - All letters are assumed to weigh an ounce
  - We must keep track of the weight of other packages.
- The company sells **boxes** and customers can put several items into them.
  - The software needs to track the contents of a box (e.g. to add up its weight, or compute the total insurance value).
  - However, most of the software should treat a box holding several items just like a single item.
- Think about how to represent packages; what are possible interfaces, classes, and methods? (letter, book, box only)

The Composite Design Pattern



The Composite Design Pattern

- Applicability
  - You want to represent part-whole hierarchies of objects
  - You want to be able to ignore the difference between compositions of objects and individual objects
- Consequences
  - Makes the client simple, since it can treat objects and composites uniformly
  - Makes it easy to add new kinds of components
  - Can make the design overly general
    - Operations may not make sense on every class
    - Composites may contain only certain components



We have seen this before

```
interface Point {
        int getX();
        int getY();
}
class MiddlePoint implements Point {
        Point a, b;
        MiddlePoint(Point a, Point b) {this.a = a; this.b = b; }
        int getX() { return (this.a.getX() + this.b.getX()) / 2;}
        int getY() { return (this.a.getY() + this.b.getY()) / 2; }
}
```


ENCAPSULATION (LANGUAGE FEATURE TO CONTROL VISIBILITY)

Controlling Access – Best practices

- Define an interface
- Client may only use the messages in the interface
- Fields not accessible from client code
- Methods only accessible if exposed in interface

```
interface Point {
    int getX();
    int getY();
}
class CartesianPoint implements Point {
    int x,y;
    Point(int x, int y) {this.x=x; this.y=y;}
    int getX() { return this.x; }
    int getY() { return this.y; }
    String getText() { return this.x + " x " + this.y; }
}
Point p = new CartesianPoint(3, -10);
p.getX();
p.getText(); // not accessible
p.x; // not accessible
```

Interface Type

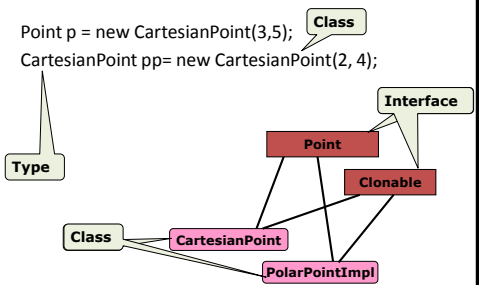
Java: Classes as Types

- Classes usable as type
  - (Public) methods in classes usable like methods in interfaces
  - (Public) fields directly accessible from other classes
  - Language constructs (public, private, protected) to control access
- Prefer programming to interfaces (variables should have **interface type**, not class type)
  - Esp. whenever there are multiple implementations of a concept
  - Allows to provide different implementations later
  - Prevents dependence on implementation details

```
int add(CartesianPoint p) { ...   // preferably no
int add(Point p) { ...            // yes!
```


Interfaces vs Classes as Types

```
Point p = new CartesianPoint(3,5);
CartesianPoint pp= new CartesianPoint(2, 4);
```



Interfaces and Classes (Review)

```
class PolarPoint implements Point {
  double len, angle;
  PolarPoint(double len, double angle)
        {this.len=len; this.angle=angle;}
  int getX() { return this.len * cos(this.angle);}
  int getY() { return this.len * sin(this.angle); }
  double getAngle() { return angle; }
}
```

```
Point p = new PolarPoint(5, .245);
p.getX();
p.getAngle(); // not accessible
p.len // not accessible
```

```
PolarPoint pp = ...
pp.getX();
pp.getAngle();
pp.len
```


Java: Visibility Modifiers

```
class Point {
    private int x, y;
    public int getX() { return this.x; } // a method; getY() is similar
    public Point(int px, int py) { this.x = px; this.y = py; // constructor creating the object
}
class Rectangle {
    private Point origin;
    private int width, height;
    public Point getOrigin() { return origin; }
    public int getWidth() { return width; }
    public void draw() {
            drawLine(this.origin.getX(), this.origin.getY(),   // first line
                     this.origin.getX()+this.width, origin.getY());
            ... // more lines here
    }
    public Rectangle(Point o, int w, int h) {
        this.origin = o; this.width = w; this.height = h;
    }
}
```


Hiding interior state

Some Client Code

```
Point o = new Point(0, 10); // allocates memory, calls ctor
Rectangle r = new Rectangle(o, 5, 10);
r.draw();
int rightEnd = r.getOrigin().getX() + r.getWidth(); // 5
```

Client Code that will *not* work in this version

```
Point o = new Point(0, 10); // allocates memory, calls ctor
Rectangle r = new Rectangle(o, 5, 10);
r.draw();
int rightEnd = r.origin.x + r.width; //  trying to "look inside"
```

Hiding interior state

```
class Point {
        private int
        public int
        public Poi
}
class Rectang
        private Po
        private int
        public Point getOrigin() { return origin; }
        public int getWidth() { return width; }
        public void draw() {
                drawLine(origin.getX(), origin.getY(),          // first line
                         origin.getX()+width, origin.getY());
                ... // more lines here
        }
        public Rectangle(Point o, int w, int h) {
                origin = o; width = w; height = h;
        }
}
```

Discussion:

- ***What are the benefits of private fields?***
- ***Methods can also be private – why is this useful?***

