BUILD THE FUTURE

thefuture.build

Thursdays, 6:30 - 8:00 pm @ 105 North Gate Hall

Project 2

Some words of warning:

- Project 2 is going to be very hard.
- … but you'll have a teammate to help.

Key resources:

- Lab 5 (Link)
- Partnerships for project 2 (Link)
- Getting started video for project 2 (Link)
- Project 2 spec (Link)

CS61B: 2018

Lecture 13: Generics, Conversion, Promotion

- Generic Basics, Autoboxing, Widening
- Immutability
- Generic Methods

Coming up Next: The Syntax Lectures

In the next three lectures, we'll build an Array based implementation of a Map, and along the way, learn some new syntax.

- Syntax1: Autoboxing, promotion, immutability, generics
- Syntax2: Exceptions, Iterables/Iterators
- Syntax3: Access control, equals, other loose ends
- Syntax4 (optional): Wildcards, type upper bounds, covariance (not in the scope of the class).

After that, we're done with Java language stuff.

Generics

For the most part, using generics is pretty straightforward.

- Generic classes require us to provide one or more ***actual type arguments***.

```
import java.util.ArrayList;

public class BasicArrayList {
    public static void main(String[] args) {
        ArrayList<String> L = new ArrayList<String>();
        L.add("potato");
        L.add("ketchup");
        String first = L.get(0);
    }
}
```

actual type argument: String.

In Java 8: No longer necessary at instantiation if also declaring a variable at the same time.

Primitives Cannot Be Used as Actual Type Arguments

We cannot use primitive types as actual type arguments.

- Code below causes a compile time error.

```
import java.util.ArrayList;

public class BasicArrayList {
    public static void main(String[] args) {
        ArrayList<int> L = new ArrayList<int>();
        L.add(5);
        L.add(6);
        int first = L.get(
    }
}
```

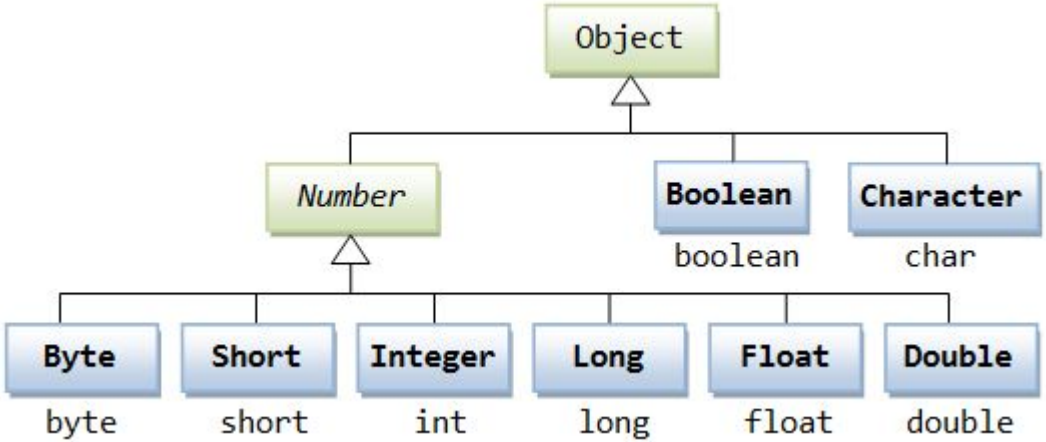
```
jug ~/temp
$ javac BasicArrayList.java
BasicArrayList.java:5: error: unexpected type
        ArrayList<int> L = new ArrayList<int>();
                   ^
  required: reference
  found:    int
```

Reference Types

Reminder: Java has 8 primitive types. All other types are reference types.

For each primitive type, there is a corresponding reference type called a wrapper class.

- For example, boolean's wrapper class is Boolean.



Reference Types as Actual Type Arguments

Solution: Use wrapper type as actual type parameter instead of primitive type.

```
import java.util.ArrayList;

public class BasicArrayList {
    public static void main(String[] args) {
        ArrayList<Integer> L = new ArrayList<Integer>();
        L.add(new Integer(5));
        L.add(new Integer(6));
        int first = L.get(0).valueOf();
    }
}
```

Conversion between int and Integer is annoying, so in Java 1.5 they also introduced...

