CSE 331
Software Design & Implementation

Kevin Zatloukal

Summer 2017

Identity, `equals`, and `hashCode`

(Based on slides by Mike Ernst, Dan Grossman, David Notkin, Hal Perkins, Zach Tatlock)

Overview

- Notions of object equality are important in any language

- In Java, collection classes depend on `equals` and `hashCode`
  - EJ 47: "Know and use the libraries"
    - "every programmer should be familiar with the contents of java.lang and java.util"
  - e.g., `TreeSet` may not work properly if `equals` is wrong
  - e.g., `HashSet` may not work properly of `hashCode` is wrong

Object equality

A simple idea??

- Two objects are equal if they have the same **value**

A subtle idea: intuition can be misleading

- Same object or same contents?
- Same concrete value or same abstract value?
- Same right now or same forever?
- Same for instances of this class or also for subclasses?
- When are two collections equal?
  - How related to equality of elements? Order of elements?
  - What if a collection contains itself?
- How can we implement equality efficiently?

Expected properties of equality

Reflexive `a.equals(a) == true`

- Confusing if an object does not equal itself

Symmetric `a.equals(b)` **iff** `b.equals(a)`

- Confusing if order-of-arguments matters

Transitive `a.equals(b) && b.equals(c) => a.equals(c)`

- Confusing again to violate centuries of logical reasoning

A relation that is reflexive, transitive, and symmetric is an *equivalence relation*

Reference equality

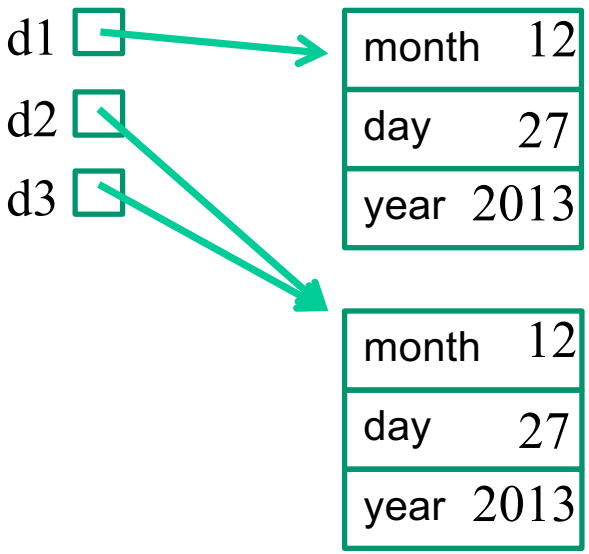
- Reference equality means an object is equal only to itself
  - `a == b` only if `a` and `b` refer to (point to) the same object

- Reference equality is an equivalence relation
  - Reflexive
  - Symmetric
  - Transitive

- Reference equality is the *smallest* equivalence relation on objects
  - "Hardest" to show two objects are equal (must be same object)
  - Cannot be smaller without violating reflexivity
  - Sometimes but not always what we want

What might we want?

```
Date d1 = new Date(12,27,2013);
Date d2 = new Date(12,27,2013);
Date d3 = d2;
// d1==d2 ?
// d2==d3 ?
// d1.equals(d2) ?
// d2.equals(d3) ?
```



- Sometimes want equivalence relation bigger than ==
  - Java takes OOP approach of letting classes *override* **`equals`**

`Object.equals` method

```
public class Object {
  public boolean equals(Object o) {
    return this == o;
  }
  …
}
```

- Implements reference equality
- Subclasses can override to implement a different equality
- But library includes a *contract* **`equals`** should satisfy
  - Reference equality satisfies it
  - So should *any* overriding implementation
  - Balances flexibility in notion-implemented and what-clients-can-assume even in presence of overriding

`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 be `false`

Why all this?

- Remember the goal is a contract:
  - weak enough to allow different useful overrides
  - strong enough so clients can assume equal-ish things
    - example: to implement a set
  - this gives a good balance in practice

- In summary:
  - equivalence relation
  - consistency, but allow for mutation to change the answer
  - asymmetric with **`null`** (other way raises exception)
    - final detail: argument of **`null`** must return **`false`**
    - weird but useful
    - often see, e.g., “left”.equals(direction) – false for null

An example

A class where we may want **`equals`** to mean equal contents

```
public class Duration {
    private final int min; // RI: min>=0
    private final int sec; // RI: 0<=sec<60
    public Duration(int min, int sec) {
        assert min>=0 && sec>=0 && sec<60;
        this.min = min;
        this.sec = sec;
    }
}
```

- Should be able to implement what we want and satisfy the **`equals`** contract…

How about this?

```
public class Duration {
    …
  public boolean equals(Duration d) {
     return this.min==d.min && this.sec==d.sec;
  }
}
```

Two bugs:

1. Violates contract for **`null`** (not that interesting)
   - Can add **`if(d==null) return false;`**
     - But our fix for the other bug will make this unnecessary
2. Does not override **`Object`**'s **`equals`** method (more interesting)

