6.005 Elements of Software Construction

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basics of mutable types

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heap semantics of Java

pop quiz

what happens when this code is executed?

```
String s = "hello";
s.concat("world");
System.out.println (s);
s = s.concat(" world");
System.out.println (s);
```

and how about this?

```
StringBuffer sb = new StringBuffer ("hello");
sb.append(" world");
System.out.println (sb);
StringBuffer sb2 = sb;
sb2.append ("!");
System.out.println (sb);
```

solutions

what you needed to know to answer correctly

immutable and mutable types

- **String** is immutable, **StringBuffer** is mutable
- method call on immutable object can't affect it

assignment semantics

- the statement **x = e** makes **x** point to the object that **e** evaluates to

aliasing

- the statement **x = y** makes **x** point to the same object as **y**
- subsequent mutations of the object are seen equivalently through **x** and **y**
- since immutable objects can't be mutated, sharing is not observable

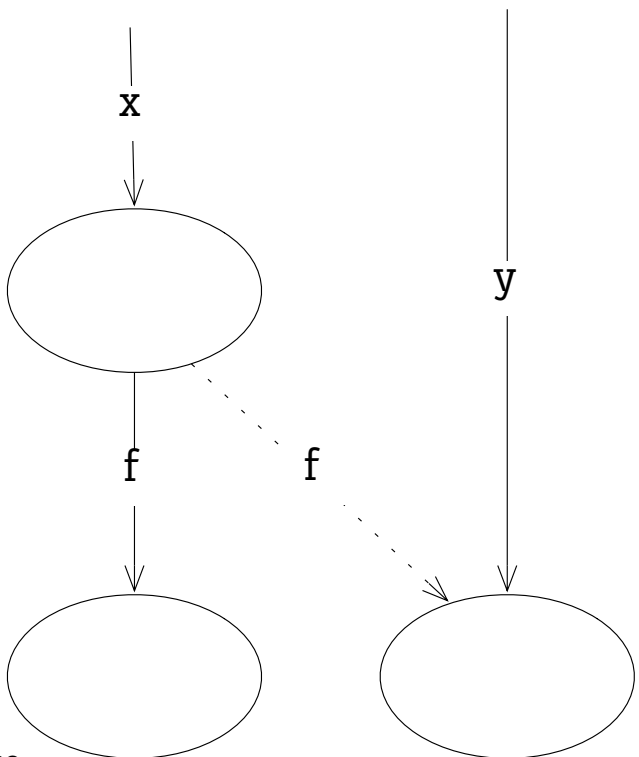
how mutation happens

through field setting

- statement **x.f = y** makes **f** field of **x** point to object **y**

through array update

- statement **a[i] = y** makes **element_i** 'field' of **a** point to object **y**



null and primitives

primitive values

- eg, integers, booleans, chars
- are immutable (and aren't objects)
- so whether shared is not observable

null

- is a value of object type
- but does not denote an object
- cannot call method on null, or get/set field

the operator ==

the operator ==

- returns true when its arguments denote the same object
  (or both evaluate to null)

for mutable objects

- if **x == y** is false, objects **x** and **y** are observably different
- mutation through **x** is not visible through **y**

for immutable objects

- if **x == y** is false, objects **x** and **y** might not be observably different
- in that case, can replace **x** by **y** and save space (called 'interning')
- Java does this with **String**s, with unpredictable results
- lesson: don't use **==** on immutables (unless you're doing your own interning)

heap reachability

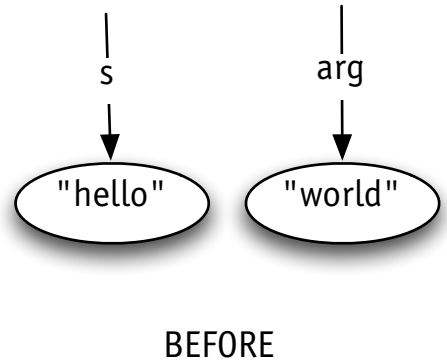
an assignment or field set can leave an object unreachable

from example before

- after these statements

```
String s = "hello";
s = s.concat(" world");
```

- the two string literal objects are unreachable



once an object is unreachable

- it cannot be reached again
- so removing it will not be observable

garbage collector (aka "automatic memory management")

- marks unreachable objects, then deallocates them

conceptual leaks

storage leak

- use of memory grows, but active state isn't growing

no storage leaks in garbage-collected language?