Autoboxing

Autoboxing (auto-unboxing): Implicit conversions between wrapper/primitives.

```
import java.util.ArrayList;

public class BasicArrayList {
    public static void main(String[] args) {
        ArrayList<Integer> L = new ArrayList<Integer>();
        L.add(5);
        L.add(6);
        int first = L.get(0);
    }
}
```

Code above works even though we're passing an int into an Integer parameter, and assigning a return value of type Integer to an int.

Autoboxing and Unboxing

Wrapper types and primitives can be used almost interchangeably.

- If Java code expects a wrapper type and gets a primitive, it is autoboxed.

```
public static void blah(Integer x) {
   System.out.println(x);
}
```

```
int x = 20;
blah(x);
```

- If the code expects a primitive and gets a wrapper, it is unboxed.

```
public static void blahPrimitive(int x) {
   System.out.println(x);
}
```

```
Integer x = new Integer(20);
blahPrimitive(x);
```

Some notes:

- Arrays are never autoboxed/unboxed, e.g. an Integer[] cannot be used in place of an int[] (or vice versa).
- Autoboxing / unboxing incurs a measurable performance impact!
- Wrapper types use MUCH more memory than primitive types.

Wrapper Types Are (Mostly) Just Like Any Class

You can read the source code to all built-in Java libraries.

- e.g. google “grepcode java Integer” yields this link.
- Integer has no magic powers except autoboxing/auto-unboxing.

```
public final class Integer
        extends Number implements Comparable<Integer> {

    private final int value;

    public Integer(int value) {
        this.value = value;
    }
    ...
}
```

Wrapper Type Memory: http://shoutkey.com/appear

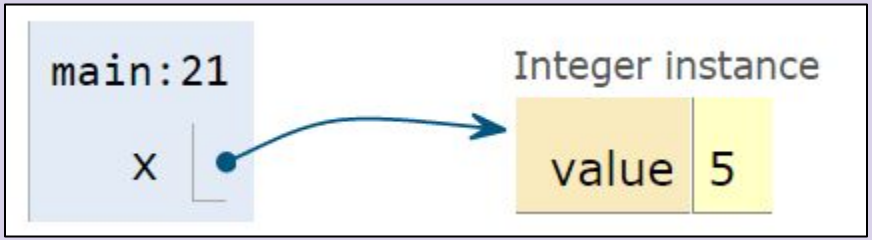
```
public static void bleepblorp() {
    Integer x = new Integer(5);
    System.out.println(x);
}
```

Assuming:

- Addresses are 64 bits.
- ints are 32 bits.
- All Java objects take 64 bits + their fields.

How much total memory is used by bleepblorp to store its local variables?

a. 32 bits.
b. 64 bits.
c. 96 bits.
d. 128 bits.
e. 160 bits.



Wrapper Type Memory: http://shoutkey.com/appear

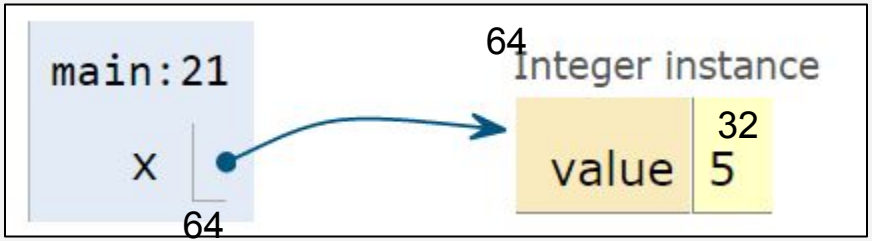
```
public static void bleepblorp() {
    Integer x = new Integer(5);
    System.out.println(x);
}
```

Assuming:

- Addresses are 64 bits.
- ints are 32 bits.
- All Java objects take 64 bits + their fields.

How much total memory is used by bleepblorp to store its local variables?

a. 32 bits.
b. 64 bits.
c. 96 bits.
d. 128 bits.
e. 160 bits: 64 + 96 for object



Another Type of Conversion: Primitive Widening

A similar thing happens when moving from a primitive type with a narrower range to a wider range.

