

301AA - Advanced Programming

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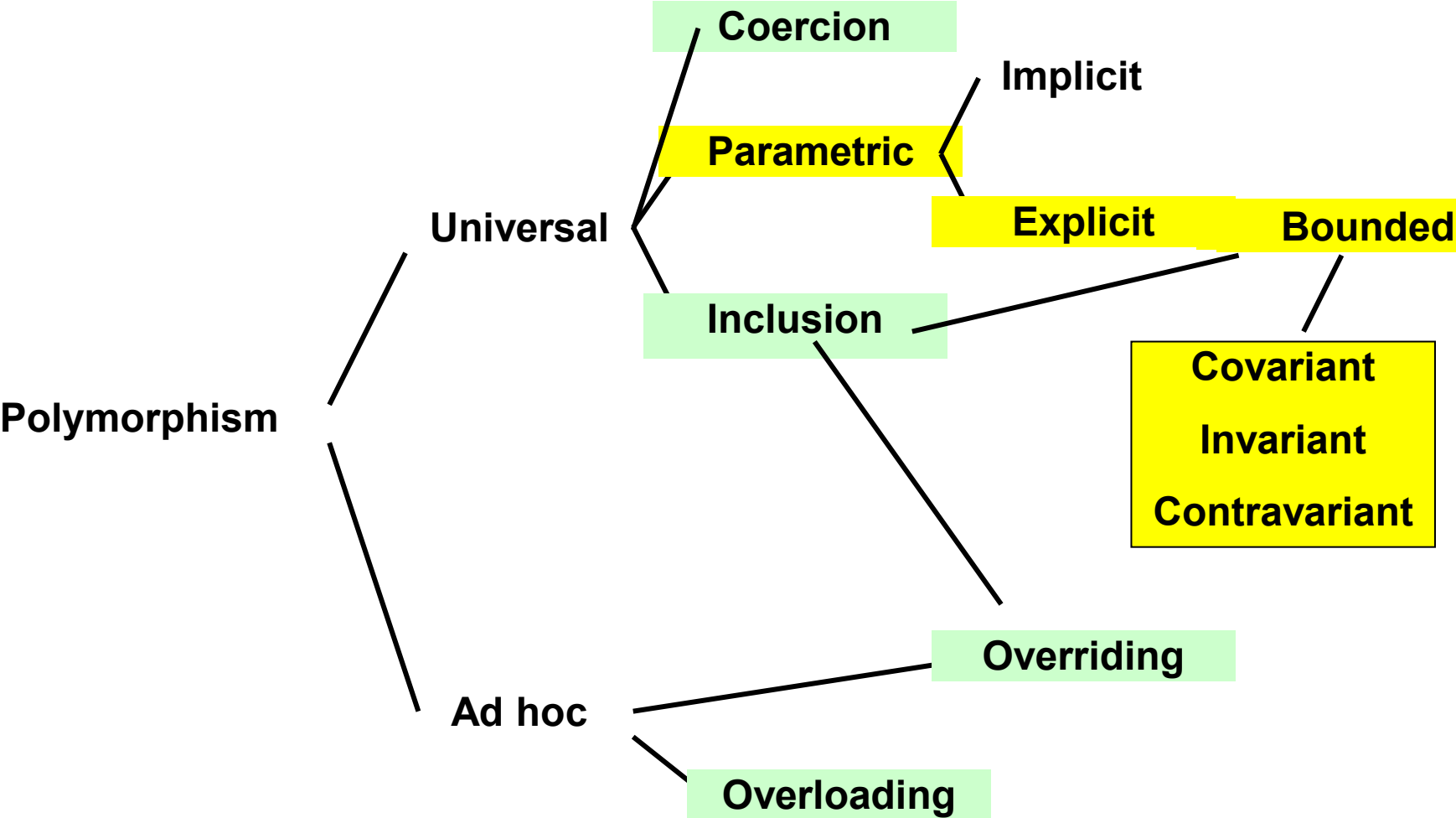
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AP-11: *Java Generics*