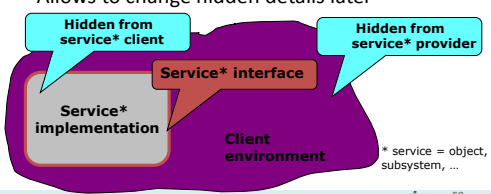
Discussion

- Types vs Classes and Interfaces
- Subtypes

DESIGN PRINCIPLE: INFORMATION HIDING

Fundamental Design Principle for Change: Information Hiding

- Expose as little implementation detail as necessary
- Allows to change hidden details later



Information Hiding

- Interfaces (contracts) remain stable
- Hidden implementation can be changed easily
- => Identify what is likely to change, and hide it
- => Requires anticipation of change (judgment)

- Points example: Minimal stable interface, allows alternative implementations and flexible composition

- (Not all change can be anticipated, causing maintenance work or reducing flexibility)

Information Hiding promotes Reuse

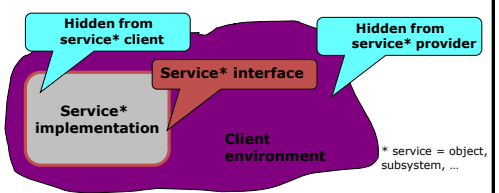
- Think in terms of abstractions not implementations
  - e.g., Point vs CartesianPoint
- Abstractions can often be reused
- Different implementations of the same interface possible,
  - e.g., reuse Rectangle but provide different Point implementation
- Decoupling implementations
- Hiding internals of implementations

More on reuse next week

INFORMATION HIDING CASE STUDY

CONTRACTS (BEYOND TYPE SIGNATURES)

Contracts and Clients



Contracts

- Agreement between provider and users of an object
- Includes
  - Interface specification
  - Functionality and correctness expectations
  - Performance expectations
- "Focus on concepts rather than operations"

Who's to blame?

```
Algorithms.shortestDistance(g,
   "Tom", "Anne");

> ArrayOutOfBoundsException
```

Who's to blame?

```
Algorithms.shortestDistance(g,
   "Tom", "Anne");

> -1
```


Who's to blame?

```
Algorithms.shortestDistance(g,
   "Tom", "Anne");

> 0
```


Who's to blame?

```
class Algorithms {
    /**
     * This method finds the
     * shortest distance between to
     * verticies. It returns -1 if
     * the two nodes are not
     * connected. */
    int shortestDistance(…) {…}
}
```


Who's to blame?

```
Math.sqrt(-5);

> 0
```


Who's to blame?

```
/**
  * Returns the correctly rounded positive square root of a
  * {@code double} value.
  * Special cases:
  * <ul><li>If the argument is NaN or less than zero, then the
  * result is NaN.
  * <li>If the argument is positive infinity, then the result
  * is positive infinity.
  * <li>If the argument is positive zero or negative zero, then
  * the result is the same as the argument.</ul>
  * Otherwise, the result is the {@code double} value closest to
  * the true mathematical square root of the argument value.
  *
  * @param a a value.
  * @return the positive square root of {@code a}.
  * If the argument is NaN or less than zero, the result is NaN.
  */
public static double sqrt(double a) { …}
```


Textual Specification

public int read(byte[] b, int off, int len) throws IOException

- Reads up to len bytes of data from the input stream into an array of bytes. An attempt is made to read as many as len bytes, but a smaller number may be read. The number of bytes actually read is returned as an integer. This method blocks until input data is available, end of file is detected, or an exception is thrown.
- If len is zero, then no bytes are read and 0 is returned; otherwise, there is an attempt to read at least one byte. If no byte is available because the stream is at end of file, the value -1 is returned; otherwise, at least one byte is read and stored into b.
- The first byte read is stored into element b[off], the next one into b[off+1], and so on. The number of bytes read is, at most, equal to len. Let *k* be the number of bytes actually read; these bytes will be stored in elements b[off] throughb[off+*k*-1], leaving elements b[off+*k*] through b[off+len-1] unaffected.
- In every case, elements b[0] through b[off] and elements b[off+len] through b[b.length-1] are unaffected.

- Throws:
  - IOException - If the first byte cannot be read for any reason other than end of file, or if the input stream has been closed, or if some other I/O error occurs.
  - NullPointerException - If b is null.
  - IndexOutOfBoundsException - If off is negative, len is negative, or len is greater than b.length - off

Textual Specification

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  1], leaving elements b[off+k]
- In every case, elements b[0] through b[off] and elements b[off+len] through b[b.length-1] are unaffected.

- Specification of return
- Timing behavior (blocks)
- Case-by-case spec
  - len=0 → return 0
  - len>0 && eof → return -1
  - len>0 && !eof →return >0
- Exactly where the data is stored
- What parts of the array are not affected

- Throws:
  - IOException - If the first byte c
    or if the input stream has been
  - NullPointerException - If b is n
  - IndexOutOfBoundsException -
    than b.length - off

- Multiple error cases, each with a precondition
- Includes "runtime exceptions" not in throws clause

Specifications

- Contains
  - Functional behavior
  - Erroneous behavior
  - Quality attributes (performance, scalability, security, …)
- Desirable attributes
  - Complete
    - Does not leave out any desired behavior
  - Minimal
    - Does not require anything that the user does not care about
  - Unambiguous
    - Fully specifies what the system should do in every case the user cares about
  - Consistent
    - Does not have internal contradictions
  - Testable
    - Feasible to objectively evaluate
  - Correct
    - Represents what the end-user(s) need

Function Specifications

- A function's contract is a statement of the responsibilities of that function, and the responsibilities of the code that calls it.
  - Analogy: legal contracts - If you pay me $30,000, I will build a new room on your house
  - Helps to pinpoint responsibility
- Contract structure
  - Precondition: the condition the function relies on for correct operation
  - Postcondition: the condition the function establishes after correctly running
- (Functional) correctness with respect to the specification
  - If the client of a function fulfills the function's precondition, the function will execute to completion and when it terminates, the postcondition will be fulfilled
- What does the implementation have to fulfill if the client violates the precondition?