- In this case, we say the value is “widened”.
- Code below is fine since double is wider than int.

```
public static void blahDouble(double x) {
   System.out.println(“double: “ + x);
}
```

```
int x = 20;
blahDouble(x);
```

To move from a wider type to a narrower type, must use casting:

```
public static void blahInt(int x) {
   System.out.println(“int: “ + x);
}
```

```
double x = 20;
blahInt((int) x);
```

Full details here: http://docs.oracle.com/javase/specs/jls/se8/html/jls-5.html

Immutability

Immutable Data Types

An immutable data type is one for which an instance cannot change in any observable way after instantiation.

Examples:

- Mutable: ArrayDeque, Planet.
- Immutable: Integer, String, Date.

```
public class Date {
  public final int month;
  public final int day;
  public final int year;
  private boolean contrived = true;
  public Date(int m, int d, int y) {
    month = m; day = d; year = y;
  }
}
```

The ***final*** keyword will help the compiler ensure immutability.

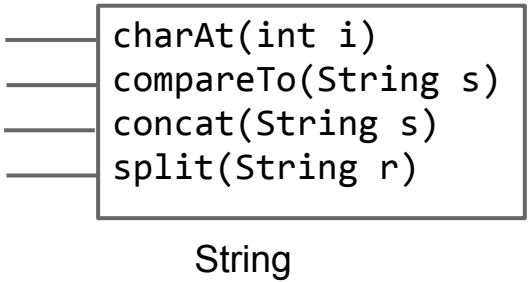
- final variable means you will assign a value once (either in constructor of class or in initializer).
- Not necessary to have final to be immutable (e.g. Dog with private varables).

Immutability

Advantage: Less to think about: Avoids bugs and makes debugging easier.

- Analogy: Immutable classes have some buttons you can press / windows you can look inside. Results are ALWAYS the same, no matter what.

Disadvantage: Must create a new object anytime anything changes.



Warning: Declaring a reference as **Final** does not make object immutable.

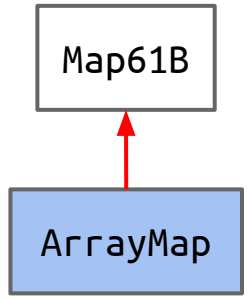
- Example: `public final ArrayDeque<String> d = new ArrayDeque<String>();`
- The d variable can never change, but the referenced deque can!

Defining Generic Classes

Goals

Goal 1: Create a class ArrayMap with the following methods:

- put(key, value): Associate key with value.
- containsKey(key): Checks to see if arraymap contains the key.
- get(key): Returns value, assuming key exists..
- keys(): Returns a list of all keys.
- size(): Returns number of keys.



Ok to ignore resizing for this exercise.

- In lecture, I'll just show the answer, but you might find implementing it useful. See study guide for this lecture for starter code.

ArrayMap (Basic Implementation)

```
public class ArrayMap<K, V> {
  private K[] keys;
  private V[] values;
  private int size;
  public ArrayMap() {
    keys = (K[]) new Object[100];
    values = (V[]) new Object[100];
    size = 0;
  }
  ...
}
```

Array implementation of a Map:

- Use an array as the core data structure.
- `put(k, v)`: Finds the array index of k
  - If -1, adds k and v to the last position of the arrays.
  - If non-negative, sets the appropriate item in values array.

ArrayMap (Basic Implementation)

```
public void put(K key, V value) {
  int i = getKeyIndex(key);
  if (i > -1) {
    values[i] = value; return; }
  keys[size] = key;
  values[size] = value;
  size += 1;
}

public V get(K key) {
  return values[findKey(key)];
}
```

```
public boolean
      containsKey(K key) {
   int i = findKey(key);
   return (i > -1);
}

public List<Keys> keys() {
  ... /* See code */
}
```

Using An ArrayMap

Generic type variables

```
public class ArrayMap<K, V> {
  private K[] keys;
  private V[] values;
  private int size;
  public ArrayMap() {
    keys = (K[]) new Object[100];
    values = (V[]) new Object[100];
    size = 0;
  }
  ...
```

Actual type arguments

```
ArrayMap<Integer, String> ismap = new ArrayMap<Integer, String>();
ismap.put(5, "hello");
ismap.put(10, "ketchup");
```

A Mysterious Error Appears

```java
@Test
public void test() {
    ArrayMap<Integer, Integer> am = new ArrayMap<Integer, Integer>();
    am.put(2, 5);
    int expected = 5;
    assertEquals(expected, am.get(2));
}
```

```
$ javac ArrayMapTest.java
ArrayMapTest.java:11: error: reference to assertEquals is ambiguous
    assertEquals(expected, am.get(2));
    ^
  both method assertEquals(long,long) in Assert and method
assertEquals(Object,Object) in Assert match
```

The Issue:

- JUnit has many assertEquals functions including (int, int), (double, double), (Object, Object), etc.

http://yellkey.com/first

Which automatic conversions are needed to call assertEquals(long, long)?

