CSE 331
Software Design & Implementation

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`==`, **`equals()`**, and all that

(Slides by David Notkin and Mike Ernst)

Programming: object equality

- The basic intuition is simple: two objects are equal if they are indistinguishable (have the same value)
- But our intuitions are incomplete in subtle ways:
  - Must the objects be the same object or “just” indistinguishable?
  - What is an object’s value? How do we interpret “the bits”?
  - What does it mean for two collections of objects to be equal?
    - Does each need to hold the same objects? In the same order? What if a collection contains itself?
    - Who decides? The programming language designer? You?
  - If a program uses inheritance, does equality change?
  - Is equality always an efficient operation?
  - Is equality temporary or forever?

Properties of equality
for any useful notion of equality

- *Reflexive* `a.equals(a)`

  $3 \neq 3$ would be confusing

- *Symmetric* `a.equals(b)` $\Leftrightarrow$ `b.equals(a)`

  $3 = 4 \wedge 4 \neq 3$ would be confusing

- *Transitive* `a.equals(b)` $\wedge$ `b.equals(c)` $\Rightarrow$ `a.equals(c)`

  $((1+2) = 3 \wedge 3 = (5-2)) \wedge$
  $((1+2) \neq (5-2))$ would be confusing

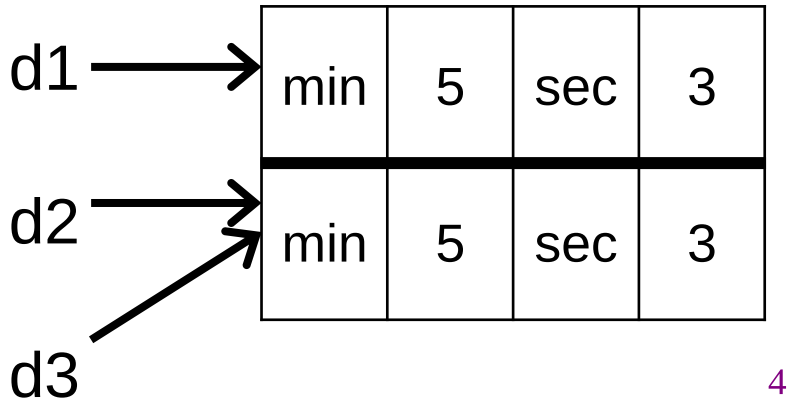
A relation that is reflexive, transitive, and symmetric is an *equivalence relation*

Reference equality

- The simplest and strongest (most restrictive) definition is *reference equality*
- **`a == b`** if and only if **`a`** and **`b`** refer (point) to the same object
- Easy to show that this definition ensures **`==`** is an equivalence relation

```
Duration d1 = new Duration(5,3);
Duration d2 = new Duration(5,3);
Duration d3 = p2;

// T/F: d1 == d2 ?
// T/F: d1 == d3 ?
// T/F: d2 == d3 ?
// T/F: d1.equals(d2) ?
// T/F: d2.equals(d3) ?
```



`Object.equals` method

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

- This implements reference equality
- What about the specification of **`Object.equals`**?
  - It's a bit more complicated…

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.

The **`equals`** method for class **`Object`** implements the most discriminating possible equivalence relation on objects; that is, for any reference values **`x`** and **`y`**, this method returns true if and only if **`x`** and **`y`** refer to the same object (**`x==y`** has the value true). …

Parameters:

obj - the reference object with which to compare.

Returns:

true if this object is the same as the obj argument; false otherwise.

See Also:

hashCode(), HashMap

The `Object` contract

- Why so complicated?
- Object class is designed for inheritance
- Its specification will apply to all subtypes
  - In other words, all Java classes
- So, its specification must be flexible
  - Specification for equals cannot later be weakened
  - If **`a.equals(b)`** were specified to test **`a==b`**, then no class could change this and still be a true subtype of **`Object`**
  - Instead spec for equals enumerates basic properties that clients can rely on it to have in subtypes of **`Object`**
  - **`a==b`** is compatible with these properties, but so are other tests

Comparing objects less strictly

```
public class Duration {
    private final int min;
    private final int sec;
    public Duration(int min, int sec) {
        this.min = min;
        this.sec = sec;
    }
}
…
Duration d1 = new Duration(10,5);
Duration d2 = new Duration(10,5);
System.out.println(d1.equals(d2));
```

`false` – but we likely prefer it to be **`true`**

An obvious improvement

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

This defines an equivalence relation for **`Duration`** objects (proof by partial example and handwaving)

```
Duration d1 = new Duration(10,5);
Duration d2 = new Duration(10,5);
System.out.println(d1.equals(d2));
```

```
Object o1 = new Duration(10,5);
Object o2 = new Duration(10,5);
System.out.println(o1.equals(o2));  // False!
```

But oops

Overloading

- We have two `equals` methods:

  `equals(Object)` in class `Object`

  `equals(Duration)` in class `Duration`
- The one in `Duration` does ***not*** override the inherited one – it overloads it (different parameter type)
- If `d` has type `Duration`, `d.equals(Duration)` invokes the method in `Duration`
- If `o` has type `Object`, `o.equals(Duration)` invokes the `equals(Object)` method declared in `Object`
  - *Even if* the dynamic type of `o` is `Duration`!
  - `Object` does not have an `equals(Duration)` method. Method types are resolved using static types.
  - Dynamic types are used to select appropriate method at runtime (dynamic dispatch), but selected from possible methods with the correct static type.