Formal Specifications

```
/*@ requires len >= 0 && array != null && array.length == len;
  @
  @ ensures \result ==
  @           (\sum int j;  0 <= j && j < len;  array[j]);
  @*/
int total(int array[], int len);
```

Advantage of formal specifications:

* runtime checks (almost) for free
* basis for formal verification
* assisting automatic analysis tools

JML (Java Modelling Language) as specifications language in Java (inside comments)

Runtime Checking of Specifications with Assertions

```
/*@ requires len >= 0 && array.length == len
  @ ensures \result ==
  @           (\sum int j;  0 <= j && j < len;  array[j])
  @*/
float sum(int array[], int len) {
    assert len >= 0;
    assert array.length == len;
    float sum = 0.0;
    int i = 0;
    while (i < len) {
        sum = sum + array[i]; i = i + 1;
    }
    assert sum …;
    return sum;
}
```

java -ea Main

Runtime Checking with Exceptions

```
/*@ requires len >= 0 && array.length == len
  @ ensures \result ==
  @              (\sum int j;  0 <= j && j < len;  array[j])
  @*/
float sum(int array[], int len) {
    if (len < 0 || array.length != len)
        throw IllegalArgumentException(…);
    float sum = 0.0;
    int i = 0;
    while (i < len) {
        sum = sum + array[i]; i = i + 1;
    }
    return sum;
    assert …;
}
```

Check arguments even when assertions are disabled.
Good for robust libraries!

Contacts and Interfaces

- All objects implementing an interface must adhere to the interface's contracts
  - Objects may provide different implementations for the same specification
  - Subtype polymorphism: Client only cares about interface, not about the implementation

    p.getX() **s.read()**

=> **Design for Change**

Specifications in Practice

- Describe expectations beyond the type signature
- Ideally formal pre- and post-conditions
- Textual specifications in practice
  - Best effort approach
- If any specification at all
- Specification especially necessary when reusing code and integrating code

- Writing specifications is good practice
- Writing fully formal specifications is often unrealistic

ASIDE:
SPECIFICATION OF CLASS INVARIANTS

Data Structure Invariants (cf. 122)

```
struct list {
    elem data;
    struct list* next;
};
struct queue {
    list front;
    list back;
};

bool is_queue(queue Q) {
    if (Q == NULL) return false;
    if (Q->front == NULL || Q->back == NULL) return false;
    return is_segment(Q->front, Q->back);
}
```


Data Structure Invariants (cf. 122)

- Properties of the Data Structure
- Should always hold before and after method execution
- May be invalidated temporarily during method execution

```
void enq(queue Q, elem s)
//@requires is_queue(Q);
//@ensures is_queue(Q);
{ … }
```

Class Invariants

- Properties about the fields of an object
- Established by the constructor
- Should always hold before and after execution of public methods
- May be invalidated temporarily during method execution

Class Invariants

- Properties about the fields of an object
- Established by the constructor

```
public class SimpleSet {

  int contents[];
  int size;

  //@ ensures sorted(contents);
  SimpleSet(int capacity) { ... }

  //@ requires sorted(contents);
  //@ ensures sorted(contents);
  boolean add(int i) { ... }

  //@ requires sorted(contents);
  //@ ensures sorted(contents);
  boolean contains(int i) { ... }
}
```

```
public class SimpleSet {

  int contents[];
  int size;

  //@invariant sorted(contents);

  SimpleSet(int capacity) { ... }

  boolean add(int i) { ... }

  boolean contains(int i) { ... }
}
```


Java: Constructors

- Special “Methods” to create objects
  - Same name as class, no return type
- May initialize object during creation
- Implicit constructor without parameters if none provided

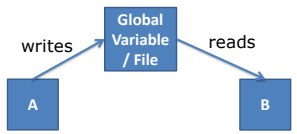
```
class APoint {
  int x,y;
}
APoint p = new APoint();
p.x=3;
p.y=-10;
```

```
class BPoint {
  int x,y;
  BPoint(int x, int y)
        {this.x=x; this.y=y;}
}
BPoint p = new BPoint(3, -10);
```


DESIGN PRINCIPLE:
EXPLICIT INTERFACES

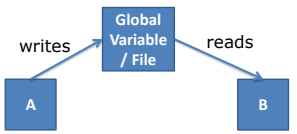
Explicit Interfaces

- Whenever two modules A and B communicate, it must be obvious from the text of A or B or both
- Avoid communication through shared state



Explicit Interfaces

- Behavior involving global state is hard to specify – redesign when writing lengthy specification involving the state of other objects / system state

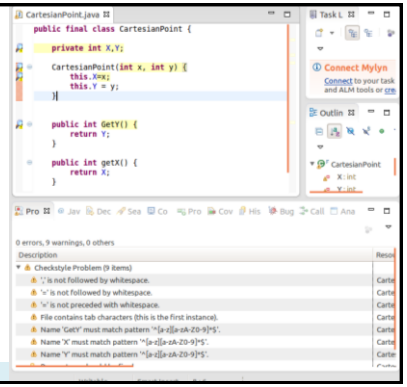


FUNCTIONAL CORRECTNESS
(UNIT TESTING AGAINST INTERFACES)

Functional Correctness

- The compiler ensures that the types are correct (type checking)
  - Prevents "Method Not Found" and "Cannot add Boolean to Int" errors at runtime
- Static analysis tools (e.g., FindBugs) recognize certain common problems
  - Warns on possible NullPointerExceptions or forgetting to close files
- How to ensure functional correctness of contracts beyond type correctness and bug patterns?

