Lesson 11
Java Generics

Lesson Outline

1. Introduction to generics
2. Generic methods
3. Wildcards
4. Generic programming with generics

Introducing Generic Parameters

Prior to jdk 1.5, a collections of any type consisted of collections of Objects, and downcasting was required to retrieve elements of the correct type.

Example:

```
List words = new ArrayList();
words.add("Hello ");
words.add("world!");
String s = ((String)words.get(0))+((String)words.get(1))
assert s.equals("Hello world!");
```

In jdk 1.5, generic parameters were added to the declaration of collection classes, so that the above code could be rewritten as follows:

```
List<String> words = new ArrayList<String>();
words.add("Hello ");
words.add("world!");
String s = words.get(0)+words.get(1);
assert s.equals("Hello world!");
```

Benefits of Generics

1. *Stronger type checks at compile time*. A Java compiler applies strong type checking to generic code and issues errors if the code violates type safety. Fixing compile-time errors is easier than fixing runtime errors, which can be difficult to find.

   <u>Example of poor type-checking</u>

   ```
   List myList = new myList();
   myList.add("Tom");
   myList.add("Bob");
    . . .
   Employee tom = (Employee)myList.get(0); //no compiler check to prevent this
   ```

2. *Elimination of casts*. Downcasting is considered an "anti-pattern" in OO programming. Typically, downcasting should not be necessary; finding the right subtype should be accomplished with late binding.

   <u>Example of bad downcasting</u>.

   ```
   ClosedCurve[] closedCurves = //…populate with Triangles and Rectangles
   if(closedCurves[0] instanceOf Triangle)
      print( (Triangle)closedCurve[0].area());
   else
      print((Rectangle)closedCurve[0].area())
   ```

3. *Supports creation of generic algorithms.*

   <u>Example</u> *Task*: Swap elements in a list (*generic methods* discussed in upcoming slide)

   ```
   public void swapFirstLastNonGeneric(List list) {
       Object temp = list.get(0);
       list.set(0, list.get(list.size()-1));
       list.set(list.size()-1, temp);
   }
   public <T> void swapFirstLast(List<T> list) {
       T temp = list.get(0);
       list.set(0, list.get(list.size()-1));
       list.set(list.size()-1, temp);
   }
   ```

Generics Terminology and Naming Conventions

1. In the List<String> example:

```
List<String> words = new ArrayList<String>();
words.add("Hello ");
words.add("world!");
String s = words.get(0)+words.get(1);
assert s.equals("Hello world!");
```

2. The class (found in the Java libraries) defined by

   `class ArrayList<T> { . . . }`

   is called a *generic class*, and `T` is called a *type variable* or *type parameter*.

3. The delcaration

   `List<String> words;`

   is called a *generic type invocation,* `String` is (in this context) a *type argument*, and `List<String>` is called a *parametrized type.* Also, the class List, with the type argument removed, is called a *raw type.*

   Note: When raw types are used where a parametrized type is expected, the compiler issues a warning because the compile-time checks that can usually be done with parametrized types cannot be done with a raw type.

4. The most commonly used type variables are:

   - E - Element (used extensively by the Java Collections Framework)
   - K - Key
   - N - Number
   - T - Type
   - V - Value
   - S,U,V etc. - 2nd, 3rd, 4th types

Creating Your Own Generic Class

```java
public class SimplePair<K,V> {
    private K key;
    private V value;

    public SimplePair(K key, V value) {
        this.key = key;
        this.value = value;
    }
    public K getKey()   { return key; }
    public V getValue() { return value; }
}
```

Implementing a Generic Interface, Extending a Generic Class

One way: Create a parametrized type implementation

```java
public class MyPair implements Pair<String, Integer>{
    private String key;
    private Integer value;

    public MyPair(String key, Integer value) {
        this.key = key;
        this.value = value;
    }

    @Override
    public String getKey() {
        return key;
    }
    @Override
    public Integer getValue() {
        return value;
    }

}
```

Another way: Create a generic class implementation

```java
public class OrderedPair<K, V> implements Pair<K, V> {
    private K key;
    private V value;

    public OrderedPair(K key, V value) {
        this.key = key;
        this.value = value;
    }

    public K getKey()   { return key; }
    public V getValue() { return value; }
```

