CSE 331
Software Design and Implementation

Lecture 10
Equality and Hashcode

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Announcements

Announcements

This coming week is the craziest part of the quarter!

- Quiz 4 due tomorrow 10 pm
- HW4 due tomorrow 10 pm

- HW5 due next Thursday
  - Hardest hw in 331 and future hws build on it
- Section tomorrow!
  - important things you need to know for HW5

- Midterm review session Friday 3:30-5 in this room
- Midterm Monday 1:10-2:10 in this room

- Mid-quarter course evaluation Friday (during part of class)
  - Visitor: Jamal from the Center for Teaching and Learning

Equality

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?

Mathematical properties of equality

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

- An object equals itself

Symmetric `a.equals(b)` ⇔ `b.equals(a)`

- Order doesn't matter

⇔ Two-way implication (if and only if)

Transitive `a.equals(b)` ∧ `b.equals(c)` ⇒ `a.equals(c)`

- "transferable"

In mathematics, a relation that is reflexive, transitive, and symmetric is an *equivalence relation*

Reference equality

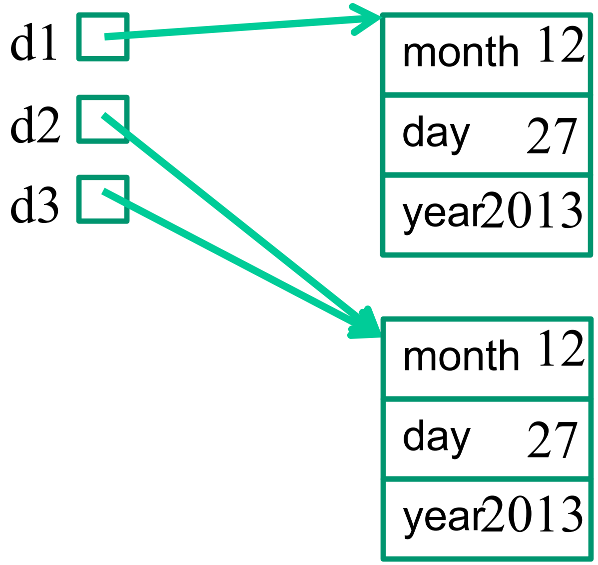
- Reference equality means an object is equal only to itself
  - `a == b` only if `a` and `b` refer to (point to) the same object

- Reference equality is an equivalence relation
  - Reflexive `a==a`
  - Symmetric `a==b` $\Leftrightarrow$ `b==a`
  - Transitive `a==b` $\land$ `b==c` $\Rightarrow$ `a==c`

- Reference equality is the *smallest* equivalence relation on objects
  - "Hardest" to show two objects are equal (must be same object)
  - Cannot be any more restrictive 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`**

Overriding Object's 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)`

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`**.

`equals` specification

- Equals contract is:
  - 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`**
    - **`null.equals(a)`** raises exception
    - for non-null **`a`**, **`a.equals(null)`** must return **`false`**

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: `String.indexOf`

```
int indexOf(int ch)
```

Returns the index within this string of the first occurrence of the specified character.

```
int indexOf(int ch, int fromIndex)
```

Returns the index within this string of the first occurrence of the specified character, starting the search at the specified index.

```
int indexOf(String str)
```

Returns the index within this string of the first occurrence of the specified substring.

```
int indexOf(String str, int fromIndex)
```

Returns the index within this string of the first occurrence of the specified substring, starting at the specified index.

Overriding: `String.equals`

In `Object`:

```
public boolean equals(Object obj)
```

... The equals method for class Object implements the most discriminating possible equivalence relation on objects; that is, for any non-null 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) ...

In `String`:

```
public boolean equals(Object anObject)
```

Compares this string to the specified object. The result is true if and only if the argument is not null and is a String object that represents the same sequence of characters as this object.

Overriding vs. Overloading

Consider the following classes

```
class Foo extends Object {
    Shoe m(Shoe x, Shoe y){ ... }
}

class Bar extends Foo {...}
```

Object
↓
Foo
↓
Bar

Footwear
↓
Shoe
↓
HighHeeledShoe

Overriding vs. Overloading

- The result is method overriding
- The result is method overloading
- The result is a type-error
- None of the above

Foo
↓
Bar

Footwear
↓
Shoe
↓
HighHeeledShoe

Method in Foo

```
Shoe m(Shoe x, Shoe y){ ... }
```

Possible Methods in Bar

```
Shoe m(Shoe q, Shoe z) { ... } overriding
HighHeeledShoe m(Shoe x, Shoe y) { ... } overriding
Shoe m(FootWear x, HighHeeledShoe y) { ... } overloading
Shoe m(FootWear x, FootWear y) { ... } overloading
Shoe m(HighHeeledShoe x, HighHeeledShoe y) { ... }overloading
Shoe m(Shoe y) { ... } overloading
FootWear m(Shoe x, Shoe y) { ... } type error
Shoe z(Shoe x, Shoe y) { ... } new method
```

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)`**

- Overloading is sometimes useful to make several closely related functions with the same name
- Overloading is sometimes confusing since the rules for what-method-gets-called are complicated
- [Overriding covered in CSE143, but not overloading]

Overload resolution

Java's [language spec for resolving Method Invocations](#)(including overload resolution) is about 18 pages long.

