Covariance and contravariance of parameterized types

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Definition

- **A generic type is a type with formal type parameters. A parameterized type is an instantiation of a generic type with actual type arguments.**

[Angelika Langer – Java Generics FAQs]

- **Also called parametric polymorphism**

Generic type	Parameterized type

`// E is the (formal) type parameter`
 	
`interface List<E> {`
`  public void add(E e);`
`  E get(int I);`
`  //...`
`}`
	`// String is the type argument (or Actual type parameter)`
	
	`List<String>`

Raw type = List

Generic purpose

- **Objects handling**
  - Collection API
  - WeakReference, SoftReference…
- **Type safety**
  - Early error detection and avoid cast exception without visible cast

```
List<String> myList = new ArrayList<>();
myList.add(“aString”);
String str = myList.get(0);  // Hidden cast to String
```

Generic type creation

```
Class MyGenericType<T, U> { // At least one parameter
    private T t;
    private U u;

    public MyGeneric(T t, U u) {
        this.t = t;
        this.u = u;
    }
    public T getT() {return t;}
    public U getU() {return u;}
    // ...
}


MyGenericType<String, Double> mgt = new MyGenericType<>(“a”,  1.0);
```

- Not possible with anonymous class, exceptions or enum. Not usable to define arrays.
- Primitive types not usable with generics

Bounded type parameter

- **Restrict the type of a parameter type**

```
class MyType<T extends Number> { // T is a bounded type parameter
    T t;
    int getNearestInt() {
       return t.intValue();  // Can use “t” as a Number
    }
}

MyType<Double> d = new MyType<>();

MyType<Integer> i = new MyType<>();

MyType<String> s = new MyType<>(); // Error
```

- **Multiple bounds allowed**

```
<T extends A & B & C & ...>

ComparableCollectionBox<T, C extends Collection<T> & Comparable<C>> {
    //…
}
```