The same points apply for extending a generic class

Either:

```java
class MyList<T> extends ArrayList<T>{

}
```

Or:

```java
public class MyList extends ArrayList<String >{

}
```

How Java Implements Generics: *Type Erasure*

The compiler transforms the following generic code

```
List<String> words = new ArrayList<String>();
words.add("Hello ");
words.add("world!");
String s = words.get(0)+words.get(1);
assert s.equals("Hello world!");
```

into the following non-generic code:

```
List words = new ArrayList();
words.add("Hello ");
words.add("world!");
String s = ((String)words.get(0))+((String)words.get(1))
assert s.equals("Hello world!");
```

1. Java implements generics *by erasure* because the parametrized types like List<String>, List<Integer> and List<List<Integer>> are all reprsented at runtime by the single type List.
2. Also *erasure* is the process of converting the first piece of code to the second
3. The compiled code for generics will carry out the same downcasting as was required in pre-generics Java.

Benefits of this implemenation approach:

A. No increase in the number of types in the language (in C++, each parametrized type is a genuinely different type)

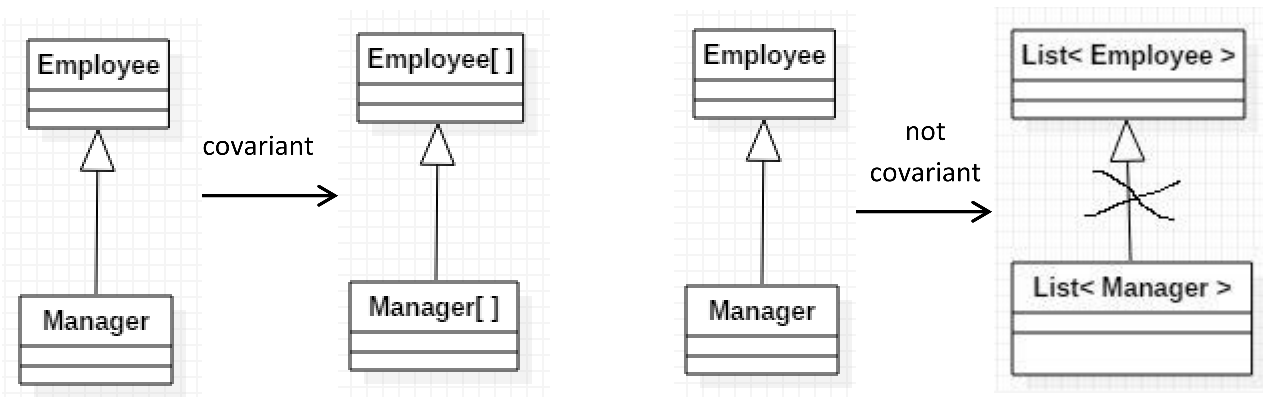
B. Backwards compatibilty with non-generic code – for instance, in both generic and non-generic code, there is, at runtime, only one type List, so legacy code and generic code can intermingle without much difficulty.

The Downside of Java’s Implementation of Generics

1. *Generic Subtyping Is Not Covariant.* For example: ArrayList<Manager> is not a subclass of ArrayList<Employee> (this is different from arrays: ArrayList<Employee> is a subclass of AbstractList<Employee>)

   Example: What if this type of covariance were allowed?

```
List<Integer> ints = new ArrayList<Integer>();
ints.add(1);
ints.add(2);
List<Number> nums = ints;  // compile-time error
nums.add(3.14);
assert ints.toString().equals("[1, 2, 3.14]");
```



Optional: (Requires strong mathematical background) The real meaning of “covariant”. A mathematical *category* is a collection of objects of the same type together with structure-preserving maps that map one object in the category to another. The *category of set*s has as its objects sets together with functions from one set to another. The collection Class of all classes (say Java classes) also forms a category; in this case, the “maps” between objects of this category are the arrows given by the subclass relation. Another category ClassArray is the collection of arrays having component type a Java class, like Employee[], Manager[], etc. Again the “maps” between these objects can be taken to be the subclass relation. The statement “array subtyping is covariant” means, technically speaking, that the transformation F: Class -> ClassArr defined by F(C) = C[ ] is *functorial*: If C is a subclass of D, then F(C) is a subclass of F(D). The transformation G: Class -> ParamList, given by G(C) = List<C> is *not* functorial according to the rules of Java generics.

