Identity, equals, and hashCode
(Based on slides by Mike Ernst, Dan Grossman, 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** \( a \text{.equals}(a) == \text{true} \)
- Confusing if an object does not equal itself

**Symmetric** \( a \text{.equals}(b) \iff b \text{.equals}(a) \)
- Confusing if order-of-arguments matters

**Transitive** \( a \text{.equals}(b) \land b \text{.equals}(c) \Rightarrow a \text{.equals}(c) \)
- 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`

```java
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) ?
```
Object.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
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; // 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...
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(!)
o1.equals(o1); // true [using Object’s equals]
```
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:

```java
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)
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

- 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 NanoDuration(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:

  ```java
  @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)

```java
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

```java
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 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
Avoid subclassing

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

```java
public 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 NanoDuration where Duration 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
  – Or implement the same interface
  – 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) { // 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 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`
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:**
  
  \[
  o . \text{hashCode}() == o . \text{hashCode}()
  \]
  
  ...so long as \( o \) doesn’t change between the calls

- **Consistent with equality:**

  \[
  a . \text{equals}(b) \Rightarrow a . \text{hashCode}() == b . \text{hashCode}()
  \]
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?
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:
  ```java
  public int hashCode() { return 1; }
  ```

- Correct but expect better-but-still-possibly-poor performance:
  ```java
  public int hashCode() { return min; }
  ```

- Better:
  ```java
  public int hashCode() { return min ^ sec; }
  ```
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 \texttt{HashSet} or \texttt{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:

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 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