301AA - Advanced Programming [AP-2017]

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AP-2018-15: *Java Generics*

301AA - Advanced Programming

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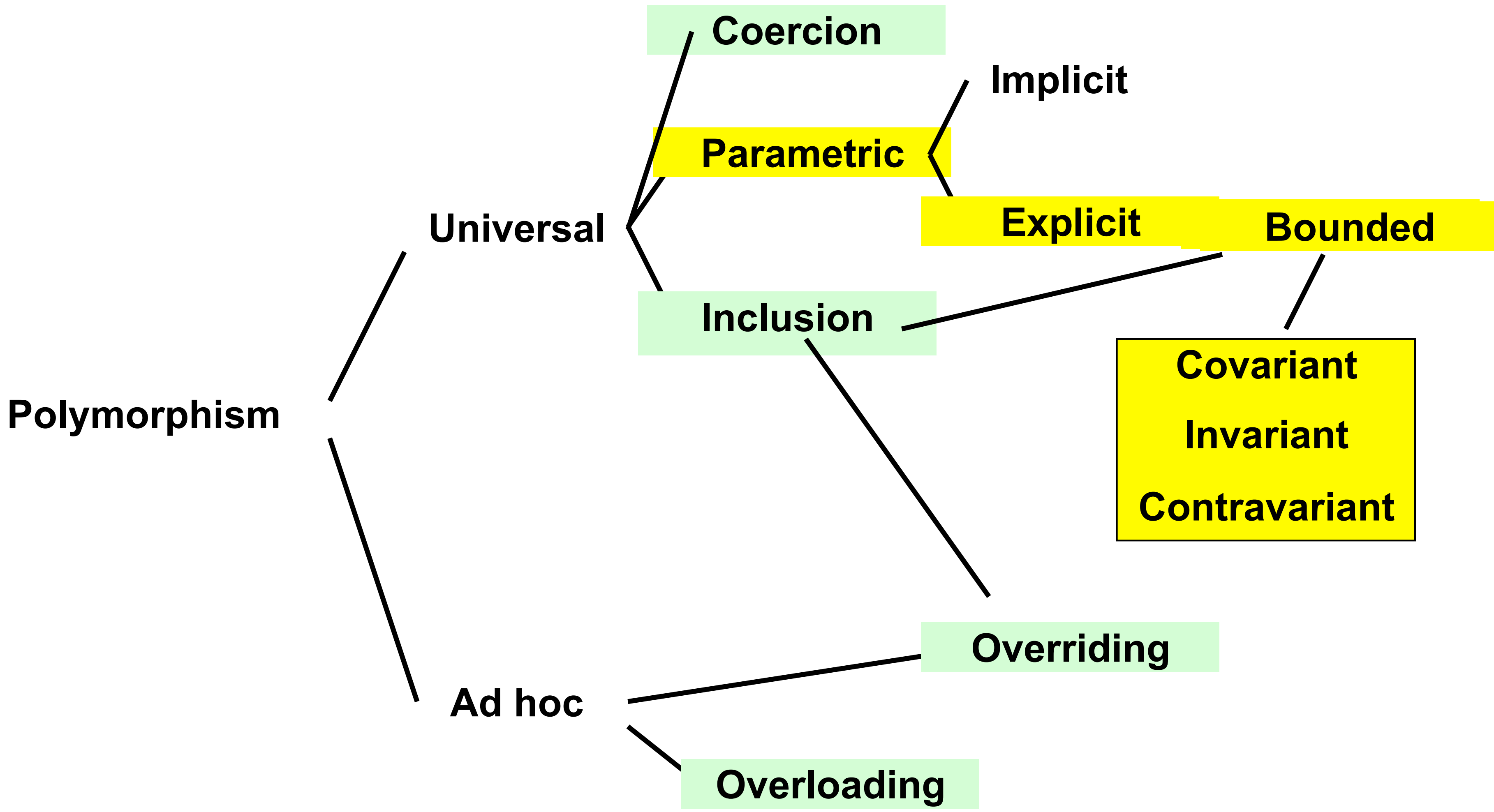
http://pages.di.unipi.it/corradini/Didattica/AP-18/