A. Widen expected to long.
B. Autobox expected as a Long.
C. Autobox expected as an Long.
D. Unbox am.get(2).
E. Widen the unboxed am.get(2) to long.

There may be more than one right answer.

Hint, the actual call is: assertEquals(int, Integer)

```
@Test
public void test() {
    ArrayMap<Integer, Integer> am = new ArrayMap<Integer, Integer>();
    am.put(2, 5);
    int expected = 5;
    assertEquals(expected, am.get(2));
}
```

http://shoutkey.com/first

Which automatic conversions are needed to call assertEquals(long, long)?

A. Widen expected to long.
B. Autobox expected as a Long.
C. Autobox expected as an Long.
D. Unbox am.get(2).
E. Widen the unboxed am.get(2) to long.

There may be more than one right answer.

Hint, the actual call is: assertEquals(int, Integer)

```
@Test
public void test() {
    ArrayMap<Integer, Integer> am = new ArrayMap<Integer, Integer>();
    am.put(2, 5);
    int expected = 5;
    assertEquals(expected, am.get(2));
}
```

Open Question

What automatic conversions are needed to call assertEquals(Object, Object)?

```
@Test
public void test() {
    ArrayMap<Integer, Integer> am = new ArrayMap<Integer, Integer>();
    am.put(2, 5);
    int expected = 5;
    assertEquals(expected, am.get(2)); }
```

Open Question

What automatic conversions are needed to call assertEquals(Object, Object)?

```
@Test
public void test() {
    ArrayMap<Integer, Integer> am = new ArrayMap<Integer, Integer>();
    am.put(2, 5);
    int expected = 5;
    assertEquals(expected, am.get(2)); }
```

Only one conversion needed (unless you count Integer → Object)

- Autobox “expected” into an Integer.

Even though this is ‘easier’ than the 3-step process needed to get to assertEquals(long, long), it’s still ambiguous and thus Java won’t let the code above compile.

Open Question

How do we get the code to compile, e.g. how do we resolve the ambiguity?

```
@Test
public void test() {
    ArrayMap<Integer, Integer> am = new ArrayMap<Integer, Integer>();
    am.put(2, 5);
    int expected = 5;
    assertEquals(expected, am.get(2)); }
```

Open Question

How do we get the code to compile, e.g. how do we resolve the ambiguity?

```
@Test
public void test() {
    ArrayMap<Integer, Integer> am = new ArrayMap<Integer, Integer>();
    am.put(2, 5);
    int expected = 5;
    assertEquals(expected, am.get(2)); }
```

Many possible answers, one of them is:

```
@Test
public void test() {
    ArrayMap<Integer, Integer> am = new ArrayMap<Integer, Integer>();
    am.put(2, 5);
    int expected = 5;
    assertEquals((Integer) expected, am.get(2)); }
```

Generic Methods

Goals

Goal: Create a class MapHelper with two methods:

- get(Map61B, key): Returns the value corresponding to the given key in the map if it exists, otherwise null.
  - Unlike the ArrayMap's get method, which crashes if the key doesn't exist.
- maxKey(Map61B): Returns the maximum of all keys in the given ArrayMap. Works only if keys can be compared.

Goals

Goal: Create a class MapHelper with two methods:

- get(key): Returns the item in the map if it exists, otherwise null.
- maxKey(): Returns the maximum of all keys. Works only if keys can be compared.

MapHelper.java

Generic Methods

Can create a method that operates on generic types by defining type parameters *before the return type* of the method:

Formal type parameter definitions.

```
public static <X, Zerp> Zerp get(ArrayMap<X, Zerp> am, X key) {
  if (am.containsKey(key)) {
     return am.get(key);
  }
  return null;
}
```

Return type: Zerp (whatever that is)

In almost all circumstances, using a generic method requires no special syntax:

```
ArrayMap<Integer, String> ismap =
             new ArrayMap<Integer, String>();
System.out.println(MapHelper.get(ismap, 5));
```

It's that easy.