- unfortunately, can still happen

exercise: what's wrong with this code? (hint: think about rep invariant)

```
public class ArraySet {
    private Object [] elements;
    private int size;
    ...
    public void delete (Object o) {
        for (int i = 0; i < size; i++) {
            if (elements[i].equals(o)) {
                elements[i] = elements[size-1];
                size--;
            }
        }
    }
```

mutable datatypes

mutable vs. immutable

String is an immutable datatype

- computation creates new objects with producers

```
class String {
    String concat (String s);
    ...}
```

StringBuffer is a mutable datatype

- computation gives new values to existing objects with mutators

```
class StringBuffer {
    void append (String s);
    ...}
```

classic mutable types

interface in java.util	principal implementations	key mutators
List	ArrayList, LinkedList	add, set
Set	HashSet, TreeSet	add, remove, addAll, removeAll
Map	HashMap, TreeMap	put

how to pick a rep

lists

- use ArrayList unless you want insertions in the middle

sets and maps

- hashing implementations: constant time
- tree implementations: logarithmic time
- use hashing implementations unless you want determinism
- we'll see later in this lecture how non-determinism arises

concurrency

- none of these are thread-safe
- if using with concurrent clients, must synchronize clients yourself
- if you want concurrency in operations, use java.util.concurrent versions

equality revisited

the object contract

every class implicitly extends Object

- two fundamental methods:

```
class Object {
    boolean equals (Object o) {...}
    int hashCode () {...}
    ...
    }
```

"Object contract": a spec for equals and hashCode

- equals is an equivalence (reflexive, symmetric, transitive)
- equals is consistent: if x.equals(y) now, x.equals(y) later
- hashCode respects equality:

```
x.equals(y) implies x.hashCode() = y.hashCode()
```

equivalence

can define your own equality notion

- but is any spec reasonable?

reasonable equality predicates

- define objects to be equal when they represent the same abstract value

a simple theorem

- if we define $a \approx b$ when $f(a) = f(b)$ for some function f
- then the predicate $\approx$ will be an equivalence

an equivalence relation is one that is

- reflexive: $a \approx a$
- symmetric: $a \approx b \Rightarrow b \approx a$
- transitive: $a \approx b \wedge b \approx c \Rightarrow a \approx c$