AP-2018-15*:* *Java Generics*

Outline

- Java generics
- Type bounds
- Generics and subtyping
- Covariance, contravariance in Java and other languages
- Subtyping and arrays in Java
- Wildcards
- Type erasure
- Limitations of generics

Classification of Polymorphism



Java Generics

Explicit Parametric Polymorphism

- Classes, Interfaces, Methods can have type parameters
- The type parameters can be used arbitrarily in the definition
- They can be instantiated by providing arbitrary (reference) type arguments
- We discuss only a few issues about Java generics…

```
interface List<E> {
  boolean add(E n);
  E get(int index);
}
```

```
List<Integer>
List<Number>
List<String>
List<List<String>>
…
```

Tutorials on Java generics:

https://docs.oracle.com/javase/tutorial/java/generics/index.html

http://thegreyblog.blogspot.it/2011/03/java-generics-tutorial-part-i-basics.html

Generic methods

- Methods can use the type parameters of the class where they are defined, if any
- They can also introduce their own type parameters

```
public static <T> T getFirst(List<T> list)
```

- Invocations of generic methods must instantiate all type parameters, either explicitly or implicitly
  - A form of **type inference**

Bounded Type Parameters

```
interface List<E extends Number> {
  void m(E arg) {
    arg.asInt();  // OK, Number and its subtypes
                  // support asInt()
  }
}
```

- Only classes implementing **Number** can be used as type arguments
- Method defined in the bound (**Number**) can be invoked on objects of the type parameter

Type Bounds

`<TypeVar extends SuperType>`

- *upper bound*; SuperType and any of its subtype are ok.

`<TypeVar extends ClassA & InterfaceB & InterfaceC & …>`

- *Multiple* upper bounds

`<TypeVar super SubType>`

- *lower bound*; SubType and any of its supertype are ok

- Type bounds for methods guarantee that the type argument supports the operations used in the method body
- Unlike C++ where overloading is resolved and can fail after instantiating a template, in Java type checking ensures that overloading will succeed

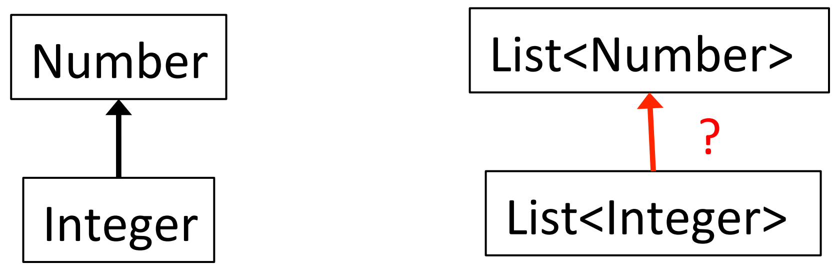
A generic algorithm with type bounds

```
public static <T> int countGreaterThan(T[] anArray, T elem) {
    int count = 0;
    for (T e : anArray)
        if (e > elem)  // compiler error
            ++count;
    return count;
}
```

```
public interface Comparable<T> {  // classes implementing
    public int compareTo(T o);    // Comparable provide a
}       // default way to compare their objects
```

```
public static <T extends Comparable<T>>
               int countGreaterThan(T[] anArray, T elem) {
    int count = 0;
    for (T e : anArray)
        if (e.compareTo(elem) > 0)    // ok, it compiles
            ++count;
    return count;
}
```

Generics and subtyping



- **Integer** is subtype of **Number**
- Is **List<Integer>** subtype of **List<Number>**?
- NO!

What are Java rules?

- Given two concrete types **A** and **B**, **MyClass<A>** has **no relationship** to **MyClass<B>**, regardless of whether or not **A** and **B** are related.
- Formally: subtyping in Java is **invariant** for generic classes.
- Note: The common parent of **MyClass<A>** and **MyClass<B>** is **MyClass<?>**: the "wildcard" **?** Will be discussed later.
- On the other hand, as expected, if **A** extends **B** and they are generic classes, for each type **C** we have that **A<C>** extends **B<C>**.
- Thus, for example, **`ArrayList<Integer>`** is subtype of **`List<Integer>`**

