CSE 331
Software Design & Implementation

Kevin Zatloukal

Spring 2021

Subtypes and Subclasses

SUBTYPES VS SUBCLASSES

Substitution principle for classes

If B is a subtype of A, then a B can *always* **be substituted** for an A

Any property guaranteed by A must be guaranteed by B

- anything provable about an A is provable about a B
- if an instance of subtype is treated purely as supertype (only supertype methods/fields used), then the result should be consistent with an object of the supertype being manipulated

B is *permitted to strengthen* properties and add properties

- an overriding method must have a stronger (or equal) spec
- fine to add new methods (that preserve invariants)

B is *not permitted to weaken* the spec

- no overriding method with a weaker spec
- no method removal

Substitution principle for methods

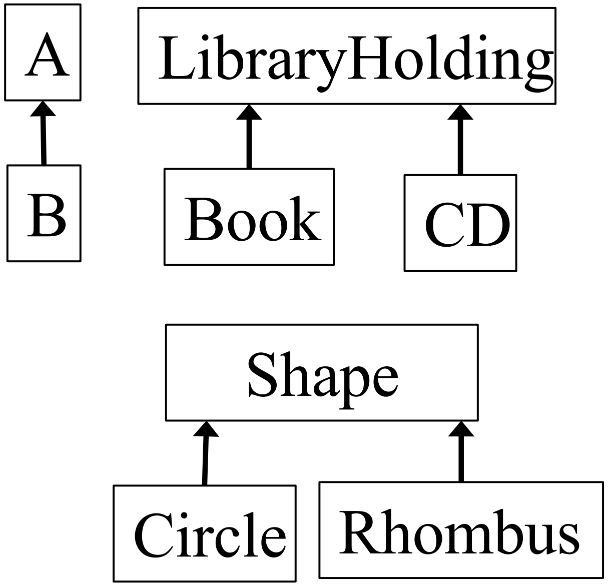
Constraints on methods

- For each supertype method, subtype must have such a method
  - (could be inherited or overridden)

Each overridden method must *strengthen* (or match) the spec:

- ask nothing extra of client (“weaker precondition”)
  - *requires* clause is at most as strict as in supertype’s method
- guarantee at least as much (“stronger postcondition”)
  - *effects* clause is at least as strict as in the supertype method
  - no new entries in *modifies* clause
  - promise more (or the same) in *returns* & *throws* clauses
    - cannot change return values or switch between return and throws

Spec strengthening: argument/result types



For method inputs:

- argument types in A's foo *could* be replaced with supertypes in B's foo
- places no extra demand on the clients
- **but** Java *does not have* such overriding
  - these are different methods in Java!

For method outputs:

- result type of A's foo may be replaced by a subtype in B's foo
- no new exceptions (for values in the domain)
- existing exceptions can be replaced with subtypes (none of this violates what client can rely on)

Recall: Subtyping Example

```
class Product {
    private int price; // in cents
    public int getPrice() {
        return price;
    }
    public int getTax() {
        return (int)(getPrice() * 0.086);
    }
}

class SaleProduct extends Product {
    private float factor;
    public int getPrice() {
      return (int)(super.getPrice()*factor);
    }
}
```

Substitution exercise

Suppose we have a method which, when given one product, recommends another:

```
class Product {
    Product recommend(Product ref);
}
```

Which of these are possible forms of this method in **`SaleProduct`** (a true subtype of **`Product`**)?

```
Product recommend(SaleProduct ref);  // bad
SaleProduct recommend(Product ref);  // good
Product recommend(Object ref); // good, but in Java is
                                  overloading
Product recommend(Product ref)   // bad
      throws NoSaleException;
```

Java subtyping

- Java types:
  - defined by classes, interfaces, primitives

- Java subtyping stems from **`B extends A`** and **`B implements A`** declarations

- In a Java subtype, each corresponding method has:
  - same argument types
    - if different, then *overloading* — unrelated methods
  - compatible return types
  - no additional declared exceptions

Java subtyping guarantees

A variable's run-time type (i.e., the class of its run-time value) is a Java subtype of its declared type

```
Object o = new Date(); // OK
Date d = new Object(); // compile-time error
```

If a variable of *declared (compile-time)* type T1 holds a reference to an object of *actual* (*runtime)* type T2, then T2 must be a Java subtype of T1