Goals

Goal: Create a class MapHelper with two methods:

- get(key): Returns the item in the map if it exists, otherwise null.
- maxKey(): Returns the maximum of all keys. Works only if keys can be compared.

MapHelper.java

The Issue with Generic Methods

We had the code below with a major problem: Cannot compare Ks using >.

- Only numerical primitives can be compared with >.

… though due to auto-unboxing: numerical wrapper types can be compared with >

```
public static <K, V> K maxKey(ArrayMap<K, V> map) {
    List<K> keylist = map.keys();
    K largest = keylist.get(0);
    for (K k : keylist) {
        if (k > largest) {
            largest = k;
        }
    }
    return largest;
}
```

The Issue with Generic Methods

New problem: K's don't necessarily have a compareTo method.

```
public static <K, V> K maxKey(ArrayMap<K, V> map) {
    List<K> keylist = map.keys();
    K largest = keylist.get(0);
    for (K k : keylist) {
        if (k.compareTo(largest) > 0) {
            largest = k;
        }
    }
    return largest;
}
```

Issue with The compareTo Approach

```
public static <K, V> K maxKey(ArrayMap<K, V> map) {
    List<K> keylist = map.keys();
    K largest = keylist.get(0);
    for (K k : keylist) {
        if (k.compareTo(largest) > 0) {
            largest = k;
        }
    }
    return largest;
}
```

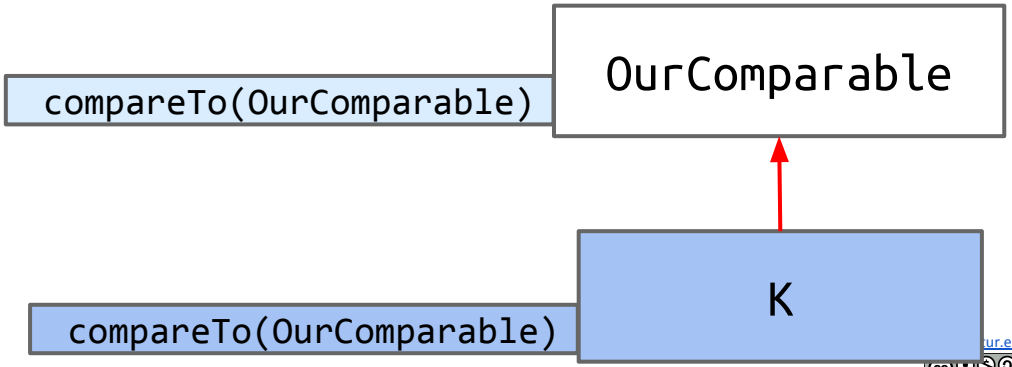
```
$ javac MapHelper.java
MapHelper.java:14: error: cannot find symbol
        int cmp = k.compareTo(largest);
                              ^
  symbol:   method compareTo(K)
  location: class Object
```

Type Upper Bounds to The Rescue

Can use extends keyword as a ***type upper bound***. Only allow use on ArrayMaps with OurComparable keys.

Meaning: Any ArrayMap you give me must have actual parameter type that is a subtype of OurComparable.

```
public static <K extends OurComparable, V> K maxKey(ArrayMap<K, V> am) {
    ...
        if (k.compareTo(largest) > 0) {
    ...
}
```



Note: Type lower bounds also exist, specified using the word super. Won't cover in 61B.

A Better Type Upper Bound: Comparable

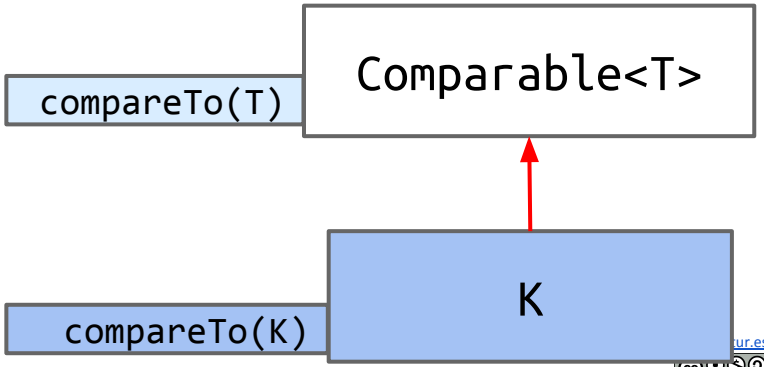
Can use extends keyword as a ***type upper bound***. Only allow use on ArrayMaps with Comparable keys.