2. *Component type of an array may not be a type variable*. For example, cannot create an array like this:

   T[] arr = new T[5];

   Example:

```
class Annoying {
  public static <T> T[] toArray(Collection<T> c) {
    T[] a = new T[c.size()];  // compile-time error
    int i=0; for (T x : c) a[i++] = x;
    return a;
  }
}
```

3. *Component type of an array may not be a parametrized type*. For example: you cannot create an array like this:

   List<String>[] = new List<String>[5];

   Example:

```
class AlsoAnnoying {
  public static List<Integer>[] twoLists() {
    List<Integer> a = Arrays.asList(1,2,3);
    List<Integer> b = Arrays.asList(4,5,6);
    return new List<Integer>[] {a, b};  // compile-time error
  }
}
```

The reason for rules (2) and (3) is that *the component type of an array must be a reifiable type.*

Consider the analogous situation with arrays: The following statement

```
new String[size]
```

allocates an array, and stores in that array an indication that its components are of type String. However, executing

```
new ArrayList<String>()
```

allocates a list, but does not store in the list any indication of the type of its elements. We say that Java *reifies* array component types but does not reify list element types (or other generic types). In the case of

```
new T[5]
```

there is no type information – we say a type variable is *not reifiable.*

Precise definition: A type is *reifiable* if the type is completely represented at run time — that is, if erasure does not remove any useful information.

Generic Methods

Generic methods are methods that introduce their own type parameters. This is similar to declaring a generic type, but the type parameter's scope is limited to the method where it is declared. Static and non-static generic methods are allowed, as well as generic class constructors.

The syntax for a generic method includes a type parameter, inside angle brackets, and appears before the method's return type. For static generic methods, the type parameter section must appear before the method's return type.

```
public static <K, V> boolean compare(SimplePair<K, V> p1, SimplePair<K, V> p2) {
    return p1.getKey().equals(p2.getKey()) &&
           p1.getValue().equals(p2.getValue());
}
```

The complete syntax for invoking this method would be:

```
SimplePair<Integer, String> p1 = new SimplePair<>(1, "apple");
SimplePair<Integer, String> p2 = new SimplePair<>(2, "pear");
boolean areTheySame = Util.<Integer, String>compare(p1, p2);
```

In this case, as in most cases, the generic type can be inferred by the compiler, and can be left out.

```
SimplePair<Integer, String> q1 = new SimplePair<>(1, "apple");
SimplePair<Integer, String> q2 = new SimplePair<>(2, "pear");
boolean areTheySame2 = Util.compare(q1, q2);
```

Two cases where generic type must be displayed:

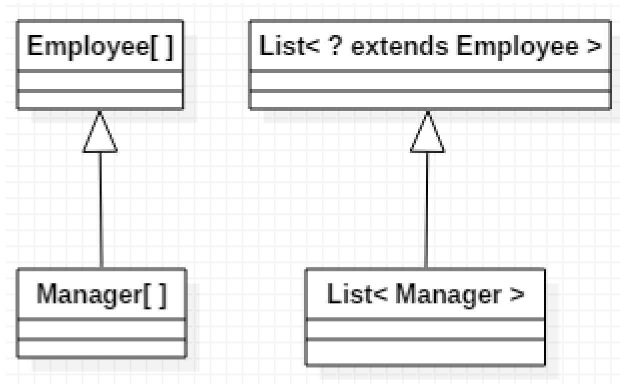
```
List<Integer> ints = Lists.<Integer>toList();
List<Object> objs = Lists.<Object>toList(1, "two");
```

In the first case, without the type parameter, there is too little information. In the second, the possible types would be ambiguous – could be Object, Serializable, or Comparable.

RULE: In a call to a generic method:
(1) if there are one or more arguments that correspond to a type parameter and they all have the same type then the type parameter may be inferred
(2) if either
   (a) there are no arguments that correspond to the type parameter, or
   (b) the arguments belong to different subtypes of the intended type
then the type parameter must be given explicitly

The `? extends` Bounded Wildcard

The fact that generic subtyping is not covariant – as in the example that `List<Manager>` is not a subtype of `List<Employee>` is inconvenient and unintuitive. This is remedied with the `extends` *bounded wildcard*.



The ? is a *wildcard* and the "bound" in `List<? extends Employee>` is the class `Employee`. `List<? extends Employee>` is a *parametrized type with a bound.*

For any subclass C of `Employee`, `List<C>` is a subclass of `List<? extends Employee>` .

