Identity, equals, and hashCode

(Based on slides by Mike Ernst, David Notkin, Hal Perkins)

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 \[ a.equals(a) == \text{true} \]
- Confusing if an object does not equal itself

Symmetric \[ a.equals(b) \iff b.equals(a) \]
- Confusing if order-of-arguments matters

Transitive \[ a.equals(b) \land b.equals(c) \Rightarrow a.equals(c) \]
- 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?

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

Object\(\text{.equals}\) method

```java
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)
Indicates whether some other object is “equal to” this one.

The equals method implements an equivalence relation:
- It is reflexive: for any reference value $x$, $x.equals(x)$ should return true.
- It is symmetric: for any reference values $x$ and $y$, $x.equals(y)$ should return true if and only if $y.equals(x)$ returns true.
- It is transitive: for any reference values $x$, $y$, and $z$, if $x.equals(y)$ returns true and $y.equals(z)$ returns true, then $x.equals(z)$ should return true.
- It is consistent: for any reference values $x$ and $y$, multiple invocations of $x.equals(y)$ consistently return true or consistently return false, provided no information used in equals comparisons on the object is modified.
- For any non-null reference value $x$, $x.equals(null)$ should return 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
    - Complete enough for real software
- So:
  - 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

An example

A class where we may want equals to mean equal contents

```java
public class Duration {
    private final int min;
    private final int sec;
    public Duration(int min, int sec) {
        this.min = min;
        this.sec = sec;
    }
}
```

How about this?

```java
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
- [Overriding covered in CSE143, but not overloading]

Example: no overriding

```java
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)

```java
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 = o2;
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:

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

Really fixed now

```java
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;
    }
}
```

Satisfies the contract

```java
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;
    }
}
```

Even better

- Great style: use the `@Override` annotation when overriding
  ```java
  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
Okay, so are we done?

- Done:
  - Understanding the equals contract
  - Implementing equals correctly for Duration
    - Overriding
    - Satisfying the contract [for all types of arguments]
  - Alas, matters can get worse for subclasses of Duration
    - No perfect solution, so understand the 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 CountedDuration(int min, int sec, int nano) {
        super(min, sec);
        this.nano = nano;
    }
    public boolean equals(Object o) { … } 
    …
}

CountedDuration is good

- CountedDuration does not override equals
- Will (implicitly) treat any CountedDuration like a Duration when checking equals
- 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

Now NanoDuration [not so good!]

- If we don’t override equals in NanoDuration, then objects with different nano fields will be equal
- So using everything 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
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 \(d_1 = \text{new NanoDuration}(1, 2, 3)\);
Duration \(d_2 = \text{new Duration}(1, 2)\);
Duration \(d_3 = \text{new NanoDuration}(1, 2, 4)\);
d1.equals(d2); // true
d2.equals(d3); // true
d1.equals(d3); // false!

No great solution

- *Effective Java* says not to (re)override `equals` like this
  - Unless superclass is non-instantiable (e.g., abstract)
  - “Don’t do it” a non-solution given the equality we want for `NanoDuration` objects
- Two far-from-perfect approaches on next two slides:
  1. Don’t make `NanoDuration` a subclass of `Duration`
  2. Change `Duration`’s `equals` such that only `Duration` objects that are not (proper) subclasses of `Duration` are equal

The transitivity bug

Avoid subclassing

Choose composition over subclassing
- Often good advice: many programmers overuse (abuse) subclassing [see future lecture on proper subtyping]

```java
class NanoDuration {
    private final Duration duration;
    private final int nano;
    ...
}
```

NanoDuration and Duration now unrelated
- No presumption they can be compared to one another
Solves some problems, introduces others
- Can’t use NanoDurations where Durations are expected (not a subtype)
- No inheritance, so need explicit forwarding methods

Slight alternative

- Can avoid some method redefinition by having `Duration` and `NanoDuration` both extend a common abstract class
  - Leave overriding `equals` to the two subclasses
- Keeps `NanoDuration` and `Duration` from being used “like each other”
- But requires advance planning or willingness to change `Duration` when you discover the need for `NanoDuration`

The getClass trick

Different run-time class checking to satisfy the `equals` contract:

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

But now `Duration` objects never equal `CountedDuration` objects
- 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

- Due to subtleties, no perfect solution to how to design and implement `NanoDuration`
- Unresolvable tension between
  - “What we want for equality”
  - “What we want for subtyping”
- Now:
  - `Duration` still does not satisfy contracts relevant to `equals`
  - Have to discuss another `Object` method: `hashCode`
hashCode

Another method in Object:

```
public int hashCode()
```

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

Contract (again essential for correct overriding):
- Self-consistent:
  
  `o.hashCode() == o.hashCode()`

  ...so long as `o` doesn’t change between the calls
- Consistent with equality:
  
  `a.equals(b) ⇒ a.hashCode() == b.hashCode()`

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 two objects have the 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
  
  - A common collection implementation
  
  - 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?

Correctness depends on `equals`

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

```java
// true if o and this represent same # of seconds
public boolean equals(Object o) {
    if (! (o instanceof Duration))
        return false;
    Duration d = (Duration) o;
    return 60*min+sec == 60*d.min+d.sec;
}
```

Must update `hashCode` – why?

- This works:
  
  ```java
  public int hashCode() {
      return 60*min+sec;
  }
  ```

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:

- Stick with reference equality
- “No” equality is not forever
  
  - Mutation changes abstract value, hence what-object-equals
Examples

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

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

By contrast:

```java
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 therefore violate rep invariant of a `Set` by mutating after insertion:

```java
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`.

(Libraries choose not to copy-in for performance and to preserve object identity)

Another container wrinkle: self-containment

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

```java
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:

```java
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 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