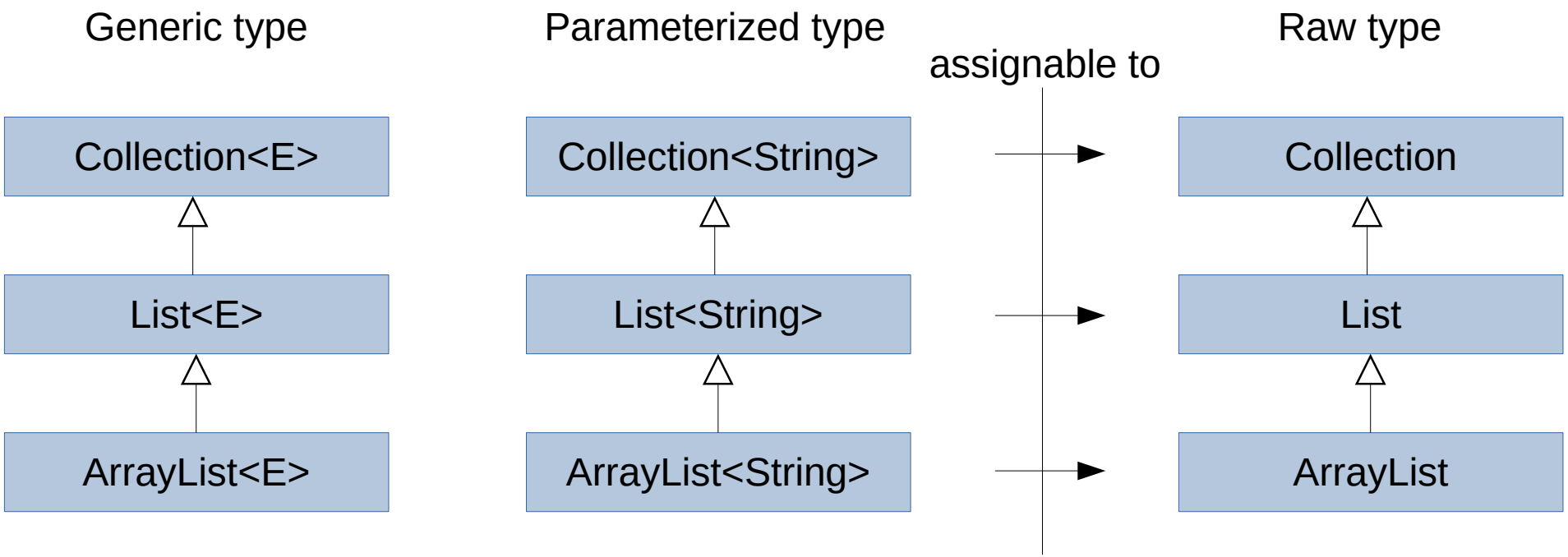
Type erasure

- **Type erasure**
  - Less type information on runtime than compile time
- **Reification**
  - Same type information on runtime than compile time

Reified type	(Generic) Type erasure

`// .Upcast done on compile time`
`Object o = new String(“”);`
 	
`// .Type information available on`
`// runtime (o.getClass())`
`// .Downcast done at runtime`
`String s = (String) o;`
	`// .Upcast done on compile time`
	`Object o = new ArrayList<String>();`
	
	`// .Generic type argument information`
	`// NOT available on runtime`
	`// .Downcast only done at runtime`
	`// towards RAW type`
	`List l = (List) o;`
	
	`// .Downcast not fully checked`
	`List<String> ls = (List<String>) o;`

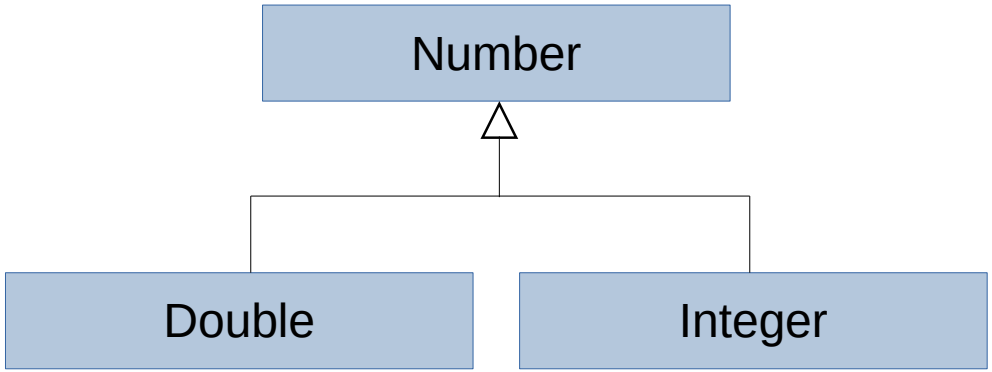
Inheritance and parameterized type (1/4)