List<Number> e List<Integer>

```
interface List<T> {
  boolean add(T elt);
  T get(int index);
}
```

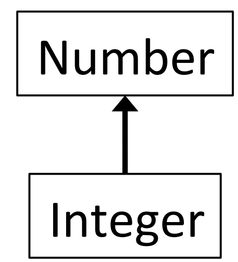
```
List<Integer> lisInt = new …;
List<Number> lisNum = new …;
lisNum = lisInt;         // ???
lisNum.add(new Number(…));//no
listInt = lisNum;        // ???
Integer n = lisInt.get(0); //no
```

type **List<Number>** has:

```
  boolean add(Number elt);
  Number get(int index);
```

type **List<Integer>** has:

```
  boolean add(Integer elt);
  Integer get(int index);
```

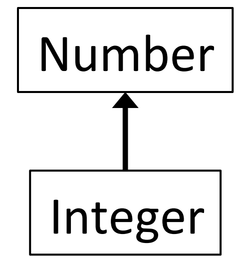


Is the **Substitution Principle** satisfied in either direction?

Thus **List<Number>** is neither a supertype nor a subtype of **List<Integer>**: Java rules are adequate here

But in more specific situations…

```
interface List<T> {
  T get(int index);
}
```



type **List<Number>**:

```
  Number get(int index);
```

type **List<Integer>**:

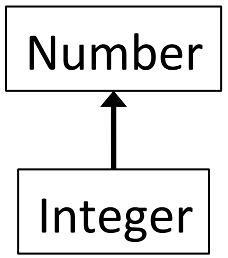
```
  Integer get(int index);
```

A ***covariant*** **notion of subtyping would be safe**:

- **List<Integer>** can be subtype of **List<Number>**
- Not in Java

- In general: **covariance** is safe if the type is **read-only**

Viceversa… contravariance!




```
interface List<T> {
  boolean add(T elt);
}
```

type `List<Number>`:

```
  boolean add(Number elt);
```

type `List<Integer>`:

```
  boolean add(Integer elt);
```

A ***contravariant*** **notion of subtyping would be safe**:

- `List<Number>` can be a subtype of `List<Integer>`
- But Java …..

In general: **contravariance** is safe if the type is **write-only**

Generics and subtypes in C#

- In C#, the type parameter of a generic class can be annotated **out** (covariant) or **in** (contravariant), otherwise it is invariant. Examples:
- **Ienumerator** is covariant, because the only method returns an enumerator, which accesses the collection in read-only

```
public interface IEnumerable<out T> : […] {
   public […]IEnumerator<out T> GetEnumerator ();
}
```

- **IComparable** is contravariant, because the only method has an argument of type **T**

```
public interface IComparable<in T> {
   public int CompareTo (T other);
}
```

Co- and Contra-variance in Scala

- Also Scala supports co/contra-variance annotations (**–** and **+**) for type parameters:

```
class VendingMachine[+A]{…}

class GarbageCan[-A]{…}

trait Function1[-T, +R] extends AnyRef
{ def apply(v1: T): R }
```

http://blog.kamkor.me/Covariance-And-Contravariance-In-Scala/

A digression: Java arrays

- Arrays are like built-in containers
  - Let **`Type1`** be a subtype of **`Type2`**.
  - How are **`Type1[]`** e **`Type2[]`** related?
- Consider the following generic class, mimicking arrays:

```
class Array<T> {
   public T get(int i) { … "op" … }
   public T set(T newVal, int i) { … "op" … }
}
```

According with Java rules, **Array<Type1>** and **Array<Type2>** are not related by subtyping

