Equality

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Equality

In the physical world
- Every object is distinct -- at some level, even two snowflakes are different
  - Even if the distinction is just the position they occupy in space
- Not true of all subatomic particles, actually, but true enough of large objects like snowflakes and baseballs and people
- So two physical objects are never truly “equal” to each other, only degrees of similarity

In the world of human (or mathematical) language
- You can have multiple names for the same object
- So it’s natural to ask when two expressions represent the same object
  - 1+2
  - 3
  - \( \sqrt{9} \)
  - \((\lambda x \mid x+1)\) 2
Two Ways to Regard Equality

As a relation

An equivalence is a relation $R \subseteq T \times T$ that is:
- **reflexive**: $R(t,t)$ for all $t \in T$
- **symmetric**: $R(t,u) \Rightarrow R(u,t)$
- **transitive**: $R(t,u) \land R(u,v) \Rightarrow R(t,v)$

To use $R$ as a definition for equality: $a$ equals $b$ if and only if $R(a,b)$

As an interpretation function

An interpretation function $f: E \rightarrow V$ maps expressions to abstract values

To use $f$ as a definition for equality of expressions: $a$ equals $b$ if and only if $f(a)=f(b)$

These notions are equivalent

an equivalence relation induces an interpretation function (the relation partitions $T$, so $f$ maps each element to its partition class)

the relation induced by an interpretation function is an equivalence relation (check the three properties)

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Two Views of Equality

Two possible definitions

- Two expressions are equal when they denote the same abstract value.
- Two expressions are equal when they cannot be distinguished by observation.

Example

- Consider the set expressions \{1,2\} and \{2,1\}.
- The unique abstract set they both denote contains exactly 1 and 2.
- Under the observers \(|...|\) and \(\in\), they’re indistinguishable.
  - \(|\{1,2\}| = 2\) and \(\{|2,1\}| = 2\).
  - \(1 \in \{1,2\}\) is true, and \(1 \in \{2,1\}\) is true.
  - \(2 \in \{1,2\}\) is true, and \(2 \in \{2,1\}\) is true.
  - \(3 \in \{1,2\}\) is false, and \(3 \in \{2,1\}\) is false.
- So both approaches produce the same results in the world of mathematical expressions.

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Equality in Immutable ADTs

Mapping these viewpoints to abstract data types

- Interpretation function is the abstraction function
  - i.e., two rep objects r1 and r2 are equal iff the abstraction function A maps them to the same abstract value, i.e. $A(r1) = A(r2)$

- “Indistinguishable by observation” means calling methods
  - i.e., two immutable objects are equal iff they cannot be distinguished by calling methods on the objects
Example

class Duration {
    // abstract duration is an integer representing total number of seconds
    // A(r) = r.getSecs()
    private final int mins;
    private final int secs;
    public Duration(int m, int s) {mins = m; secs = s;}
    public int getSecs() {return mins*60 + secs;}
}

Duration d1 = new Duration (1, 2);
Duration d2 = new Duration (1, 3);
Duration d3 = new Duration (0, 62);

Which of these should be considered equal?
In Java

- `==` compares object locations
  - Or, more precisely, it tests *referential* equality: two references are `==` if they point to the same storage in memory
- `equals()` compares object contents
  - In other words, *object* equality

- Our first try at `Duration.equals()`:

```java
public class Duration {
  ...
  public boolean equals(Duration that) {
    return this.getSecs() == that.getSecs();
  }
}
```

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equals() must be an equivalence

Implementation of equals() must satisfy the three properties

- Reflexive: a.equals(a) for all non-null references a
- Symmetric: a.equals(b) \(\Rightarrow\) b.equals(a)
- Transitive: a.equals(b) \(\land\) b.equals(c) \(\Rightarrow\) a.equals(c)

Suprisingly easy to get this wrong

- What if b is null? Better return false if we want symmetry
- What if we wanted a tolerance in comparing Durations:

```java
class Duration {
    private static final int CLOCK_SKEW = 5; // seconds

    public boolean equals(Duration that) {
        return Math.abs(this.getSecs() - that.getSecs()) <= CLOCK_SKEW;
    }
}
```