Corollaries:

- objects always have implementations of the methods specified by their declared type
- ***if*** all subtypes are true subtypes, then all objects meet the specification of their declared type

Rules out a huge class of bugs

Java subtyping non-guarantees

Java subtyping does **not** guarantee that overridden methods

- have smaller requires
- have smaller modifies
- have stronger postconditions
  - Java only checks the *return type* not the postcondition
  - could compute a completely different function
- have stronger effects
- have stronger throws (& only for the same cases as before)
- have no new unchecked exceptions

EQUALS WITH SUBCLASSES

`equals` specification

`public boolean equals(Object obj)` should be:

- *reflexive*: for any reference value **`x`**, **`x.equals(x) == true`**
- *symmetric*: for any reference values **`x`** and **`y`**, **`x.equals(y) == y.equals(x)`**
- *transitive*: for any reference values **`x`**, **`y`**, and **`z`**, if **`x.equals(y)`** and **`y.equals(z)`** are **`true`**, then **`x.equals(z)`** is **`true`**
- *consistent*: for any reference values **`x`** and **`y`**, multiple invocations of **`x.equals(y)`** consistently return **`true`** or consistently return **`false`** (provided neither is mutated)
- For any *non-null* reference value **`x`**, **`x.equals(null)`** should return **`false`**

Really fixed now

```
public class Duration {
   @Override
   public boolean equals(Object o) {
      if (!(o instanceof Duration))
        return false;
      Duration d = (Duration) o;
      return this.min==d.min && this.sec==d.sec;
   }
}
```

- Correct and idiomatic Java
- Gets **`null`** case right (**`null instanceof C`** always **`false`**)
- Cast cannot fail

Two subclasses

```
class CountedDuration extends Duration {
  public static numCountedDurations = 0;
  public CountedDuration(int min, int sec) {
    super(min,sec);
    ++numCountedDurations;
  }
}
class NanoDuration extends Duration {
  private final int nano;
  public NanoDuration(int min, int sec, int nano){
    super(min,sec);
    this.nano = nano;
  }
  public boolean equals(Object o) { … }
  …
}
```

`CountedDuration` is (probably) fine

- `CountedDuration` does not override `equals`
  - inherits `Duration.equals(Object)`
- Will (implicitly) treat any `CountedDuration` like a `Duration` when checking `equals`
  - `o instanceof Duration` is true if `o` is `CountedDuration`
- Any combination of `Duration` and `CountedDuration` objects can be compared
  - equal if same contents in `min` and `sec` fields
  - works because `o instanceof Duration` is `true` when `o` is an instance of `CountedDuration`

`NanoDuration` is (probably) not fine

- If we don't override **`equals`** in **`NanoDuration`**, then objects with different **`nano`** fields will be equal

- Using what we have learned:

```
@Override
public boolean equals(Object o) {
  if (!(o instanceof NanoDuration))
    return false;
  NanoDuration nd = (NanoDuration) o;
  return super.equals(nd) && nano == nd.nano;
}
```

- But we have violated the **`equals`** contract
  - Hint: Compare a **`Duration`** and a **`NanoDuration`**

The symmetry bug

```
public boolean equals(Object o) {
  if (!(o instanceof NanoDuration))
    return false;
  NanoDuration nd = (NanoDuration) o;
  return super.equals(nd) && nano == nd.nano;
}
```

This is ***not symmetric***!

```
Duration d1 = new NanoDuration(5, 10, 15);
Duration d2 = new Duration(5, 10);
d1.equals(d2); // false
d2.equals(d1); // true
```

Fixing symmetry

This version restores symmetry by using **`Duration`**'s **`equals`** if the argument is a **`Duration`** (and not a **`NanoDuration`**)