a running example

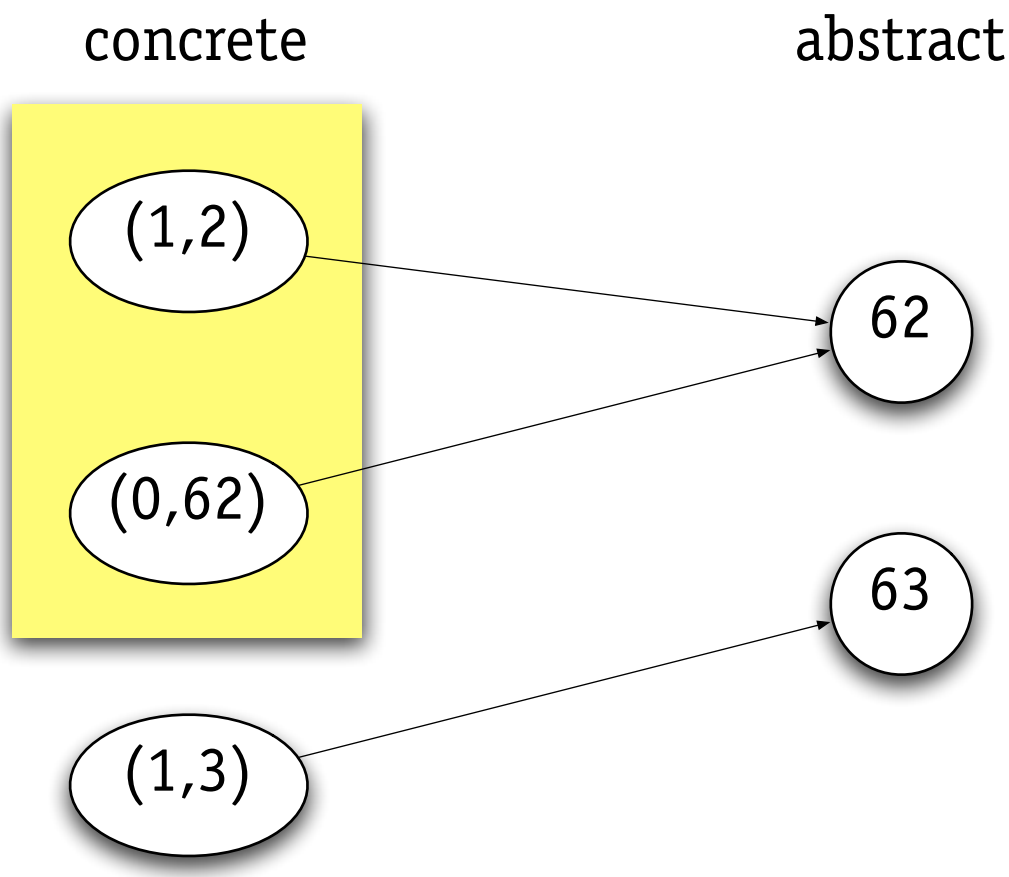
a duration class

- represents durations measured in minutes

```
public class Duration {
  private final int hours;
  private final int mins;
  public Duration(int h, int h) {hours = h; mins = m;}
  public int getMins() {return hours*60 + mins;}
  }
```

abstraction function

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



bug #1

here's our first broken equality method

- violates transitivity: easy to see why

```
public class Duration {
  private final int hours;
  private final int mins;
  static final int CLOCK_SKEW = ...;
  public boolean equals (Duration d) {  // problematic, see next slide
    if (d == null) return false;
    return Math.abs(d.getMins()-this.getMins()) < CLOCK_SKEW;
    }
  }
```

bug #2

what happens if you fail to override equals

- note that outcome depends on declaration, not runtime type (aagh!)

```
public class Duration {
  private final int hours;
  private final int mins;
  public Duration(int h, int h) {hours = h; mins = m;}
  public boolean equals (Duration d) {
    return d.getMins() == this.getMins();
    }
  }

Duration d1 = new Duration(1,2);
Duration d2 = new Duration(1,2);
System.out.println(d1.equals(d2)); // prints true

Object d1 = new Duration(1,2);
Object d2 = new Duration(1,2);
System.out.println(d1.equals(d2)); // prints false!
```

explaining bug #2

what's going on?

- we've failed to override Object.equals
- method is chosen using compile-time type
- method has been **overloaded**, not **overridden**

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

public class Duration extends Object {
  public boolean equals (Object o) {return o == this;}
  public boolean equals (Duration d) {
    return d.getMins() == this.getMins();
    }
  }
```

fixing equals

here's a fix to the problem

- compile-time declaration no longer affects equality

```
@Override // compile error if doesn't override superclass method
public boolean equals(Object o) {
  if (! (o instanceof Duration))
    return false;
  Duration d = (Duration) o;
  return d.getMins() == this.getMins();
  }
```

equality and subclassing

now considering extending the type

- how should equality be determined?
- can't rely on inherited equals method, because seconds ignored

```
public class ShortDuration extends Duration {
  private final int secs;
  ...
  private ShortDuration (int h, int m, int s) {...};
  public int getSecs () {return 3600*hours + 60*mins + secs;}
  ...
  }
```

bug #3

an attempt at writing equals for subclass

```
@Override
public boolean equals(Object o) {
   if (! (o instanceof ShortDuration))
     return false;
   ShortDuration d = (ShortDuration) o;
   return d.getSecs () == this.getSecs();
   }
```

will this work?

- no, now it's not symmetric!