- Which property is violated?
public class Duration {
    public boolean equals (Duration that) {
        return this.getSecs() == that.getSecs();
    }
}

Duration d1 = new Duration (1, 2);
Duration d2 = new Duration (1, 2);
Object o2 = new Duration(1,2);

d1.equals(d2) → true
d1.equals(o2) → false
Overriding vs. Overloading

What’s going on?
➢ Duration has overloaded the equals() method inherited from Object, instead of overriding it

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

public class Duration extends Object {
    public boolean equals (Object o) {return o == this;}
    public boolean equals (Duration that) {
        return this.getSecs() == that.getSecs();
    }
}

```
Fixing Equals()

```java
@Override // compile-time error if doesn’t match a superclass method
public boolean equals (Object _that) {
    if (! (_that instanceof Duration)) return false; // also handles _that == null
    Duration that = (Duration) _that;
    return this.getSecs() == that.getSecs();
}
```

This fixes the immediate problem:

Duration d1 = new Duration(1, 2);
Object o2 = new Duration(1,2);

d1.equals(o2) → true
o2.equals(d1) → ?? // is it symmetric?
Subclassing

**Suppose we subclass Duration**

```java
public class PreciseDuration extends Duration {
    private final int millisecs;
    public PreciseDuration(int m, int s, int ms) {
        super(m, s); millisecs = ms;
    }
    public int getMillisecs() {
        return super.getSecs() * 1000 + millisecs;
    }
}
```

➢ How should equality be defined for PreciseDuration?
   • Can we simply use the equals() inherited from Duration? No, because it ignores milliseconds.
Subclassing and Equals()

Can we simply override equals() in the same way?

```java
public class PreciseDuration extends Duration {
    ...
    @Override
    public boolean equals (Object _that) {
        if (! (_that instanceof PreciseDuration)) return false;
        PreciseDuration that = (PreciseDuration) _that;
        return this.getMillisecs() == that.getMillisecs();
    }
}
```

Not symmetric!
Another Try

Suppose we use the superclass definition of equals() in all cases except for comparing two PreciseDuration objects.

```java
public class PreciseDuration extends Duration {
    ...
    @Override
    public boolean equals (Object _that) {
        if (! (_that instanceof PreciseDuration)) return super.equals(_that);
        PreciseDuration that = (PreciseDuration) _that;
        return this.getMillisecs() == that.getMillisecs();
    }
}
```

Not transitive!

• Allows two different PreciseDuration objects to be equal to the same Duration object.

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Solving the Subclassing Problem

No really satisfactory solution

- Standard approach: superclass equality should reject all subclass objects
  - i.e., instead of
    ```java
    if (! (_that instanceof Duration)) return false;
    ```
  - use:
    ```java
    if (! _that.getClass().equals(getClass())) return false;
    ```
- but this is inflexible
  - e.g., doesn’t permit a subclass that doesn’t add any new abstract values

Better solution

- avoid inheritance, and use composition instead
- see Bloch, Effective Java, Item 14
Beneficent Side Effects

Immutable objects can change internal state without losing their immutability

- As long as the state change has no observable effect on the object’s abstract value
- A change like this is called a beneficent side-effect
- Often done for performance reasons

Examples

- Caching results: e.g. Expr.eval() might store the result of the evaluation in the root of the tree, so that it doesn’t have to do it again
- Rebalancing: e.g., a splay tree is a binary search tree that moves the most recently accessed element to the top of the tree

State changes caused by beneficent side effects shouldn’t affect equality
equals and hashCode Contract

equals() and hashCode() have a specific relationship

\[ a.\text{equals}(b) \implies a.\text{hashCode}() == b.\text{hashCode}() \]

➢ Note that the converse is not necessarily true – a and b can have the same hash code even if they are different objects

This relationship is required by Object’s specification

➢ Without it, hash sets and hash maps don’t work correctly
Enforcing the Object Contract

Object’s default hashCode() implementation is consistent with its default equals()