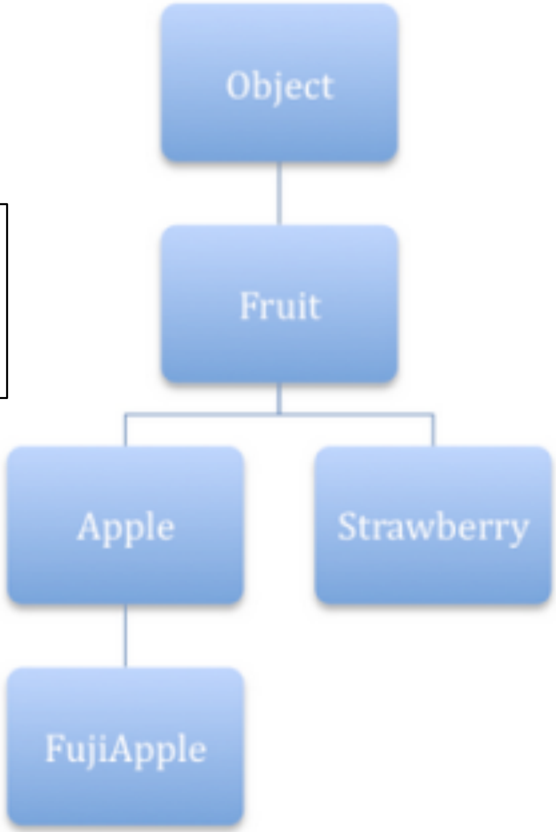
But instead...

- In Java, if **`Type1`** is a subtype of **`Type2`**, then **`Type1[]`** is a subtype of **`Type2[]`**. Thus Java arrays are covariant.
- Java (and also C#, .NET) fixed this rule before the introduction of generics.
- Why? Think to `void sort(Object[] o);`
- Without covariance, a new sort method is needed for each reference type different from Object!
- But sorting does not insert new objects in the array, thus it cannot cause type errors if used covariantly

Problems with array covariance

Even if it works for `sort`, covariance may cause type errors in general

```
Apple[] apples = new Apple[1];
Fruit[] fruits = apples; //ok, covariance
fruits[0] = new Strawberry(); // compiles!
```



This breaks the general Java rule: For each reference variable, the **dynamic type** (type of the object referred by it) must be a **subtype** of the **static one** (type of declaration).

Java's design choices

```
(1) Apple[] apples = new Apple[1];
(2) Fruit[] fruits = apples; //ok, covariance
(3) fruits[0] = new Strawberry(); // compiles!
```

- The dynamic type of an array is known at runtime
  - During execution the JVM knows that the array bound to **fruits** is of type `Apple[]` (or better `[LApple;` in JVM type syntax)
- Every array update includes a **run-time check**
- Assigning to an array element an object of a non-compatible type throws an `ArrayStoreException`
  - Line (3) above throws an exception

Recalling "Type erasure"

All type parameters of generic types are transformed to **Object** or **to their first bound** after compilation

- Main Reason: backward compatibility with legacy code
- Thus at run-time, all the instances of the same generic type have the same type

```
List<String>  lst1 = new ArrayList<String>();
List<Integer> lst2 = new ArrayList<Integer>();
lst1.getClass() == lst2.getClass()  // true
```

Array covariance and generics

- Every Java array-update includes run-time check, but
- Generic types are not present at runtime due to ***type erasure***, thus
- **Arrays of generics are not supported in Java**
- In fact they would cause type errors not detectable at runtime, **breaking Java strong type safety**

```
List<String>[] lsa = new List<String>[10]; // illegal
Object[] oa = lsa;   // OK by covariance of arrays
List<Integer> li = new ArrayList<Integer>();
li.add(new Integer(3));
oa[0] = li;  // should throw ArrayStoreExeception,
   // but JVM only sees "oa[0]:List = li:ArrayList"
String s = lsa[0].get(0); // type error !!
```

Wildcards for covariance

- Invariance of generic classes is restrictive
- Wildcards can alleviate the problem
- What is a "general enough" type for **addAll**?

```
interface Set<E> {
  // Adds to this all elements of c
  // (not already in this)
  void addAll(??? c);
}
```

- `void addAll(Set<E> c) //` and **List<E>**?
- `void addAll(Collection<E> c)`
  `//` and collections of `T <: E`?
- `void addAll(Collection<? extends E> c); // ok`

Wildcards, for both co- and contra-variance

- wildcard = anonymous variable
  - `?` Unknown type
  - Wildcard are used when a type is used exactly once, and the name is unknown
  - They are used for **use-site variance** (not **declaration-site** variance)
- Syntax of wildcards:
  - `? extends Type`, denotes an unknown subtype of `Type`
  - `?`, shorthand for `? extends Object`
  - `? super Type`, denotes an unknown supertype of `Type`