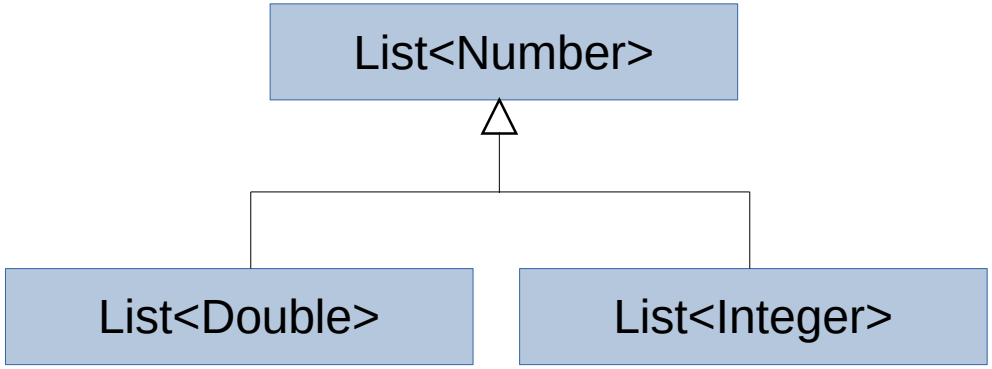


// Safe but not safely reversible

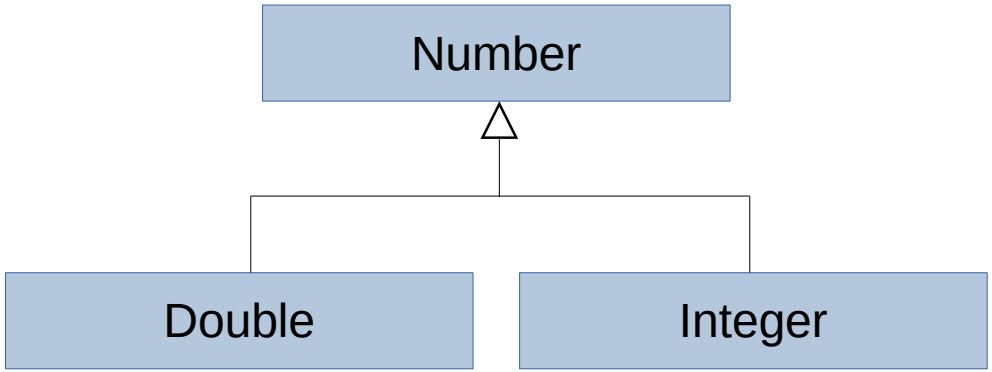
```
List<String> stringList;
@SuppressWarnings("rawtypes")
List rawList = stringList;
```

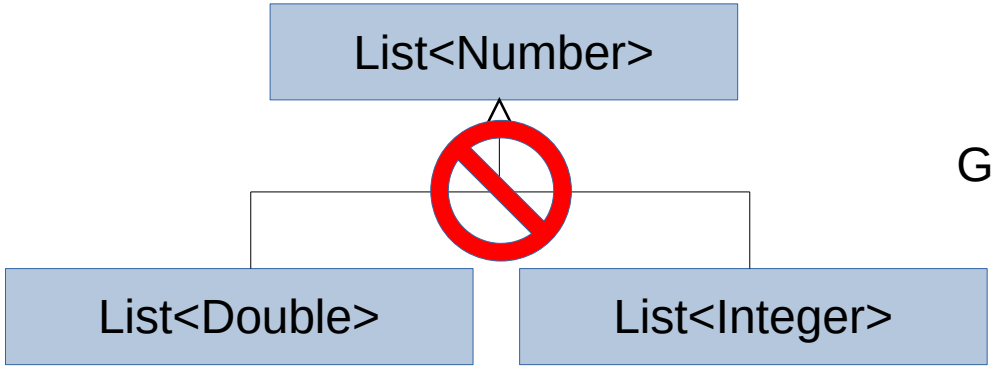
Inheritance and parameterized type (2/4)





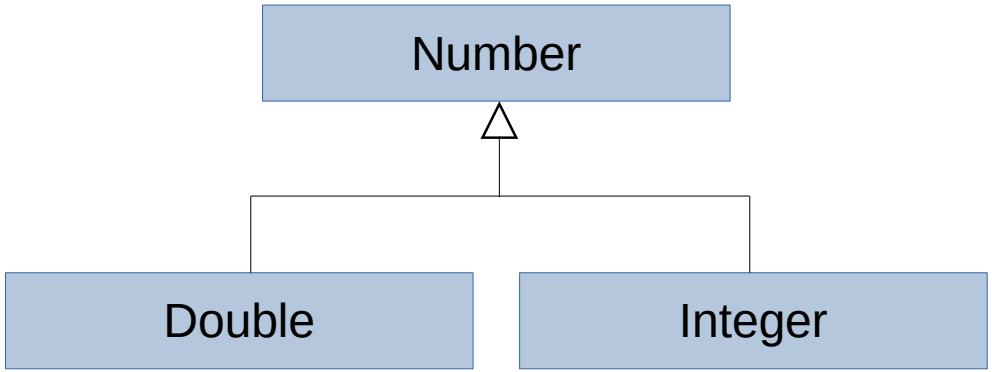
Inheritance and parameterized type (2/4)