```java
public class Object {
    public boolean equals (Object that) { return this == that; }
    public int hashCode () { return /* the address of this */; }
}
```

➢ For references a, b, if a == b, then the address of a == the address of b

**But immutable objects need a different hashCode()**

Duration d1 = new Duration(1,2);
Duration d2 = new Duration(1,2);
d1.equals(d2) → true
d1.hashCode() → 2392
d2.hashCode() → 4823
Override hashCode()

Always override hashCode() when you override equals()

- Your hash code should be computed from the same parts of the abstract value that equals() compares

```java
public class Duration {
    @Override
    public boolean equals(Object _that) {
        if (_that == null || !this.getClass().equals(_that.getClass())) return false;
        Duration that = (Duration) _that;
        return this.getSecs() == that.getSecs();
    }
    @Override
    public int hashCode() {
        return this.getSecs();
    }
}
```

- See other hashCode() examples in lecture code, particularly BigInt
- See also Bloch, Effective Java, item 8
Equality of Mutable Objects

Recall our definition

- Two objects are equal when they cannot be distinguished by observation

With mutable objects, there are two ways to interpret this

- ... when they cannot be distinguished by observation that doesn’t change the current state of the program
  - i.e., by calling only observer, producer, and creator methods
  - This is often called observational equality, since it tests whether the two objects “look” the same, in the current state of the program
- ...when they cannot be distinguished by any observation, even state changes
  - i.e., allow calling any methods, including mutators
  - This is often called behavioral equality, since it tests whether the two objects will “behave” the same, in this and all future states

- For immutable objects, observational and behavioral equality are identical
Consistency over Time

Consistency property
➢ Equality shouldn’t change over time
➢ if a.equals(b) now, then a.equals(b) later too

Here’s why
List<String> list = makeList("hello");
Set<List<String>> set = new HashSet<List<String>>() {
    set.add(list);
    set.contains(list) → true
    set.contains(makeList("hello")) → true

    list.add("goodbye");
    set.contains(list) → false!
    set.contains(makeList("hello", "goodbye")) → false!
for (List<String> l : set) { set.contains(l) → false! } // set is clearly broken

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Breaking the Rep

What’s going on?

- List<String> is a mutable object
- In the standard Java implementation of collection classes like List, mutations affect the result of equals() and hashCode()
  - i.e., equals() and hashCode() implement observational equality
- When the list is first put into the HashSet, it is stored in the hash bucket corresponding to its hashCode() result at that time
- When the list is subsequently mutated, its hashCode() changes, but HashSet doesn’t realize it should be moved to a different bucket
- So it can never be found again
True Confessions

Quote from the specification of java.util.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. A special case of this prohibition is that it is not permissible for a set to contain itself as an element.

Java library is inconsistent about equals()

- Collections use observational equality
- Other classes (like StringBuffer) use behavioral equality

Lesson: equals() should implement behavioral equality

- Mutable objects should just inherit equals() and hashCode() from Object
- For observational equality (whether two objects “look” the same in the current state), define a new method, e.g. similar()
The Full Object Contract

- equals must define an equivalence relation (reflexive, symmetric, transitive)
- equals must be consistent with itself (repeated calls must yield the same result unless the objects are mutated)
  - the Object contract permits equals() to implement observational equality, but that doesn’t mean you should do it
- x.equals(null) should return false (assuming x is non-null)
- equals and hashCode must be consistent with each other (a.equals(b) implies a.hashCode() == b.hashCode())
Summary

**Equivalence relations**
- `equals()` should be reflexive, symmetric, and transitive

**Abstraction function as a basis for equality**
- Two objects with the same abstract value should be `equals()`

**Object contract**
- `a.equals(b)` implies `a.hashCode() == b.hashCode()`

**Observational equality vs. behavioral equality**
- If clients can’t distinguish two objects by method calls, they’re equal

**Consistency over time**
- Using behavioral equality avoids messy issues with putting objects in collections

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