The “PECS principle”: Producer Extends, Consumer Super

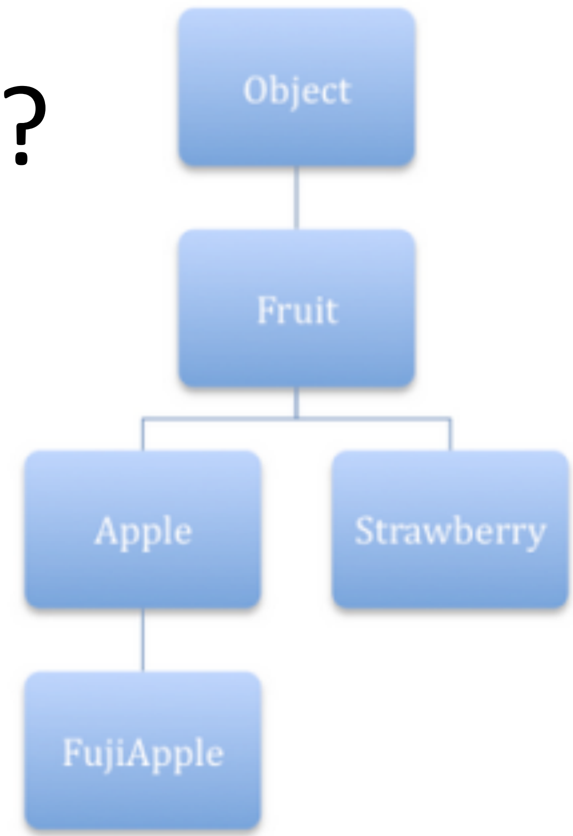
When should wildcards be used?

- Use `? extends T` when you want to get values (from a producer): supports **covariance**
- Use `? super T` when you want to insert values (in a consumer): supports **contravariance**
- Do not use `?` (`T` is enough) when you both obtain and produce values.

Example:

```
<T> void copy(List<? super T> dst,
              List<? extends T> src);
```

What about type safety?



- Arrays covariance:

```
Apple[] apples = new Apple[1];
Fruit[] fruits = apples;
fruits[0] = new Strawberry();
 // JVM throws ArrayStoreException
```

- Covariance with wildcards:

```
List<Apple> apples = new ArrayList<Apple>();
List<? extends Fruit> fruits = apples;
fruits.add(new Strawberry());
    // compile-time error!!!
```

The price to pay with wildcards

- A wildcard type is anonymous/unknown, and almost nothing can be done:

```
List<Apple> apples = new ArrayList<Apple>();
List<? extends Fruit> fruits = apples; //covariance
fruits.add(new Strawberry()); // compile-time error!  OK
Fruits f = fruits.get(0); // OK
fruits.add(new Apple()); // compile-time error???
fruits.add(null); //ok, the only thing you can add  ☹
```

```
List<Fruit> fruits = new ArrayList<Fruits>();
List<? super Apples> apples = fruits; //contravariance
apples.add(new Apple()); // OK
apples.add(new FujiApple()); // OK
apples.add(new Fruit()); // compile-time error, OK
Fruits f = apples.get(0); // compile-time error???
Object o = apples.get(0); //ok, the only way to get
```

Limitations of Java Generics

Mostly due to "Type Erasure":

- Cannot Instantiate Generic Types with Primitive Types

```
ArrayList<int> a = …  //does not compile
```

- Cannot Create Instances of Type Parameters
- Cannot Declare Static Fields Whose Types are Type Parameters

```
public class C<T>{ public static T local; …}
```

- Cannot Use **casts** or **instanceof** With Parameterized Types

```
(list instanceof ArrayList<Integer>) // does not compile
(list instanceof ArrayList<?>) // ok
```

- Cannot Create Arrays of Parameterized Types
- Cannot Create, Catch, or Throw Objects of Parameterized Types
- Cannot Overload a Method Where the Formal Parameter Types of Each Overload Erase to the Same Raw Type

```
public class Example { // does not copile
public void print(Set<String> strSet) { }
public void print(Set<Integer> intSet) { } }
```