`@Override equals` in `Duration`

```
@Override                     // compiler warning if type mismatch
public boolean equals(Object o) {
  if (! (o instanceof Duration))   // Not equal if parameter
    return false;                  //    is not a Duration
  Duration d = (Duration) o;       // cast to treat o as
                                   //    a Duration
  return d.min == min && d.sec == sec;
}

Object d1 = new Duration(10,5);
Object d2 = new Duration(10,5);
System.out.println(d1.equals(d2));    // True
```

- *overriding* re-defines an inherited method from a superclass – same name & parameter list & return type
- **`Duration`**s now have to be compared as **`Duration`**s (or as **`Object`**s, but not as a mixture)

Equality and inheritance

Let's add a nanosecond field for fractional seconds

```
public class NanoDuration extends Duration {
  private final int nano;
  public NanoDuration(int min, int sec, int nano) {
    super(min, sec);
    this.nano = nano;
}
```

Inherited **`equals()`** from **`Duration`** ignores **`nano`** so **`Duration`** instances with different **`nano`**s will be **`equal`**

`equals`: account for `nano`

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

But this is not symmetric! **Oops!**

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

Let’s get symmetry

```
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;
}
```

But this is not transitive!

Oops!

```
Duration d1 = new NanoDuration(5,10,15);
Duration d2 = new Duration(5,10);
Duration d3 = new NanoDuration(5,10,30);
System.out.println(d1.equals(d2)); // true
System.out.println(d2.equals(d3)); // true
System.out.println(d1.equals(d3)); // false!
```

Fix in **Duration**

Replaces earlier version

```
if (! (o instanceof Duration))
  return false;
```

```
@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;
}
```

- Check exact class instead of **instanceOf**
- Equivalent change in **NanoDuration**

General issues

- Every subtype must override **`equals`**
  - even if it wants the identical definition
- Take care when comparing subtypes to one another
  - Consider an **`ArithmeticDuration`** class that adds operators but no new fields (on your own)

Another solution: avoid inheritance

- Use composition instead

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

- **`NanoDuration`** and **`Duration`** are unrelated
  - There is no presumption that they can be **`equal`** or unequal or even compared to one another…
- Solves some problems, introduces others
  - Example: can't use **`NanoDuration`**s where **`Duration`**s are expected (not a (Java) subtype)

Efficiency of equality

- Equality tests can be slow: Are two objects with millions of sub-objects equal? Are two video files equal?
- It is often useful to quickly pre-filter – for example

```
if (video1.length() != video2.length())
  return false
else do full equality check
```

- Java requires each class to define a standard pre-filter – a `hashCode()` method that produces a single hash value (a 32-bit signed integer) from an instance of the class
- If two objects have different hash codes, they are *guaranteed* to be different
- If they have the same hash code, they *may* be equal objects and should be checked in full

Unless you define `hashCode()` improperly!!!

specification for **`Object.hashCode`**

- **`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`**."
- The general contract of **`hashCode`** is
  - Deterministic: **`o.hashCode() == o.hashCode()`**

    ... so long as **`o`** doesn't change between the calls
  - Consistent with equality
    - **`a.equals(b)`** ⇒ **`a.hashCode()==b.hashCode()`**
    - Change **`equals()`**? Must you update **`hashCode()`**?
    - ALMOST ALWAYS! I MEAN ALWAYS!

Aside: `hashCode` and hash tables

- Classic use of hashing is selecting an index for an object in a hash table (e.g., map, set)
  - O(1) cost if done right

- Java libraries do this too, but in two distinct steps:
  - **`hashCode`** returns an **`int`** value that respects equality
  - Collections scale this value as needed
    - See CSE 332 for much more…

`Duration hashCode` implementations

Many possibilities…

```
public int hashCode() {
    return 1;           // always safe, no pre-filtering
}

public int hashCode() {
    return min;         // safe, inefficient for Durations
                        // differing only in sec field
}

public int hashCode() {
    return min+sec;     // safe and efficient
}

public int hashCode() {
    return new Random().newInt(50000); // danger! danger!
}
```