So, even though the following gives a compiler error:

```
List<Manager>  list1 = //… populate with managers
List<Employee> list2 = list1;  //compiler error
```

the following does work:

```
List<Manager> list1 = //… populate with managers
List<? extends Employee> list2 = list1;  //compiles
```

(See demo lesson11.lecture.generics.extend)

Applications of the extends Wildcard

The Java Collection interface has an `addAll` method:

```
interface Collection<E> {
  ...
  public boolean addAll(Collection<? extends E> c);
  ...
}
```

The extends wildcard in the definition makes the following possible:

```
List<Employee> list1 = //….populate
List<Manager> list2 = //… populate
list1.addAll(list2);    //OK
```

____

If the interface had been defined like this:

```
interface Collection<E> {
     . . .
     public boolean addAll(Collection<E> c);
     . . .
}
```

it would mean for example that `addAll` could accept only a `Collection` of *Employees*:

List<Employee> list1 = //….populate
List<Employee> list2 = //…populate
list1.addAll(list2); //OK

BUT

List<Employee> list1 = //….populate
List<Manager> list2 = //…populate
list1.addAll(list2); **//compiler error**

Another Example Using addAll

```
List<Number> nums = new ArrayList<Number>();
List<Integer> ints = Arrays.asList(1, 2);
List<Double> dbls = Arrays.asList(2.78, 3.14);
nums.addAll(ints);
nums.addAll(dbls);
assert nums.toString().equals("[1, 2, 2.78, 3.14]");
```

Limitations of the extends Wildcard

When the extends wildcard is used to define a parametrized type, the type cannot be used for adding new elements.

Example:

Recall the addAll method from Collection:

```
interface Collection<E> {
  ...
  public boolean addAll(Collection<? extends E> c);
  ...
}
```

The following produces a compiler error:

```
List<Integer> ints = new ArrayList<Integer>();
ints.add(1);
ints.add(2);
List<? extends Number> nums = ints;
nums.add(3.14);  // compile-time error
assert ints.toString().equals("[1, 2, 3.14]");
```

The error arises because an attempt was made to insert a value in a parametrized type with extends wildcard parameter. With the extends wildcard, values can be *gotten* but not *inserted*.

The difficulty is that adding a value to nums makes a commitment to a certain type (Double in this case), whereas nums is defined to be a List that accepts subtypes of Number, but *which* subtype is not determined. The value 3.14 cannot be added because it might not be the right subtype of Number.

NOTE: Although it is not possible to *add* to a list whose type is specified with the extends wildcard, this does not mean that such a list is read-only. It is still possible to do the following operations available to any List:

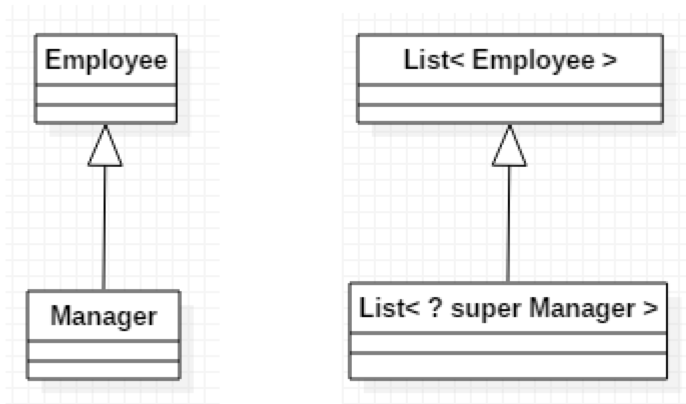
`remove, removeAll, retainAll`

and also execute the static methods from Collections:

`sort, binarySearch, swap, shuffle`

The ? `super` Bounded Wildcard

The type `List<? super Manager>` consists of objects of any supertype of the `Manager` class, so objects of type `Employee` and `Object` are allowed.



Example from the `Collections` class:

```
public static <T> void copy(List<? super T> dst, List<? extends T> src) {
  for (int i = 0; i < src.size(); i++) {
    dst.set(i, src.get(i));
  }
}
```

Typical use:

```
List<Object> objs = Arrays.<Object>asList(2, 3.14, "four");
List<Integer> ints = Arrays.asList(5, 6);
Collections.copy(objs, ints);
assert objs.toString().equals("[5, 6, four]");
```

Values can be read from (or "gotten" from) `src`, which is of type `List<? extends T>`, but then to insert values in the destination list `dst`, `dst` may not be typed using the extends wildcard. Instead, it is typed as `List<? super T>`. This means that any object whose type is a supertype of `T` may be placed in `dst`.

In the example, `src` is a `List<Integer>` and `dst` is a `List<Object>`. The type `T` is `Integer` and any supertype of `Integer` may be copied into `objs`.