CheckStyle



Excursion: Formal Verification

- Proving the correctness of an implementation with respect to a formal specification, using formal methods of mathematics.
- Formally prove that all possible executions of an implementation fulfill the specification
- Manual effort; partial automation; not automatically decidable

Recap: Hoare-Style Verification

- Formal reasoning about program correctness using pre- and postconditions
- Syntax: {P} S {Q}
  - P and Q are predicates
  - P is the precondition
  - S is a program
  - Q is the postcondition
- Semantics
  - If we start in a state where P is true and execute S, then S will terminate in a state where Q is true

Recap: Hoare-Logic Rules

- Assignments
  $\{P[E/x]\}\ x := E\ \{P\}$
- Composition
  $\dfrac{\{P\}\,S\,\{Q\} \quad \{Q\}\,T\,\{R\}}{\{P\}\,S;\,T\,\{R\}}$
- If statement
  $\dfrac{\{B \,\&\, P\}\,S\,\{Q\} \quad \{!B \,\&\, P\}\,T\,\{Q\}}{\{P\}\ \text{if (B) S else T}\ \{Q\}}$
- While loop with loop invariant P
  $\dfrac{\{P \,\&\, B\}\,S\,\{P\}}{\{P\}\ \text{while (B) S}\ \{!B \,\&\, P\}}$
- Consequence
  $\dfrac{P \rightarrow P' \quad \{P'\}\,S\,\{Q'\} \quad Q' \rightarrow Q}{\{P\}\,S\,\{Q\}}$

Recap: 122 midterm

```
int find_peak_bin(int[] A, int n)
        //@requires 0 < n && n <= \length(A);
        //@requires is_peaked(A, 0, n);
        //@ensures 0 <= \result && \result < n;
        //@ensures gt_seg(A[\result], A, 0, \result);
        //@ensures gt_seg(A[\result], A, \result+1, n);
{
        int lower = 0;
        int upper = n-1;
        while (lower < upper)
                //@loop_invariant _____ ;
                //@loop_invariant _____ ;
        {
                int mid = lower + (upper-lower)/2;
                //@assert _____ ; /* optional */
                if (A[mid] < A[mid+1])
                        lower = mid+1;
                else //@assert _____ ; /* optional */
                        upper = mid;
        }
        //@assert _____ ; /* optional */
        return lower;
}
```


Hoare Triples – Examples

- { true } x := 5 { }
- { } x := x + 3 { x = y + 3 }
- { } x := x * 2 + 3 { x > 1 }
- { x=a } if (x < 0) then x := -x { }
- { false } x := 3 { }
- { x < 0 } while (x!=0) x := x-1 { }

Hoare Triples – Examples

- { true } x := 5 { x=5 }
- { x = y } x := x + 3 { x = y + 3 }
- { x > -1 } x := x * 2 + 3 { x > 1 }
- { x=a } if (x < 0) then x := -x { x=|a| }
- { false } x := 3 { x = 8 }
- { x < 0 } while (x!=0) x := x-1 { }
  – no such triple!

Testing

- Executing the program with selected inputs in a controlled environment
- Goals:
  - Reveal bugs (main goal)
  - Assess quality (hard to quantify)
  - Clarify the specification, documentation
  - Verify contracts

"Testing shows the presence, not the absence of bugs
Edsger W. Dijkstra 1969

What to test?

Our focus now

- Functional correctness of a method (e.g., computations, contracts)
- Functional correctness of a class (e.g., class invariants)
- Behavior of a class in a subsystem/multiple subsystems/the entire system
- Behavior when interacting with the world
  - Interacting with files, networks, sensors, …
  - Erroneous states
  - Nondeterminism, Parallelism
  - Interaction with users
- Other qualities (performance, robustness, usability, security, …)

Manual Testing?

GENERIC TEST CASE: USER SENDS MMS WITH PICTURE ATTACHED.

Step ID	User Action	System Response
1	Go to Main Menu	Main Menu appears
2	Go to Messages Menu	Message Menu appears
3	Select "Create new Message"	Message Editor screen opens
4	Add Recipient	Recipient is added
5	Select "Insert Picture"	Insert Picture Menu opens
6	Select Picture	Picture is Selected
7	Select "Send Message"	Message is correctly sent

- Live System?
- Extra Testing System?
- Check output / assertations?
- Effort, Costs?
- Reproducable?