In summary

- The declared types of parameters and the object it's called on determine the signature of the method to call
  - declared type is also known as compile-time type
- The runtime type of the object it's called on determines which implementation of that method signagure gets called
  - this is called dynamic dispatch

Example: Overloading

```
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]
```

overloading…oops!

Overload resolution

In summary

- The declared types of parameters and the object it's called on determine the signature of the method to call
- The runtime type of the object it's called on determines which implementation of that method signagure gets called

`o1.equals(d2)`

- **`o1`** has declared type **`Object`** so the signature **`equals(Object)`** is chosen
- The runtime type of **`o1`** is **`Duration`**, so **`Duration`**'s **`equals(Object)`** method gets called. Since **`Duration`** doesn't implement **`equals(Object)`**, the superclass **`Object`**'s implementation is called.

Overload resolution

In summary

- The declared types of parameters and the object it's called on determine the signature of the method to call
- The runtime type of the object it's called on determines which implementation of that method signagure gets called

`o1.equals(o2)`

- **`o2`** has declared type **`Object`** so the signature **`equals(Object)`** is chosen
- The runtime type of **`o1`** is **`Duration`**, so **`Duration`**'s **`equals(Object)`** method is chosen. Since **`Duration`** doesn't implement **`equals(Object)`**, the superclass **`Object`**'s implementation is called.

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]
```

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 statement

- 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

- Great style: 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

Summary: Overriding Equals

Equals contract – Equals must implement an equivalence relation

- Reflexive **`a.equals(a)`**
- Symmetric **`a.equals(b)`** ⇔ **`b.equals(a)`**
- Transitive **`a.equals(b)`** ∧ **`b.equals(c)`** ⇒ **`a.equals(c)`**

Equals must override, not overload **`Object`**'s equals

- Must take in a parameter of type **`Object`**
- After checking instanceof, can cast argument to the right class

Equals and Subclassing

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:

```
@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`**)

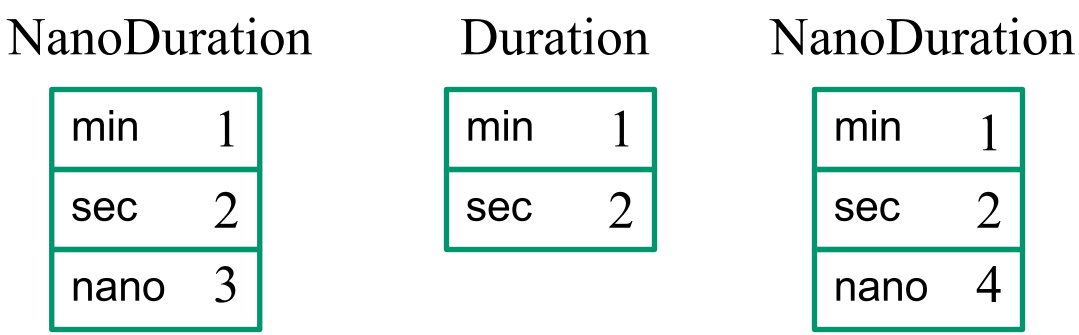
```
public boolean equals(Object o) {
  if (! (o instanceof Duration))
    return false;
  // if o is a normal Duration, compare without nano
  if (! (o instanceof NanoDuration))
    return super.equals(o);
  NanoDuration nd = (NanoDuration) o;
  return super.equals(nd) && nano == nd.nano;
}
```

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

- Transitivity: `a.equals(b)` $\wedge$ `b.equals(c)` $\Rightarrow$ `a.equals(c)`

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 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

Bad idea: the **`getClass`** trick

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

```
@Override
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

Composition

Choose composition over subclassing

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

```
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 **`NanoDurations`** where **`Durations`** are expected (not a subtype)
- No inheritance, so need explicit *forwarding* methods