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](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

```
class NumList<E extends Number> {  
    void m(E arg) {  
        arg.intValue(); // OK, Number and its  
                        // subtypes support intValue()  
    }  
}
```

- 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;  
}
```

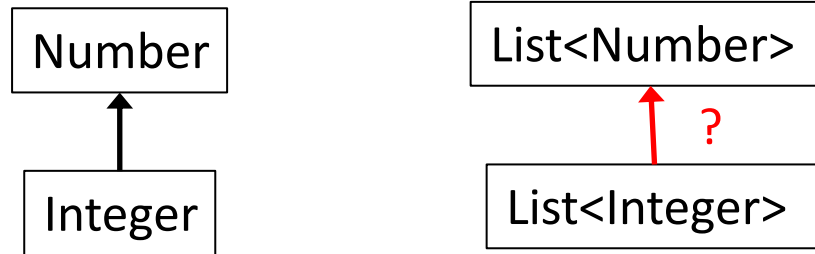
```
public interface Comparable<T> { // classes implementing  
    public int compareTo(T o); // Comparable provide a  
} // default way to compare their objects
```

```
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 other language features

- Introduction of generics in Java 5 has been pervasive
 - All the API were “generified”
 - Backward compatibility thanks to “type erasure”
- Generics are compatible with most language features, but not all.
- We discuss the problems caused by the introduction of generics with respect two important aspects of Java (and other languages):
 - Inheritance (subtyping)
 - Arrays

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**, 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** 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>**

```
void sort(List<Number> l) {  
    // efficient sorting for numbers  
}  
  
...  
List<Integer> lisInt = new ArrayList<Integer>(;  
// initialize the list of integers  
sort(lisInt);    // does not compile
```

List<Number> e List<Integer>

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

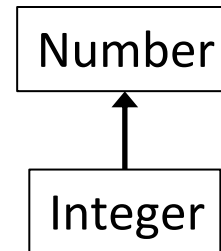
```
List<Integer> lisInt = new ...;  
List<Number> lisNum = new ...;  
lisNum = lisInt; // ???  
lisNum.add(new Number(...)); //no  
lisInt = lisNum; // ???  
Integer n = lisInt.get(0); //no
```

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

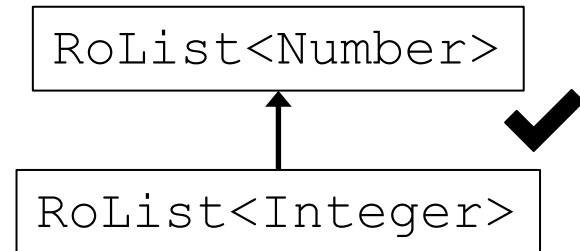
But in more specific situations...

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

```
RoList<Integer> lisInt = new ...;  
RoList<Number> lisNum = new ...;  
lisNum = lisInt; // ???  
Number n = lisNum.get(0); //ok
```

```
type RoList<Number>:  
    Number get(int index);
```

```
type RoList<Integer>:  
    Integer get(int index);
```



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

- **RoList<Integer>** can be subtype of **RoList<Number>**
- Not in Java
- In general: **covariance** is safe if the type is **read-only**

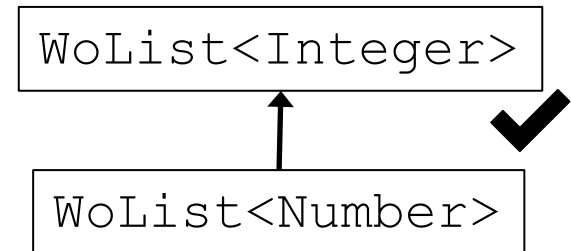
Viceversa... contravariance!