Automate Testing

- Execute a program with specific inputs, check output for expected values
- Easier to test small pieces than testing user interactions
- Set up testing infrastructure
- Execute tests regularly

Example

```
/**
 * computes the sum of the first len values of the array
 *
 * @param array array of integers of at least length len
 * @param len number of elements to sum up
 * @return sum of the array values
 */
int total(int array[], int len);
```

Black box testing

Example

```
/**
 * computes the sum of the first len values of the array
 *
 * @param array array of integers of at least length len
 * @param len number of elements to sum up
 * @return sum of the array values
 */
int total(int array[], int len);
```

Black box testing

- Test empty array
- Test array of length 1 and 2
- Test negative numbers
- Test invalid length (negative or longer than array.length)
- Test null as array
- Test with a very long array

JUnit

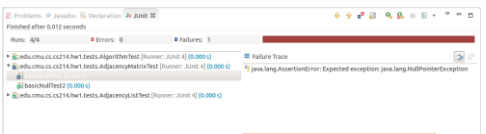
```
import org.junit.Test;
import static org.junit.Assert.assertEquals;

public class AdjacencyListTest {
        @Test
        public void testSanityTest(){
                Graph g1 = new AdjacencyListGraph(10);
                Vertex s1 = new Vertex("A");
                Vertex s2 = new Vertex("B");
                assertEquals(true, g1.addVertex(s1));
                assertEquals(true, g1.addVertex(s2));
                assertEquals(true, g1.addEdge(s1, s2));
                assertEquals(s2, g1.getNeighbors(s1)[0]);
        }

        @Test
        public void test….

        private int helperMethod…
}
```

Set up tests

Check expected results

JUnit

- Popular unit-testing framework for Java
- Easy to use
- Tool support available
- Can be used as design mechanism



Selecting Test Cases: Common Strategies

- Read specification
- Write tests for representative case
  - Small instances are usually sufficient
- Write tests for invalid cases
- Write tests to check boundary conditions
- Are there difficult cases? (error guessing)
  - Stress tests? Complex algorithms?
- Think like a user, not like a programmer
  - The tester's goal is to find bugs!
- Specification covered?
- Feel confident? Time/money left?

Unit Tests

- Unit tests for small units: functions, classes, subsystems
  - Smallest testable part of a system
  - Test parts before assembling them
  - Intended to catch local bugs
- Typically written by developers
- Many small, fast-running, independent tests
- Little dependencies on other system parts or environment
- Insufficient but a good starting point, extra benefits:
  - Documentation (executable specification)
  - Design mechanism (design for testability)

assert, Assert

- assert is a native Java statement throwing an AssertionError exception when failing
  - **assert** expression: "Error Message";
- org.junit.Assert is a library that provides many more specific methods
  - static void **assertTrue**(java.lang.String message, boolean condition)
    // Asserts that a condition is true.
  - static void **assertEquals**(java.lang.String message, long expected, long actual);
    // Asserts that two longs are equal.
  - static void **assertEquals**(double expected, double actual, double delta);
    // Asserts that two doubles are equal to within a positive delta
  - static void **assertNotNull**(java.lang.Object object)
    // Asserts that an object isn't null.
  - static void **fail**(java.lang.String message)
    //Fails a test with the given message.

JUnit Conventions

- TestCase collects multiple tests (in one class)
- TestSuite collects test cases (typically package)
- Tests should run fast
- Tests should be independent
- Tests are methods without parameter and return value
- AssertError signals failed test (unchecked exception)
- Test Runner knows how to run JUnit tests
  - (uses reflection to find all methods with @Test annotat.)

Common Setup

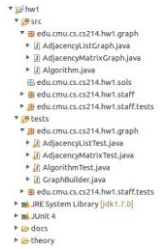
```
import org.junit.*;
import org.junit.Before;
import static org.junit.Assert.assertEquals;

public class AdjacencyListTest {
        Graph g;

        @Before
        public void setUp() throws Exception {
                graph = createTestGraph();
        }

        @Test
        public void testSanityTest(){
                Vertex s1 = new Vertex("A");
                Vertex s2 = new Vertex("B");
                assertEquals(3, g.getDistance(s1, s2));
        }
```


Checking for presence of an exception

```
import org.junit.*;
import static org.junit.Assert.fail;

public class Tests {

        @Test
        public void testSanityTest(){
                try {
                        openNonexistingFile();
                        fail("Expected exception");
                } catch(IOException e) { }
        }

        @Test(expected = IOException.class)
        public void testSanityTestAlternative() {
                openNonexistingFile();
        }
}
```

Test organization

- Conventions (not requirements)
- Have a test class XTest for each class X
- Have a source directory and a test directory
  - Store ATest and A in the same package
  - Tests can access members with default (package) visibility
  - Maven style: src/main/java and src/test/java



Testable Code

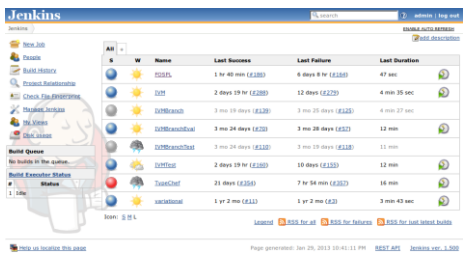
- Think about testing when writing code
- Unit testing encourages to write testable code
- Separate parts of the code to make them independently testable
- Abstract functionality behind interface, make it replaceable

- Test-Driven Development
  - A design and development method in which you write tests before you write the code!

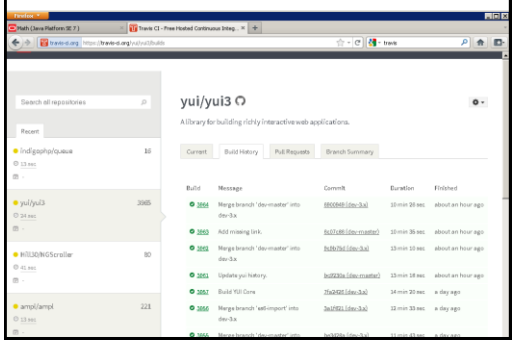
Run tests frequently

- You should only commit code that is passing all tests
- Run tests before every commit
- Run tests before trying to understand other developers' code
- If entire test suite becomes too large and slow for rapid feedback, run local tests ("smoke tests", e.g. all tests in package) frequently, run all tests nightly
  - Medium sized projects easily have 1000s of test cases and run for minutes
- Continuous integration servers help to scale testing