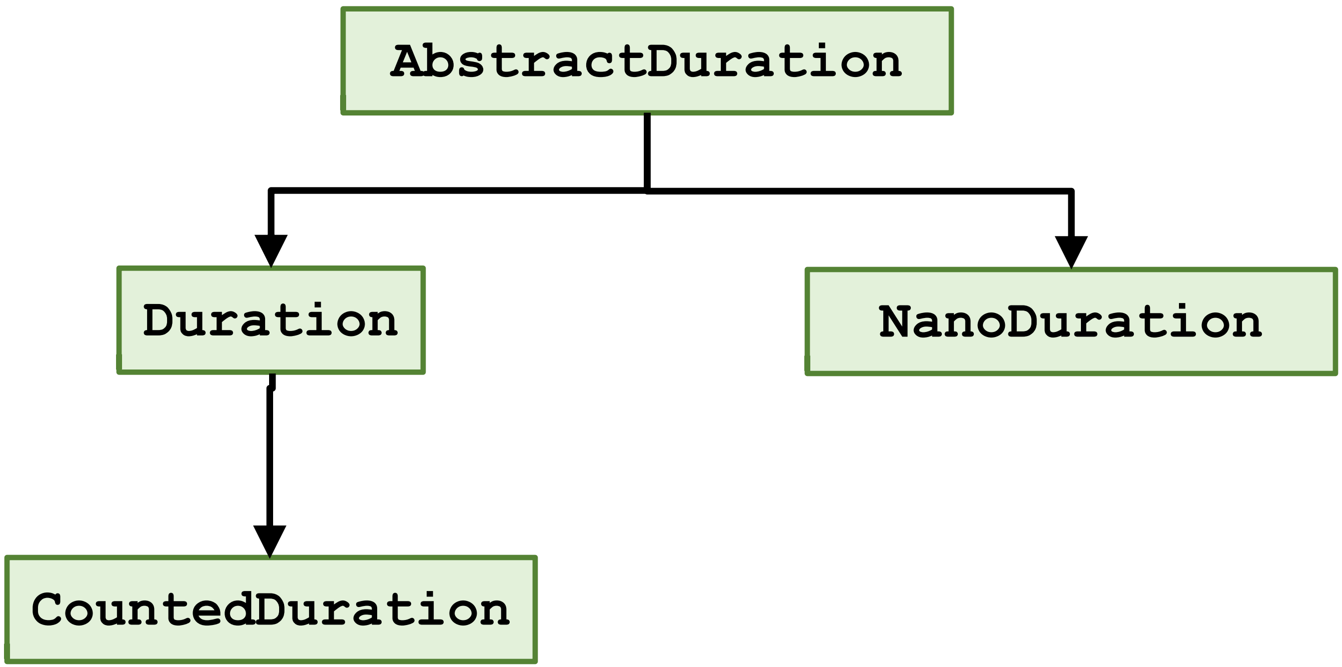
Slight alternative

- Can avoid some method redefinition by having **`Duration`** and **`NanoDuration`** both extend a common abstract class
  - 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`**

Class hierarchy



Summary: Equals and Subclassing

- Be careful when creating subclasses – `equals` needs to work!
- `NanoDuration` is not a proper Java subclass of `Duration` since we can't get `equals` to work
  - More on the nuances of subclassing later!

- Unresolvable tension between
  - "What we want for equality"
  - "What we want for subtyping"
- This is one of the limitations of Java

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- HW5 due next Thursday
  - Hardest hw in 331 and future hws build on it
- Section tomorrow!
  - important things you need to know for HW5

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- Mid-quarter course evaluation Friday (during part of class)
  - Visitor: Jamal from the Center for Teaching and Learning

Equals and Collections

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)` $\Rightarrow$ **`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?

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; }
```

- Correct but expect better-but-still-possibly-poor performance:

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

- Better:

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

Correctness depends on `equals`

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

```
// 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:

```
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:

```
StringBuffer s1 = new StringBuffer("hello");
StringBuffer s2 = new StringBuffer("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

- they look the same forever
- might live at different addresses

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

- Excludes mutators (and ==)
- they look the same now, but might look different later

Equality and mutation

`Set` class checks equality only upon insertion

Can therefore 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 mutability and collections

From the spec of **`Set`**:

"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:

```
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();
```

From the **`List`** documentation: *Note: While it is permissible for lists to contain themselves as elements, extreme caution is advised: the equals and hashCode methods are no longer well defined on such a list.*

Summary: Equals and Collections

- Reference equality (strongest)
  - a and b are the same iff they live at the same address
- Behavioral equality (weaker than Reference equality)
  - if a and b are the same now, they will be the same after **any** sequence of method calls (immutable objects)
- Observational equality (weaker than Behavioral equality)
  - if a and b are the same now, they might be different after mutator methods are called (mutable objects)

- 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