```
Duration d1 = new ShortDuration(1,2,3);
Duration d2 = new Duration(1,2);
System.out.println(d1.equals(d2)); // false
System.out.println(d2.equals(d1)); // true
```

bug #4

yet another attempt

- this time not transitive

```
@Override public boolean equals(Object o) {
   if (! (o instanceof Duration)) return false;
   if (! (o instanceof ShortDuration)) return super.equals (o);
   ShortDuration d = (ShortDuration) o;
   return d.getSecs () == this.getSecs();
   }

Duration d1 = new ShortDuration(1,2,3);
Duration d2 = new Duration(1,2);
Duration d3 = new ShortDuration(1,2,4);
System.out.println(d1.equals(d2)); // true
System.out.println(d2.equals(d3)); // true
System.out.println(d1.equals(d3)); // false!
```

solving the subclassing snag

no really satisfactory solution

superclass equality rejects subclass objects

- can write this

```
if (!o.getClass().equals(getClass())) return false;
```

- but this is inflexible: can't extend just to add functionality, eg

better solution

- avoid inheritance, and use composition instead
- see Bloch, *Effective Java*, Item 14

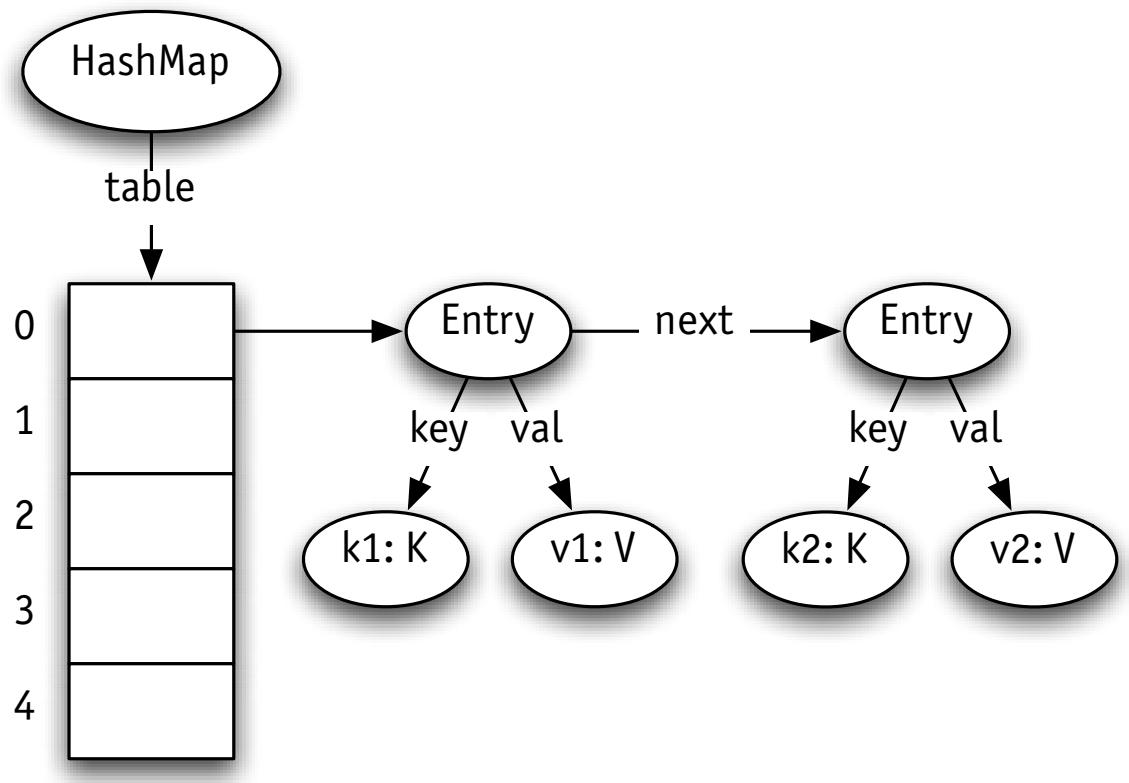
hash maps

hash map structure

representation

- array of bucket lists