Continuous Integration



Travis CI



Automating Test Execution

```
ckaestne@kastner-desktop:~/work/TypeChef/TypeChef$ sbt "project FeatureExprLib" test
Detected sbt version 0.12.2
[info] Loading global plugins from /usr0/home/ckaestne/.sbt/plugins
[info] Loading project definition from /usr0/home/ckaestne/work/TypeChef/TypeChef/project/project
[info] Loading project definition from /usr0/home/ckaestne/work/TypeChef/TypeChef/project
[info] Set current project to TypeChef (in build file:/usr0/home/ckaestne/work/TypeChef/TypeChef/)
[info] Set current project to FeatureExprLib (in build file:/usr0/home/ckaestne/work/TypeChef/TypeChef/)
[info] Compiling 10 Scala sources to /usr0/home/ckaestne/work/TypeChef/TypeChef/FeatureExprLib/target/scala-2.10/test-
classes...
[info] + FeatureExpr.parse(print(x))==x: OK, passed 100 tests.
[info] + FeatureExpr.and1: OK, passed 100 tests.
[info] + FeatureExpr.and0: OK, passed 100 tests.
[info] + FeatureExpr.andSelf: OK, passed 100 tests.
[info] + FeatureExpr.or1: OK, passed 100 tests.
[info] + FeatureExpr.or0: OK, passed 100 tests.
[info] + FeatureExpr.orSelf: OK, passed 100 tests.
[info] + FeatureExpr.a eq a: OK, passed 100 tests.
[info] + FeatureExpr.a equals a: OK, passed 100 tests.
[info] + FeatureExpr.a equivalent a: OK, passed 100 tests.
[info] + FeatureExpr.a implies a: OK, passed 100 tests.
[info] + FeatureExpr.creating (a and b) twice creates equal object: OK, passed 100 tests.
[info] + FeatureExpr.creating (a or b) twice creates equal object: OK, passed 100 tests.
[info] + FeatureExpr.creating (not a) twice creates equal object: OK, passed 100 tests.
[info] + FeatureExpr.applying not twice yields an equivalent formula: OK, passed 100 tests.
[info] + FeatureExpr.Commutativity wrt. equivalence: (a and b) produces the same object as (b and a): OK, passed 100
tests.
[info] + FeatureExpr.Commutativity wrt. equivalence: (a or b) produces the same object as (b or a): OK, passed 100 te
sts.
[info] + FeatureExpr.taut(a=>b) => contr(a and !b): OK, passed 100 tests.
[info] + FeatureExpr.featuremodel.tautology: OK, passed 100 tests.
```

Build and Test Automation

- Compile and execute from the command line
- Dependencies to all required libraries included (or downloaded on demand)
- Build tools
  - make
  - ant
  - gradle
  - maven
  - sbt
  - …

Write testable code

```
//700LOC
public boolean foo() {
  try {
    synchronized () {
      if () {
      } else {
      }
      for () {
        if () {
          if () {
            if () {
              if ()?
              {
                if () {
                  for () {
                  }
                }
              }
            } else {
              if () {
                for () {
                  if () {
                  } else {
                  }
                  if () {
                  } else {
                    if () {
                    }
                  }
                  if () {
                    if () {
                      if () {
                        for () {
                        }
                      }
                    }
                  } else {
                  }
                }
```

Unit testing as design mechanism

*** Code with low complexity**

*** Clear interfaces and specifications**

Source: http://thedailywtf.com/Articles/Coding-Like-the-Tour-de-France.aspx

Ant example

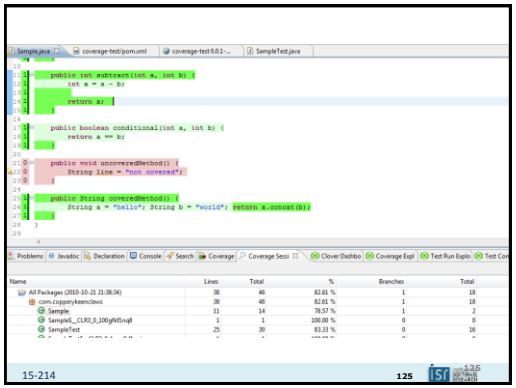
```
<project name="MyProject" default="dist" basedir=".">
  <property name="src" location="src"/>
  <property name="build" location="build"/>
  <property name="dist"  location="dist"/>

  <target name="init"><tstamp/><mkdir dir="${build}"/>  </target>

  <target name="compile" depends="init"
        description="compile the source " >
    <javac srcdir="${src}" destdir="${build}"/>
  </target>

  <target name="clean"
        description="clean up" >
    <!-- Delete the ${build} and ${dist} directory trees -->
    <delete dir="${build}"/>
    <delete dir="${dist}"/>
  </target>
</project>
```