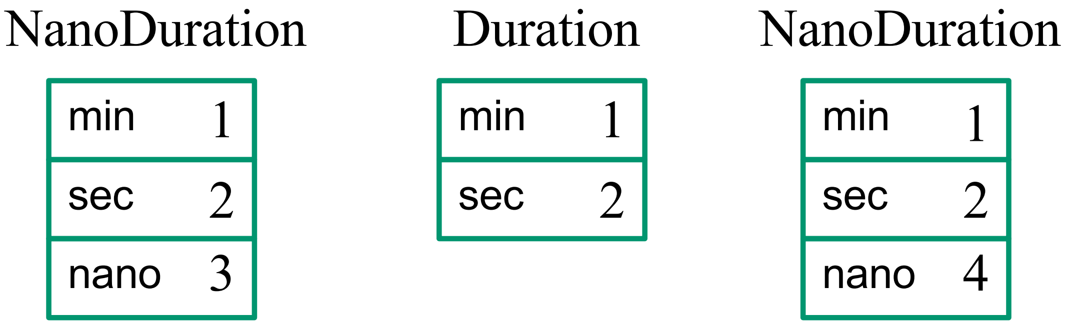
```
public boolean equals(Object o) {
  if (!(o instanceof Duration))
    return false;
  // if o is a normal Duration, compare without nano
  if (!(o instanceof NanoDuration))
    return super.equals(o);
  NanoDuration nd = (NanoDuration) o;
  return super.equals(nd) && nano == nd.nano;
}
```

Alas, this *still* violates the **`equals`** contract

- Transitivity…

The transitivity bug

```
Duration d1 = new NanoDuration(1, 2, 3);
Duration d2 = new Duration(1, 2);
Duration d3 = new NanoDuration(1, 2, 4);
d1.equals(d2);   // true
d2.equals(d3);   // true
d1.equals(d3);   // false!
```



NanoDuration

min 1
sec 2
nano 3

Duration

min 1
sec 2

NanoDuration

min 1
sec 2
nano 4

No perfect solution

- *Effective Java* says not to (re)override **`equals`** like this
  - (unless superclass is non-instantiable)
  - generally good advice
  - but there is one way to satisfy `equals` contract (see below)

- Two less-than-perfect approaches on next two slides:
  1. Don't make **`NanoDuration`** a subclass of **`Duration`**
     - fact that equals should be different is a hint it's not a subtype
  2. Change **`Duration`**'s **`equals`** so only **`Duration`** objects that are not (proper) subclasses of **`Duration`** are equal

Option 1: avoid subclassing

Choose composition over subclassing (Effective Java)

- often good advice in general (we'll discuss more later on)
- many programmers overuse subclassing

```
public class NanoDuration {
  private final Duration duration;
  private final int nano;
  …
}
```

Solves some problems:

- clients can choose which type of equality to use

Introduces others:

- can't use **`NanoDurations`** where **`Durations`** are expected (since it is not a subtype)

Option 2: the `getClass` trick

Check if `o` is a `Duration` and ***not** a subtype*:

```
@Overrides
public boolean equals(Object o) { // in Duration
  if (o == null)
    return false;
  if (!o.getClass().equals(getClass()))
    return false;
  Duration d = (Duration) o;
  return d.min == min && d.sec == sec;
}
```

But this breaks `CountedDuration`!

- subclasses do not “act like” instances of superclass because behavior of `equals` changes with subclasses
- generally considered wrong to “break” subtyping like this

Subclassing summary

- Subtypes *should* be useable wherever the type is used
  - Liskov substitution principle

- Unresolvable tension between
  - what we want for equality: *treat subclasses differently*
  - what we want for subtyping: *treat subclasses the same*

- No perfect solution for all cases...
- Choose whether you want subtyping or not
  - in former case, don't override equals (make it final)
  - in latter case, can still use composition instead
    - this matches the advice in *Effective Java* and from us (later)
  - almost always best to avoid getClass trick

DESIGNING FOR INHERITANCE

Inheritance can break encapsulation

```
public class InstrumentedHashSet<E>
                          extends HashSet<E> {
  private int addCount = 0;  // count # insertions
  public InstrumentedHashSet(Collection<? extends E> c){
     super(c);
  }
  public boolean add(E o) {
     addCount++;
     return super.add(o);
  }
  public boolean addAll(Collection<? extends E> c) {
     addCount += c.size();
     return super.addAll(c);
  }
  public int getAddCount() { return addCount; }
}
```

Dependence on implementation

What does this code print?

```
InstrumentedHashSet<String> s =
       new InstrumentedHashSet<String>();
System.out.println(s.getAddCount());    // 0
s.addAll(Arrays.asList("CSE", "331"));
System.out.println(s.getAddCount());   // 4?!
```