Consistency of equals and hashCode

Suppose we change the spec for **`Duration.equals`**:

```
// Return true if o and this represent the same number 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;
}
```

We must update hashCode, or we will get inconsistent behavior. (Why?)
This works:

```
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” – the `Object` contract doesn't specify this
- For immutable objects, equality is inherently forever
  - The object’s abstract value never changes (c.f. “abstract value” in the ADT lectures) – be sure `equal` does not depend on possibly changing internal values
- For mutable objects, equality can either
  - Compare <u>abstract</u> values field-by-field or
  - Be eternal (how can a class with mutable instances have eternal equality?)
  - But not both! (Since abstract value can change.)

examples

StringBuffer is mutable, and takes the “eternal” approach

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

This is reference (==) equality, which is the only way to guarantee eternal equality for mutable objects. (Not a problem for immutable data)

By contrast:

```
Date d1 = new Date(0); // Jan 1, 1970 00:00:00 GMT
Date d2 = new Date(0);
System.out.println(d1.equals(d2)); // true
d2.setTime(1);                     // a millisecond later
System.out.println(d1.equals(d2)); // false
```

Behavioral and observational equivalence

Two objects are "behaviorally equivalent" if:

- There is no sequence of operations that can distinguish them
- This is "eternal" equality
- Two Strings with same content are behaviorally equivalent, two Dates or StringBuffers with same content are not

Two objects are "observationally equivalent" if:

- There is no sequence of *observer* operations that can distinguish them
  - Excluding mutators
  - Excluding == (permitting == would require reference equality)
- Two Strings, Dates, or StringBuffers with same content are observationally equivalent

Equality and mutation

Date class implements observational equality

Can therefore violate rep invariant of a Set container 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 identical Dates
    System.out.println(d);
}
```

Pitfalls of observational equivalence

Equality for set elements would ideally be behavioral

Java makes no such guarantee (or requirement)

So 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

Mutation and hash codes

Sets assume hash codes don't change
Mutation and observational equivalence can break this assumption too:

```
List<String> friends =
  new LinkedList<String>(Arrays.asList("yoda","zaphod"));
List<String> enemies = ...;   // any other list, say wiith "xenu"
Set<List<String>> h = new HashSet<List<String>>();
h.add(friends);
h.add(enemies);
friends.add("weatherwax");
System.out.println(h.contains(friends)); // probably false
for (List<String> lst : h) {
      System.out.println(lst.equals(friends));
}   // one "true" will be printed - inconsistent!
```

More container wrinkles: self-containment

equals and hashCode methods on containers are recursive:

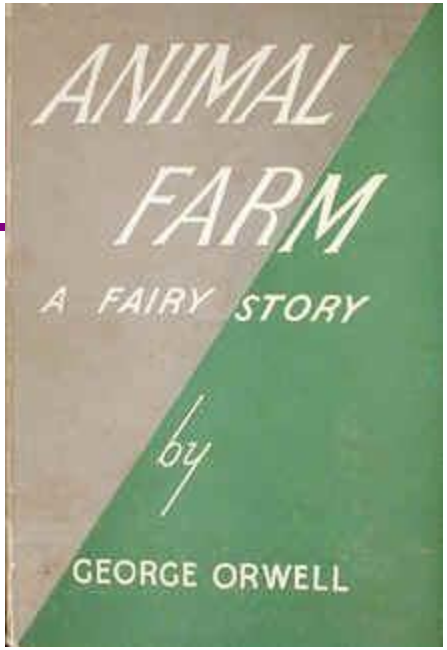
```
class ArrayList<E> {
  public int hashCode() {
     int code = 1;
     for (Object o : list)
       code = 31*code + (o==null ? 0 : o.hashCode());
    return code;
  }
```

This causes an infinite loop:

```
List<Object> lst = new LinkedList<Object>();
lst.add(lst);
int code = lst.hashCode();
```

Summary:
All equals are not equal!

– reference equality
– behavioral equality
– observational equality



Summary: Java specifics

- Mixes different types of equality
  - Objects different from collections
- Extendable specifications
  - Objects, subtypes can be less strict
- Only enforced by the specification
- Speed hack
  - hashCode

Summary: object-oriented Issues

- Inheritance
  - Subtypes inheriting equal can break the spec. Many subtle issues.
  - Forcing all subtypes to implement is cumbersome
- Mutable objects
  - Much more difficult to deal with
  - Observational equality
  - Can break reference equality in eollections
- Abstract classes
  - If only the subclass is instantiated, we are ok…

Summary: software engineering

- Equality is such a simple concept
- But…
  - Programs are used in unintended ways
  - Programs are extended in unintended ways
- Many unintended consequences
- In equality, these are addressed using a combination of:
  - Flexibility
  - Carefully written specifications
  - Manual enforcement of the specifications
    - perhaps by reasoning and/or testing