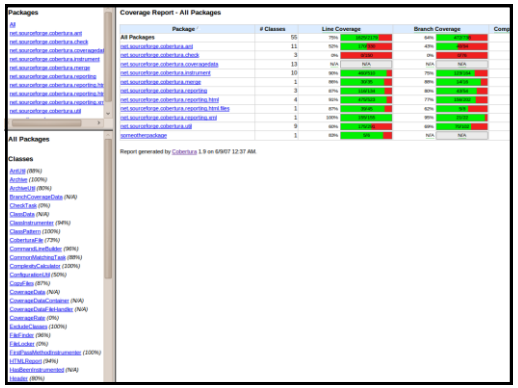

Outlook: Statement Coverage

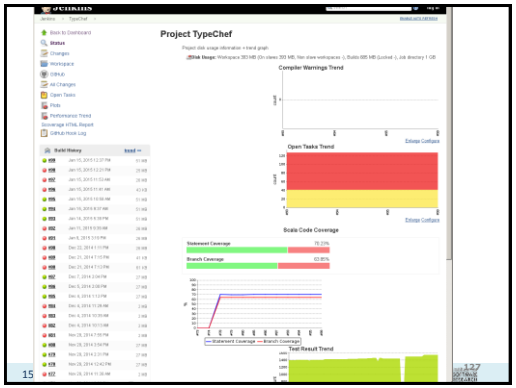
- Trying to test all parts of the implementation
- Execute every statement in at least one test

```
public boolean equals(Object anObject) {
    if (isZero())
        if (anObject instanceof IMoney)
            return ((IMoney)anObject).isZero();
    if (anObject instanceof Money) {
        Money aMoney= (Money)anObject;
        return aMoney.currency().equals(currency())
                        && amount() == aMoney.amount();
    }
    return false;
}
```

- Does this guarantee correctness?







Testing and Proofs

- Testing
  - Observable properties
  - Verify program for one execution
  - Manual development with automated regression
  - Most practical approach now
  - Does not find all problems (unsound)
- Proofs (Formal Verification)
  - Any program property
  - Verify program for all executions
  - Manual development with automated proof checkers
  - Practical for small programs, may scale up in the future
  - Sound and complete, but not automatically decidable

- So why study proofs if they aren't (yet) practical?
  - Proofs tell us how to think about program correctness
  - Important for development, inspection, dynamic assertions
  - Foundation for static analysis tools
  - These are just simple, automated theorem provers
  - Many are practical today!

Testing, Static Analysis, and Proofs

- Testing
  - Observable properties
  - Verify program for one execution
  - Manual development with automated regression
  - Most practical approach now
  - Does not find all problems (unsound)
- Static Analysis
  - Analysis of all possible executions
  - Specific issues only with conservative approx. and bug patterns
  - Tools available, useful for bug finding
  - Automated, but unsound and/or incomplete
- Proofs (Formal Verification)
  - Any program property
  - Verify program for all executions
  - Manual development with automated proof checkers
  - Practical for small programs, may scale up in the future
  - Sound and complete, but not automatically decidable

What strategy to use in your project?

JAVA: STATIC AND INSTANCEOF (BREAKING SUBTYPE POLYMORPHISM AND ENCAPUSLATION)

Java: Static Methods

- Static methods belong to a **class**, not an object
- They are global (a single implementation only)
- Direct dispatch, no subtype polymorphism
- Avoid unless really only a single implementation exists (e.g., Math.min)
- Pure object-oriented languages don't support static methods

```
Point p = …
p.getX()

Point.move(p);
```


Java: Breaking encapsulation: instanceof and typecast

- Java allows to inspect an object's runtime type

```
Point p = …
if (p instanceof PolarPoint) {
    PolarPoint q = (PolarPoint) p;
    q.getAngle()
}
```

- Objects always assignable to variables of supertypes ("upcast") (this effectively throws away parts of the interface)

```
CartesianPoint q = …
Point p = q;
```

- Assignment to subtype requires downcast (may fail at runtime!)

```
Point p = …
CartesianPoint q = (CartesianPoint) p;
```

Avoid instanceof and downcasts

Instanceof breaks encapsulation

- Never ask for the type of an object
- Instead, ask the object to do something (call a method of the interface)
- If the interface does not provide the method, maybe there was a reason? Rethink design!

- Instanceof and downcasts are indicators of poor design
- They break abstractions and encapsulation
- There are only few exceptions where **instanceof** is needed
- Use polymorphism instead

- Pure object-oriented languages do not have an instanceof operation

Excursion: Objects vs ADTs

```
interface Point {
        int getX();
        int getY();
}
class CartesianPoint
        implements Point { … }
class PolarPoint
        implements Point { … }

Point p = …
p.getX()
```

```
class CartesianPoint { … }
class PolarPoint { … }

int getX(Object p) {
  if (p instanceof CartesianPoint)
    return ((CartesianP.)p).x;
  if (p instanceof PolarPoint)
    return ((PolarPoint)p).r*…;
  …
}
```

```
datatype point
  = CartesianP of int * int
  | PolarPoint of real * real

fun getX point =
  case shape
    of CartesianP (x, _) => x
  | PolarPoint (r, a) => r*…
```


Excursion: Objects vs ADTs

```
interface Point {
        int getX();
        int getY();
}
class CartesianPoint
        implements Point { … }
class PolarPoint
        implements Point { … }
Point p = …
p.getX()
```

- OOP solution with polymorphism
  - Easy to extend with new implementations of interface
  - Functions fixed; adding a function to the interface requires changes in all implementations

```
class CartesianPoint { … }
class PolarPoint { … }

int getX(Object p) {
  if (p instanceof CartesianPoint)
    return ((CartesianP.)p).x;
  if (p instanceof PolarPoint)
    return ((PolarPoint)p).r*…;
  …
}
```

- ADT solution with case analysis/ pattern matching
  - ADTs fixed; cannot add new class without changing all functions
  - Easy to add new functions
  - No language/compiler support in Java

EXCURSION: TECHNICAL REALIZATION OF SUBTYPE POLYMORPHISM

Reminder: Subtype Polymorphism

- A type (e.g. Point) can have many forms (e.g., CartesianPoint, PolarPoint, …)