Overloading versus overriding

In Java:

- A class can have multiple methods with the same name and different parameters (number or type)
- A method *overrides* a superclass method only if it has the same name and exact same argument types

So **`Duration`**'s **`boolean equals(Duration d)`** does *not* override **`Object`**'s **`boolean equals(Object d)`**

- Sometimes useful to avoid having to make up different method names
- Sometimes confusing since the rules for what-method-gets-called are complicated

Example: *no* overriding

```
public class Duration {
  public boolean equals(Duration d) {…}
  …
}
Duration d1 = new Duration(10,5);
Duration d2 = new Duration(10,5);
Object o1 = d1;
Object o2 = d2;
d1.equals(d2); // true
o1.equals(o2); // false(!)
d1.equals(o2); // false(!)
o1.equals(d2); // false(!)
d1.equals(o1); // true [using Object's equals]
```

Example fixed (mostly)

```
public class Duration {
  public boolean equals(Object d) {…}
  …
}
Duration d1 = new Duration(10,5);
Duration d2 = new Duration(10,5);
Object o1 = d1;
Object o2 = d2;
d1.equals(d2); // true
o1.equals(o2); // true [overriding]
d1.equals(o2); // true [overriding]
o1.equals(d2); // true [overriding]
d1.equals(o1); // true [overriding]
```

A little more generally

- Won't go through all the *overloading-resolution* rules here

- In short, Java:
  - Uses (compile-time) types to pick the *signature* (at compile-time)
    - In example: if receiver or argument has compile-time type `Object`, then only signature taking an `Object` is "known to work," so it is picked
  - At run-time, uses dynamic dispatch to choose what implementation with that signature runs
    - In un-fixed example: the inherited method is the only one with the take-an-Object signature
    - In fixed example: Overriding matters whenever the run-time class of the receiver is `Duration`

But wait!

This doesn't actually compile:

```
public class Duration {
    …
   public boolean equals(Object o) {
      return this.min==o.min && this.sec==o.sec;
   }
}
```

Really fixed now

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

- Cast cannot fail
- We want equals to work on *any* pair of objects
- Gets `null` case right too (`null instanceof C` always `false`)
- So: rare use of cast that is correct and idiomatic
  - This is what you should do (cf. *Effective Java*)

Satisfies the contract

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

- Reflexive: Yes
- Symmetric: Yes, even if `o` is not a `Duration`!
  - (Assuming `o`'s `equals` method satisfies the contract)
- Transitive: Yes, similar reasoning to symmetric

Even better

- Defensive Tip: use the **`@Override`** annotation when overriding

```
public class Duration {
    @Override
    public boolean equals(Object o) {
        …
    }
}
```

- *Compiler warning* if not actually an override
  - Catches bug where argument is **`Duration`** or **`String`** or ...
  - Alerts reader to overriding
    - Concise, relevant, *checked* documentation

Where are we?

- Done:
  - Understanding the **`equals`** contract
  - Implementing **`equals`** correctly for **`Duration`**
    - override `Object.equals(Object)`
    - satisfying the contract [for all types of arguments]

- Alas, matters get worse for subclasses of **`Duration`**
  - no perfect universal solution…
  - each option involves trade-offs

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`**)

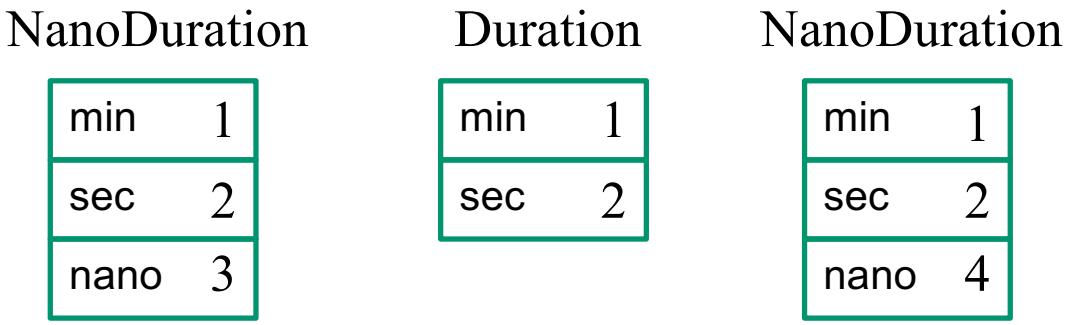
```
public boolean equals(Object o) {
  if (!(o instanceof Duration))
    return false;
  // if o is a normal Duration, compare without nano
  if (!(o instanceof NanoDuration))
    return super.equals(o);
  NanoDuration nd = (NanoDuration) o;
  return super.equals(nd) && nano == nd.nano;
}
```

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!
```



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 far-from-perfect approaches on next two slides:
  1. Don't make **`NanoDuration`** a subclass of **`Duration`**
  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 (EJ Item 81)

- 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 **`NanoDuration`**s where **`Duration`**s 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 use composition instead
    - (this matches the advice in *Effective Java*)
  - (unfortunately) must make one choice for all subtypes

`hashCode`

Another method in **`Object`**:

```
public int hashCode()
```

"Returns a hash code value for the object. This method is supported for the benefit of hash tables such as those provided by **`java.util.HashMap`**."

Contract (again essential for correct overriding):

- Self-consistent: **`o.hashCode()`** is fixed (unless **`o`** is mutated)
- Consistent with equality:

  `a.equals(b)` implies **`a.hashCode() == b.hashCode()`**

Want **`!a.equals(b)`** implies **`a.hashCode() != b.hashCode()`**

- but not actually in contract and (not true in most implementations)

Think of it as a pre-filter

- If two objects are equal, they *must* have the same hash code
  - up to implementers of **`equals`** and **`hashCode`** to satisfy this
  - if you override **`equals`**, you ***must*** override **`hashCode`**

- If objects have same hash code, they *may or may not* be equal
  - "usually not" leads to better performance
  - **`hashCode`** in **`Object`** tries to (but may not) give every object a different hash code

- Hash codes are usually cheap[er] to compute, so check first if you "usually expect not equal" – a pre-filter

Asides

- Hash codes are used for hash tables
  - common implementation of collection ADTs
  - see CSE332
  - libraries won't work if your classes break relevant contracts

- Cheaper pre-filtering is a more general idea
  - Example: Are two large video files the exact same video?
    - Quick pre-filter: Are the files the same size?

Doing it

- So: we have to override **`hashCode`** in **`Duration`**
  - Must obey contract
  - Aim for non-equals objects usually having different results
- Correct but expect poor performance:

```
public int hashCode() { return 1; }
```

- A bit better:

```
public int hashCode() { return min; }
```

- Better:

```
public int hashCode() { return min ^ sec; }
```

- Best

```
public int hashCode() { return 60*min+sec; }
```

Correctness depends on `equals`

Suppose we change the spec for `Duration`'s `equals`:

```
public boolean equals(Object o) {
  if (!(o instanceof Duration))
    return false;
  Duration d = (Duration) o;
  return min == d.min && sec/10 == d.sec/10;
}
```

Must update `hashCode` – why?

```
public int hashCode() {
  return 6*min+sec/10;
}
```

Equality, mutation, and time

If two objects are equal now, will they always be equal?

- in mathematics, “yes”
- in Java, “you choose”
- `Object` contract doesn't specify

For immutable objects:

- abstract value never changes
- equality should be forever (even if rep changes)

For mutable objects, either:

- use reference equality (never changes)
- not forever: mutation changes abstract value hence equals

Common source of bugs: mutating an object in a data structure

Examples

`StringBuilder` is mutable and sticks with reference-equality:

```
StringBuilder s1 = new StringBuilder("hello");
StringBuilder s2 = new StringBuilder("hello");
s1.equals(s1); // true
s1.equals(s2); // false
```

By contrast:

```
Date d1 = new Date(0); // Jan 1, 1970 00:00:00 GMT
Date d2 = new Date(0);

d1.equals(d2); // true
d2.setTime(1);
d1.equals(d2); // false
```

Behavioral and observational equivalence

Two objects are "behaviorally equivalent" if there is no sequence of operations (excluding **==**) that can distinguish them

Two objects are "observationally equivalent" if there is no sequence of *observer* operations that can distinguish them

- excludes mutators and **==**

Equality and mutation

`Date` class implements (only) observational equality

Can violate rep invariant of a `Set` by mutating after insertion

```
Set<Date> s = new HashSet<Date>();
Date d1 = new Date(0);
Date d2 = new Date(1000);
s.add(d1);
s.add(d2);
d2.setTime(0);
for (Date d : s) { // prints two of same date
    System.out.println(d);
}
```

Pitfalls of observational equivalence

Have to make do with caveats in specs:

> *"Note: Great care must be exercised if mutable objects are used as set elements. The behavior of a set is not specified if the value of an object is changed in a manner that affects equals comparisons while the object is an element in the set."*

Same problem applies to keys in maps

Same problem applies to mutations that change hash codes when using **`HashSet`** or **`HashMap`**

Especially hard bugs to detect! (Be frightened!)

Easy to cause when modules don't list everything they **mutate**

- why we need **`@modifies`**

Another container wrinkle: self-containment

`equals` and **`hashCode`** on containers are recursive:

```
class ArrayList<E> {
  public int hashCode() {
     int code = 1;
     for (Object o : list)
       code = 31*code + (o==null ? 0 : o.hashCode());
    return code;
  }
```

This causes an infinite loop:

```
List<Object> lst = new ArrayList<Object>();
lst.add(lst);
lst.hashCode();
```

Summary

- Different notions of equality:
  - reference equality stronger than
  - behavioral equality stronger than
  - observational equality

- Java's **`equals`** has an elaborate specification, but does not require any one of the above notions
  - also requires consistency with **`hashCode`**
  - concepts more general than Java

- Mutation and/or subtyping make things even less satisfying
  - good reason not to overuse/misuse either