Meaning: Any ArrayMap you give me must have actual parameter type that is a subtype of Comparable<T>.

```
public static <K extends Comparable<K>, V> K maxKey(ArrayMap<K, V> am) {
    ...
        if (k.compareTo(largest) > 0) {
    ...
}
```

Built in Java interface: Comparable<T>

- Implemented by Integer, String, etc.



Note: Type lower bounds also exist, specified using the word super. Won't cover in 61B.

Generics Summary

We've now seen four new features of Java that make Generics more powerful:

- Autoboxing and auto-unboxing of primitive wrapper types.
- Promotion between primitive types.
- Specification of generic types for methods (before return type).
- Type upper bounds (e.g. K extends Comparable<K>)
- In syntax4, you can also see another feature called "wildcards".

A true understand of Java generics takes a long time and lots of practice.

- You won't know all the details by the end of 61B.
- I promise not to ask questions about bounded wildcards, type erasure, or covariance (see bonus lecture entitled syntax4).

And yet there's still more, e.g. `public static <T> int binarySearch(T[] a, T key, Comparator<? super T> c) {`

Syntax4: Optional Lecture (coming later, but slides now for the curious)

A Quick Dip into Generic Hell

Second, we started building a MapHelper class hoping to provide the following:

- get(key): Returns the item in the map if it exists.
- maxKey(): Returns the maximum of all keys. Works only if keys can be compared.
- allBark(): Makes all keys bark. Works only for keys of type Dog.

```
ArrayMap<Dog, Double> am2 = new ArrayMap<Dog, Double>();
am2.put(new Dog("frank"), 10);
am2.put(new FrenchDog("francis", 20);
MapHelper.allBark(am2);
```

MapHelper.java

Problem #1: Dealing with Types We Don't Care about

Implementation below works, but only for ArrayMaps from Dog to Double.

```
public static void allBark(ArrayMap<Dog, Double> am) {
    List<Dog> dogs = am.keys();
    for (int i = 0; i < dogs.size(); i += 1) {
        dogs.get(i).bark();
    }
}
```

```
ArrayMap<Dog, Integer> am2 = new ArrayMap<Dog, Integer>();
am2.put(new Dog("frank"), 10);
am2.put(new FrenchDog("francis"), 20);
MapHelper.allBark(am2);
```

Value types mismatch!

```
$ javac MapHelper.java
MapHelper.java:62: error: incompatible types: ArrayMap<Dog,Integer>
cannot be converted to ArrayMap<Dog,Double>
```

Problem #1: Dealing with Types We Don't Care about

How could we fix the allBark method so that it works for any value type?

```
public static void allBark(ArrayMap<Dog, Double> am) {
    List<Dog> dogs = am.keys();
    for (int i = 0; i < dogs.size(); i += 1) {
        dogs.get(i).bark();
    }
}
```

```
ArrayMap<Dog, Integer> am2 = new ArrayMap<Dog, Integer>();
am2.put(new Dog("frank"), 10);
am2.put(new FrenchDog("francis"), 20);
MapHelper.allBark(am2);
```

Value types mismatch!

```
$ javac MapHelper.java
MapHelper.java:62: error: incompatible types: ArrayMap<Dog,Integer>
cannot be converted to ArrayMap<Dog,Double>
```

Fix #1

Can add generic parameter to method to fix.

```
public static <V> void allBark(ArrayMap<Dog, V> am) {
    List<Dog> dogs = am.keys();
    for (int i = 0; i < dogs.size(); i += 1) {
        dogs.get(i).bark();
    }
}
```

Alternate Fix #1

Fix #1 and Alternate Fix #1 are both perfectly acceptable!

Alternately: Use Wildcard character: ?

```
public static void allBark(ArrayMap<Dog, ?> am) {
    List<Dog> dogs = am.keys();
    for (int i = 0; i < dogs.size(); i += 1) {
        dogs.get(i).bark();
    }
}
```

Basic idea:

- We don't care about the actual type, since we never used V anywhere.
- This is a fairly advanced feature you're unlikely to use in 61B. Will only appear on a midterm or final if it ends up being on a HW/lab/project.