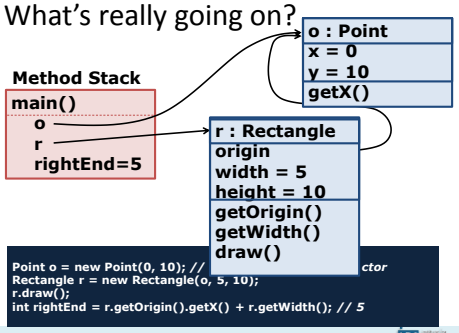
- All implementations of an interface can be used interchangeably

- When invoking a method p.x() the specific implementation of x() from object p is executed
  - The executed method depends on the actual object p, i.e., on the runtime type
  - It does not depend on the static type, i.e., how p is declared

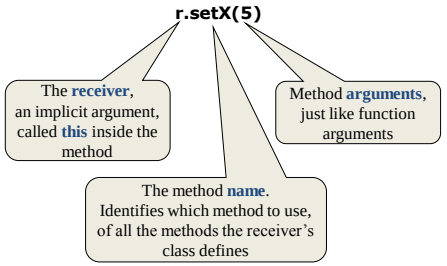
Objects and References (example)

```
// allocates memory, calls constructor
Point o = new PolarPoint(0, 10);

Rectangle r = new MyRectangle(o, 5, 10);

r.draw();

int rightEnd = r.getOrigin().getX() +
   r.getWidth(); // 5
```

What's really going on?



Anatomy of a Method Call



Java Specifics: The keyword **this** refers to the "receiver"

```
class Point {
    int x, y;
    int getX() { return this.x; }
    Point(int x, int y) { this.x = x; this.y = y; }
}
```

can also be written in this way:

```
class Point {
    int x, y;
    int getX() { return x; }
    Point(int px, int py) { x = px; y = py; }
}
```

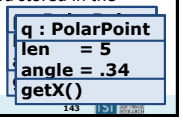

Static types vs dynamic types

- Static type: how is a variable declared
- Dynamic type: what type has the object in memory when executing the program (we may not know until we execute the program)

```
Point createZeroPoint() {
        if (new Math.Random().nextBoolean())
                return new CartesianPoint(0, 0);
        else    return new PolarPoint(0,0);
}
Point p = createZeroPoint();
p.getX();
p.getAngle();
```

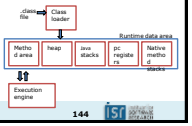

Method dispatch (conceptually)

- Step 1 (compile time): determine what type to look in
  - Look at the **static type** (Point) of the receiver (p)
- Step 2 (compile time): find the method in that type
  - Find the method in the **interface/class** with the right name
    `int getX();`
  - Error if there is no such method
  - Error if the method is not accessible (e.g., private)
- Step 3 (run time): Execute the method stored in the **object**

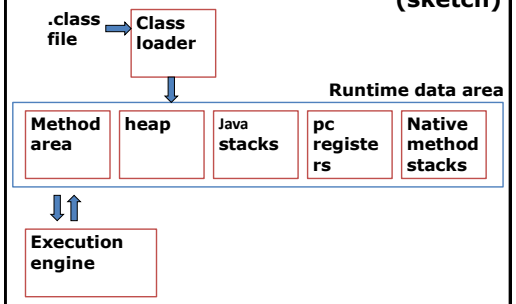


Method dispatch (actual; simplified)

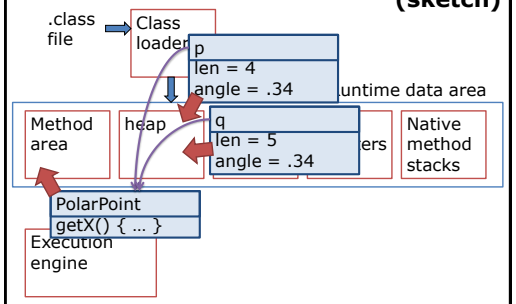
- Step 3 (run time): Determine the run-time type of the receiver
  - Look at the object in the **heap** and get its **class**
- Step 4 (run time): Locate the method implementation to invoke
  - Look in the class for an implementation of the method
  - Invoke that implementation



The Java Virtual Machine (sketch)



The Java Virtual Machine (sketch)

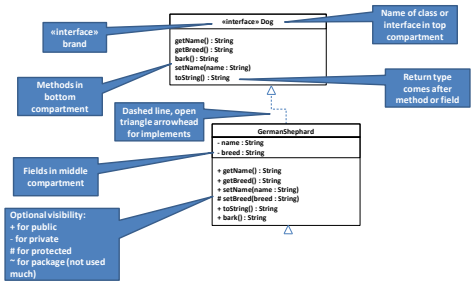


SUMMARY: DESIGN FOR CHANGE/ DIVISION OF LABOR

Design Goals

- Design for Change such that
  - Classes are *open for extension* and modification without invasive changes
  - Subtype polymorphism enables changes behind interface
  - Classes encapsulate details likely to change behind (small) stable interfaces
- Design for Division of Labor such that
  - Internal parts can be *developed* independently
  - Internal details of other classes do not need to be *understood*, contract is sufficient
  - Test classes and their contracts separately (unit testing)

Aside: UML class diagram notation



Outlook

- Specifying contracts, formally and informally
- Testing
- Technical realization of dynamic dispatch

- Reading assignment:
  - Chapters 14 and 16, in-class quiz on Tuesday
  - Homework 1, due Tuesday 11:59pm