```
class HashMap <K,V> {
    Entry<K,V>[] table;
    class Entry<K, V> { K key; V val; Entry<K,V> next; ... }
```



hash map operations

operations

- put(k,v): to associate value v with key k

  compute index i = hash(k)

  hash(k) = k.hashCode & table.length-1 (eg)

  if find entry in table[i] with key equal to k, replace val by v

  otherwise add new entry for (k, v)

- get(k): to get value associated with key k

  examine all entries in table[i] as for insertion

  if find one with key equal to k, return val

  else return null

resizing

- if map gets too big, create new array of twice the size and rehash

hashing principle

e: table[i].*next means e ranges over set of all entries reachable from table[i] in zero or more applications of next

why does hashing work?

- rep invariant: entries are in buckets indexed by hash

  all i: table.indexes, e: table[i].*next | hash(e.key) == i

- from object contract: equal keys have equal hashes

  all k, k': Key | k.equals(k') ⇒ hash(k) == hash(k')

- consequence: need only look at one index

  all k: Key, i: table.indexes | i != hash(k) ⇒ all e: table[i].*next | !e.key.equals(k)

- also additional rep invariant: only one entry per key
- consequence: can stop at first match

finally, keep buckets to small constant number of entries

- then put and get will be constant time

mutating keys

what happens if you mutate a hash map's key?

if equals and hashCode depend only on key's identity

- nothing bad happens

if equals and hashCode depend on key's fields

- then value of hashCode can change
- rep invariant of hash map is violated
- lookup may fail to find key, even if one exists

problem is example of 'abstract aliasing'

- hash map and key are aliased

example

what does this print?

```
public class BrokenHash {
    static class Counter {
        int i;
        void incr () {i++;}
        @Override public boolean equals (Object o) {
            if (!(o instanceof Counter)) return false;
            Counter c = (Counter) o;
            return c.i == i;
        }
        @Override public int hashCode () {return i;}
    }

    public static void main (String[] args) {
        Set m = new HashSet <Counter> ();
        Counter c = new Counter();
        m.add(c);
        System.out.println ("m contains c: " + (m.contains(c) ? "yes" : "no"));
        c.incr();
        System.out.println ("m contains c: " + (m.contains(c) ? "yes" : "no"));
    }
}
```

so what to do?

option #1 (Liskov)

- equals on mutable types compares references
- no problem with keys, but two sets with same elements are not equal

option #2 (Java Collections)

- equals on mutable types compares current values
- forbid modification of objects held as keys
- more convenient for comparing collections, but dangerous

is Java consistent?

- Object contract in Java says

> 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

non-determinism

to iterate over elements of a hash set

- use HashSet.iterator()
- elements yielded in unspecified order

what determines order?

- code iterates over table indices
- so order related to hashing function
- depends on hash code, thus (for mutables) on object addresses

so this means

- different program runs likely to give different order
- this can be a real nuisance: consider regression testing, for example
- solution: use a TreeSet instead

summary

principles

object heap is a graph

- to understand mutation & aliasing, can't think in terms of values

equality is user-defined but constrained

- must be consistent and an equivalence

abstract aliasing complicates

- may even break rep invariant (eg, mutating hash key)