Quick Aside: Code Optimization

Lists in Java support for-each loop, sometimes called enhanced for loop.

```
public static void allBark(ArrayMap<Dog, ?> am) {
    List<Dog> dogs = am.keys();
    for (int i = 0; i < dogs.size(); i += 1) {
        dogs.get(i).bark();
    }
}
```

```
public static void allBark(ArrayMap<Dog, ?> am) {
    for (Dog d : am.keys()) {
        d.bark();
    }
}
```

Same output.

Avoids need to iterate through list using indices.

Problem #2: Covariance

Surprisingly, cannot pass an ArrayMap of FrenchDog keys!

```
public static void allBark(ArrayMap<Dog, ?> am) {
    for (Dog d : am.keys()) {
        d.bark();
    }
}
```

```
ArrayMap<FrenchDog, Integer> am2 = new ArrayMap<FrenchDog, Integer>();
am2.put(new FrenchDog("francis"), 10);
am2.put(new FrenchDog("francis jr"), 20);
allBark(am2);
```

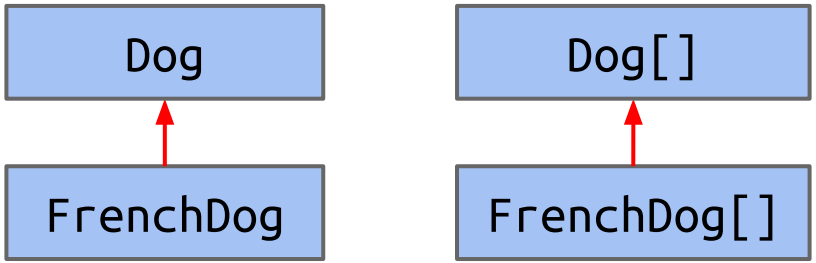
```
$ javac MapHelper.java
MapHelper.java:62: error: incompatible types:
ArrayMap<FrenchDog,Integer> cannot be converted to ArrayMap<Dog,?>
```

Covariance

Arrays are **covariant** in Java, but generic types are invariant.

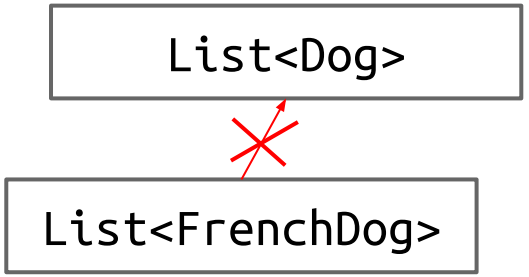
Arrays are covariant:

- A FrenchDog is-a Dog.
- An FrenchDog[] is-a Dog[].



Generic types are invariant:

- A List<FrenchDog> is NOT a List<Dog>.



This maddening feature is my least favorite part of Java.

- Leads to lots of syntactical contortions. See next slide.
- Why did Java designers do this to us? See extra slides.

Fixing Problem #2

Two equivalent fixes:

- Approach 1: Add a generic type to our method.
- Approach 2: Add a bounded-wildcard (unlikely to use in 61B).

```
public static <K extends Dog> void allBark(ArrayMap<K, ?> am) {
    for (Dog d : am.keys()) {
        d.bark();
    }
}
```

```
public static void allBark(ArrayMap<? extends Dog, ?> am) {
    for (Dog d : am.keys()) {
        d.bark();
    }
}
```

Code never uses K so need to actually specify a generic type.

Generics Summary

We've now seen four new features of Java that make Generics more powerful:

- Autoboxing and auto-unboxing of primitive wrapper types.
- Promotion between primitive types.
- Specification of generic types for methods (before return type).
- Type upper bounds (e.g. K extends Comparable<K>)
- Wildcards: ?

A true understand of Java generics takes a long time and lots of practice.

- You won't know all the details by the end of 61B.
- I promise not to ask questions about bounded wildcards or type erasure (see extra slides).

And yet there's still more, e.g. `public static <T> int binarySearch(T[] a, T key, Comparator<? super T> c) {`

Citations

Drink:

http://hilanddairy.com/image-library/sites/default/files/styles/large/public/Hiland_GrapeDrink_Gal.jpg

Wrapper class image from Nanyang Technological University:
https://www3.ntu.edu.sg/home/ehchua/programming/java/images/OOP_WrapperClass.png