- Answer *depends on implementation* of **`addAll`** in **`HashSet`**
  - different implementations may behave differently!
  - if **`HashSet`**'s **`addAll`** calls **`add`**, then double-counting
- **`AbstractCollection`**'s **`addAll`** specification:
  - "adds all elements in the specified collection to this collection."
  - does not specify whether it calls **`add`**
- Lesson: subclassing typically requires designing for inheritance
  - self-calls is not the only example… (more in future lectures)

Solutions

1. Change spec of **`HashSet`**
   - indicate all self-calls
   - less flexibility for implementers

2. Avoid spec ambiguity by avoiding self-calls
   a) "re-implement" methods such as **`addAll`**
      - more work

   b) use composition not inheritance
      - no longer a subtype (unless an interface is handy)
      - bad for equality tests, callbacks, etc.

Solution: composition

```
public class InstrumentedHashSet<E> {
  private final HashSet<E> s = new HashSet<E>();
  private int addCount = 0;
  public InstrumentedHashSet(Collection<? extends E> c){
      this.addAll(c);
  }
  public boolean add(E o) {
     addCount++;   return s.add(o);
  }
  public boolean addAll(Collection<? extends E> c) {
     addCount += c.size();
     return s.addAll(c);
  }
  public int getAddCount() {  return addCount; }
  // ... and every other method specified by HashSet<E>
}
```

Delegate

The implementation no longer matters

Composition (wrappers, delegation)

Implementation *reuse* without *inheritance*

- Easy to reason about. Self-calls are irrelevant
- Example of a “wrapper” class
- Works around badly-designed / badly-specified classes
- Disadvantages (may be worthwhile price to pay):
  - does not preserve subtyping
  - sometimes tedious to write
  - may be hard to apply to equality tests, callbacks, etc.
    - (although we already saw equals is hard for subclasses)

Composition does not preserve subtyping

- **`InstrumentedHashSet`** is not a **`HashSet`** anymore
  - so can't easily substitute it

- It may be a true subtype of **`HashSet`**
  - but Java doesn't know that!
  - Java requires declared relationships
  - not enough just to meet specification

- Interfaces to the rescue
  - can declare that we implement interface **`Set`**
  - if such an interface exists

normal Java style

Interfaces reintroduce Java subtyping

```
public class InstrumentedHashSet<E> implements Set<E> {
  private final Set<E> s = new HashSet<E>();
  private int addCount = 0;
  public InstrumentedHashSet(Collection<? extends E> c){
      this.addAll(c);
  }
  public boolean add(E o) {
      addCount++;
      return s.add(o);
  }
  public boolean addAll(Collection<? extends E> c) {
      addCount += c.size();
      return s.addAll(c);
  }
  public int getAddCount() {  return addCount; }
  // ... and every other method specified by Set<E>
}
```

Interfaces and abstract classes

Provide *interfaces* for your functionality

- client code to interfaces rather than concrete classes
- allows different implementations later
- facilitates composition, wrapper classes
  - basis of lots of useful, clever techniques
  - we'll see more of these later

Consider also providing helper/template *abstract classes*

- makes writing new implementations much easier
- not necessary to use them to implement an interface, so retain freedom to create radically different implementations

Java library interface/class example

```
// root interface of collection hierarchy
interface Collection<E>
// skeletal implementation of Collection<E>
abstract class AbstractCollection<E>
                  implements Collection<E>
// type of all ordered collections
interface List<E> extends Collection<E>
// skeletal implementation of List<E>
abstract class AbstractList<E>
                  extends AbstractCollection<E>
                  implements List<E>
// an old friend...
class ArrayList<E> extends AbstractList<E>
```

Why interfaces instead of classes?

Java design decisions:

- a class has **exactly one** superclass
- a class may implement multiple interfaces
- an interface may extend multiple interfaces

Observation:

- multiple superclasses are difficult to use and to implement
- multiple interfaces, single superclass gets most of the benefit

Pluses and minuses of inheritance

- Inheritance is a powerful way to achieve code reuse

- Inheritance can break encapsulation
  - a subclass may need to depend on unspecified details of the implementation of its superclass
    - e.g., pattern of self-calls
  - subclass may need to evolve in tandem with superclass
    - okay when implementation of both is under control of the same programmer
  - this is tricky to get right and is a source of subtle bugs

- Effective Java:
  - either **design for inheritance** or else **prohibit it**
  - favor composition (and interfaces) to inheritance