The Get and Put Principle for Bounded Wildcards

The Get and Put Principle: use an `extends` wildcard when you only *get* values out of a structure, use a `super` wildcard when you only *put* values into a structure, and don't use a wildcard when you *both* get and put.

<u>Example</u>. This method takes a collection of numbers, converts each to a double,and sums them up:

```
public static double sum(Collection<? extends Number> nums) {
  double s = 0.0;
  for (Number num : nums) s += num.doubleValue();
  return s;
}
```

Since this uses `extends`, all of the following calls are legal:

```
List<Integer> ints = Arrays.asList(1,2,3);
assert sum(ints) == 6.0;

List<Double> doubles = Arrays.asList(2.78,3.14);
assert sum(doubles) == 5.92;

List<Number> nums = Arrays.<Number>asList(1,2,2.78,3.14);
assert sum(nums) == 8.92;
```

The first two calls would not be legal if `extends` was not used.

Whenever you use the `add` method for a `Collection`, you are inserting values, and so `? super` must be used.

Example:

```
public static void count(Collection<? super Integer> ints, int n) {
    for(int i = 0; i < n; ++i) {
        ints.add(i);
    }
}
```

Since `super` was used, the following are legal:

```
List<Integer> ints1 = new ArrayList<>();
count(ints1, 5);
System.out.println(ints1); //output: [0,1,2,3,4]

List<Number> ints2 = new ArrayList<>();
count(ints2, 5);
ints2.add(5.0);
System.out.println(ints2); //output: [0,1,2,3,4, 5.0]

List<Object> ints3 = new ArrayList<>();
count(ints3, 5);
ints3.add("five");
System.out.println(ints3); //output: [0,1,2,3,4, five]
```

The last two calls would not be legal without the use of the `? super` wildcard.

Whenever you both put values into and get values out of the same structure, you should not use a wildcard.

```
public static double sumCount(Collection<Number> nums, int n) {
  count(nums, n);
  return sum(nums);
}
```

The collection is passed to both `sum` and `count`, so its element type must both extend `Number` (as `sum` requires) and be super to `Integer` (as `count` requires). The only two classes that satisfy both of these constraints are `Number` and `Integer`, and we have picked the first of these. Here is a sample call:

```
List<Number> nums = new ArrayList<Number>();
double sum = sumCount(nums,5);
assert sum == 10;
```

Since there is no wildcard, the argument must be a collection of `Number`.

.Two Exceptions to the Get and Put Rule

1. In a Collection that uses the extends wildcard, null can always be added legally (null is the “ultimate” subtype)

```
List<Integer> ints = new ArrayList<Integer>();
ints.add(1);
ints.add(2);
List<? extends Number> nums = ints;
nums.add(null);  // ok
assert nums.toString().equals("[1, 2, null]");
```

2. In a Collection that uses the super wildcard, any object of type Object can be read legally (Object is the “ultimate” supertype).

```
List<Object> objs = Arrays.<Object>asList(1,"two");
List<? super Integer> ints = objs;
String str = "";
for (Object obj : ints) str += obj.toString();
assert str.equals("1two");
```

Unbounded Wildcard, Wildcard Capture, Helper Methods

1. The wildcard ?, without the super or extends qualifier, is called the *unbounded wildcard.*
2. `Collection<?>` is an abbreviation for `Collection<? extends Object>`
3. Important application of the unbounded wildcard involves *wildcard capture:*

Example: Try to copy the 0^{th} element of a general list to the end of the list

First Try:

```
public void copyFirstToEnd(List<?> items) {
    items.add(items.get(0)); //compiler error
}
```

Compiler error arises because we are trying to add to a List whose type involves the extends wildcard.

Solution: Write a helper method that *captures the wildcard.*

```
public void copyFirstToEnd2(List<?> items) {
    copyFirstToEndHelper(items);
}

private <T> void copyFirstToEndHelper(List<T> items) {
    T item = items.get(0);
    items.add(item);
}
```

Notes:

A. Passing `items` into the helper method causes the unknown type ? to be “captured” as the type `T`.
B. In the helper method, getting and setting values is legal because we are not dealing with wildcards in that method.

Generic Programming Using Generics

Generic programming is the technique of implementing a procedure so that it can accommodate the broadest possible range of inputs.

For instance, consider implementation of a max function. It is not desirable to have a different max function for Integer, String, Double, etc. Generic programming , in this case, would create a max function that could handle every possible type for which the concept "max" makes sense.

See demo lecture.generics.BoundedTypeVariable for examples.