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

```
WoList<Integer> lisInt = new ...;  
WoList<Number> lisNum = new ...;  
lisInt = lisNum; // ???  
lisInt.add(new Integer(...)); //ok
```

```
type WoList<Number>:  
    boolean add(Number elt);
```

```
type WoList<Integer>:  
    boolean add(Integer elt);
```



A *contravariant* notion of subtyping would be safe:

- `WoList<Number>` can be a subtype of `WoList<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/>

Arrays and generics

- 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) { ... }  
    public T set(T newVal, int i) { ... }  
}
```

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

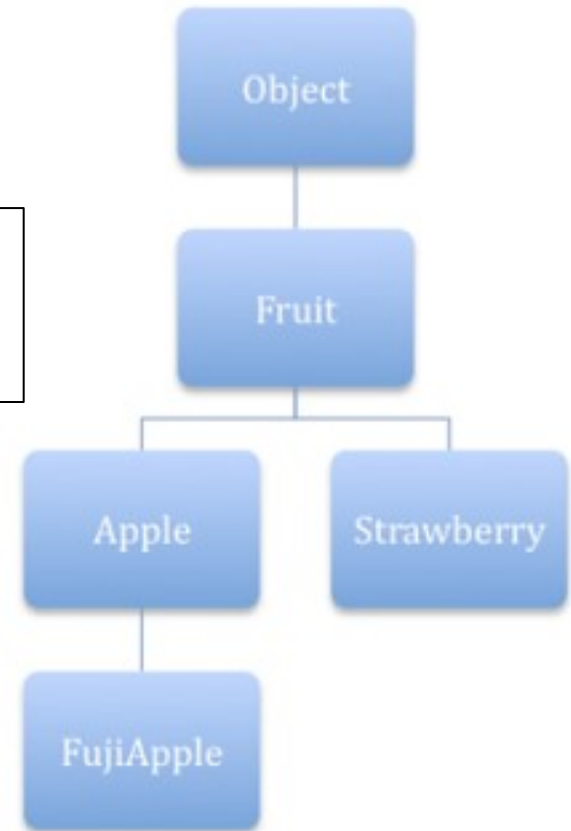
```
void sort (Object [] o) ;
```
- Without **covariance**, a new sort method is needed for each reference type different from Object!
- But sorting does not insert new objects in the array, thus it cannot cause type errors if used covariantly

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

Let's check on godbolt.org...

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 ArrayStoreException,
// 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);
```

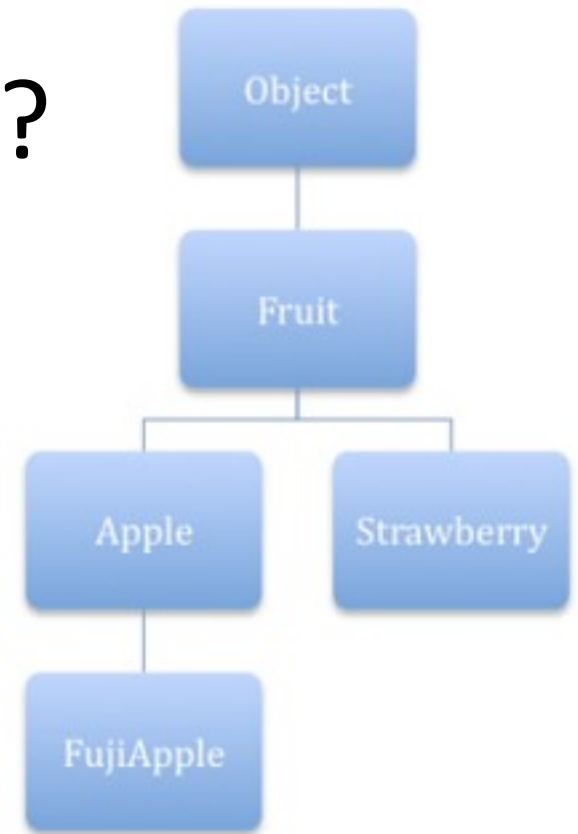
What about type safety?

- 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 compile
```

```
public void print(Set<String> strSet) { }
```

```
public void print(Set<Integer> intSet) { } }
```