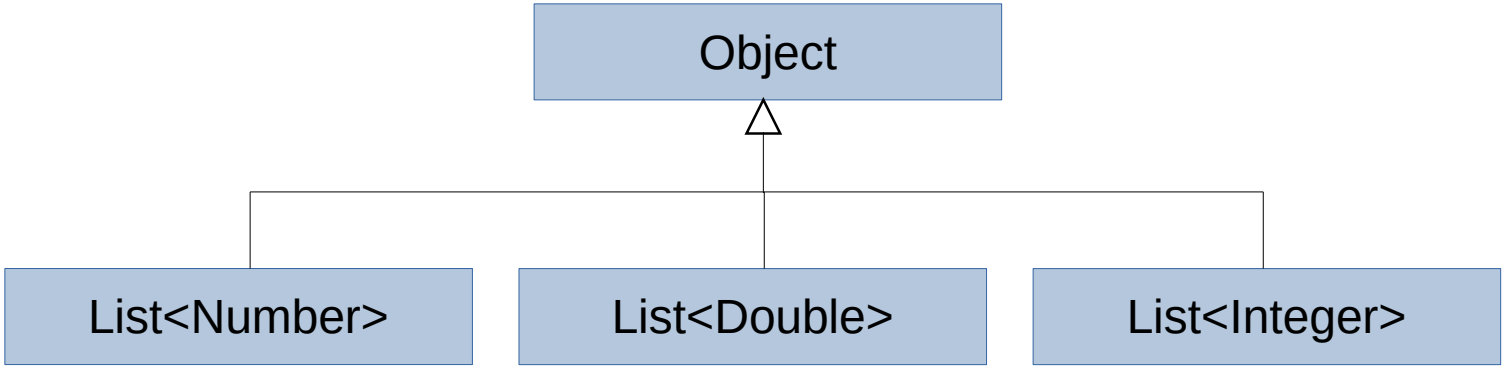




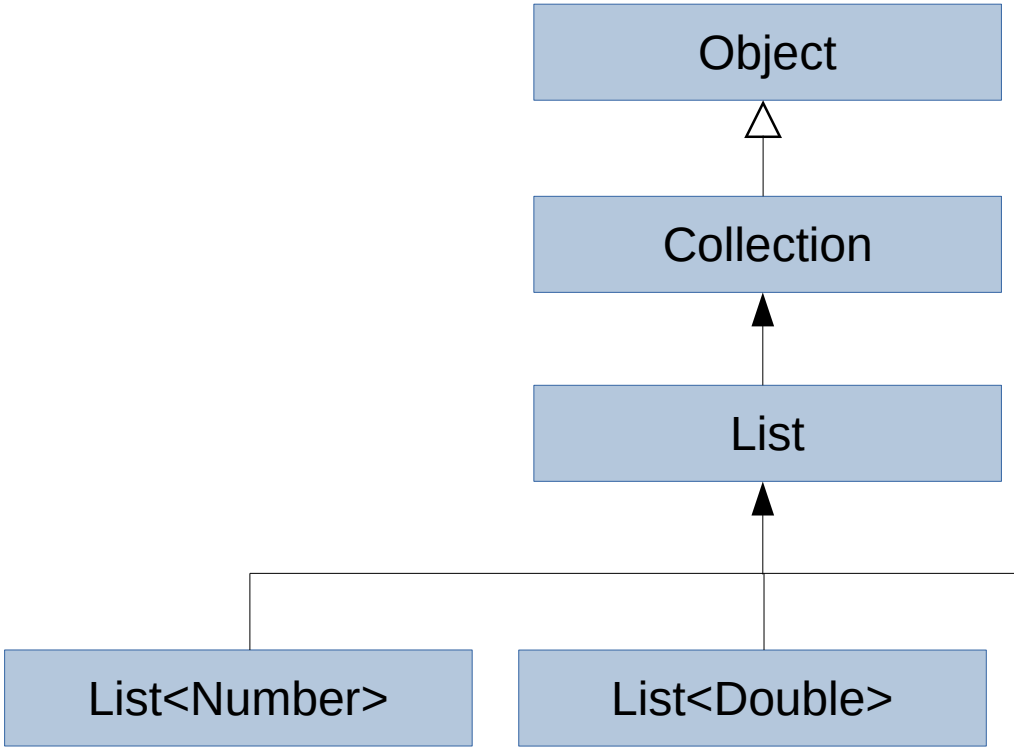
Generics are invariant

Inheritance and parameterized type (3/4)





Inheritance and parameterized type (4/4)



Assignable (upcast) but not safely downcastable

Loose type safety

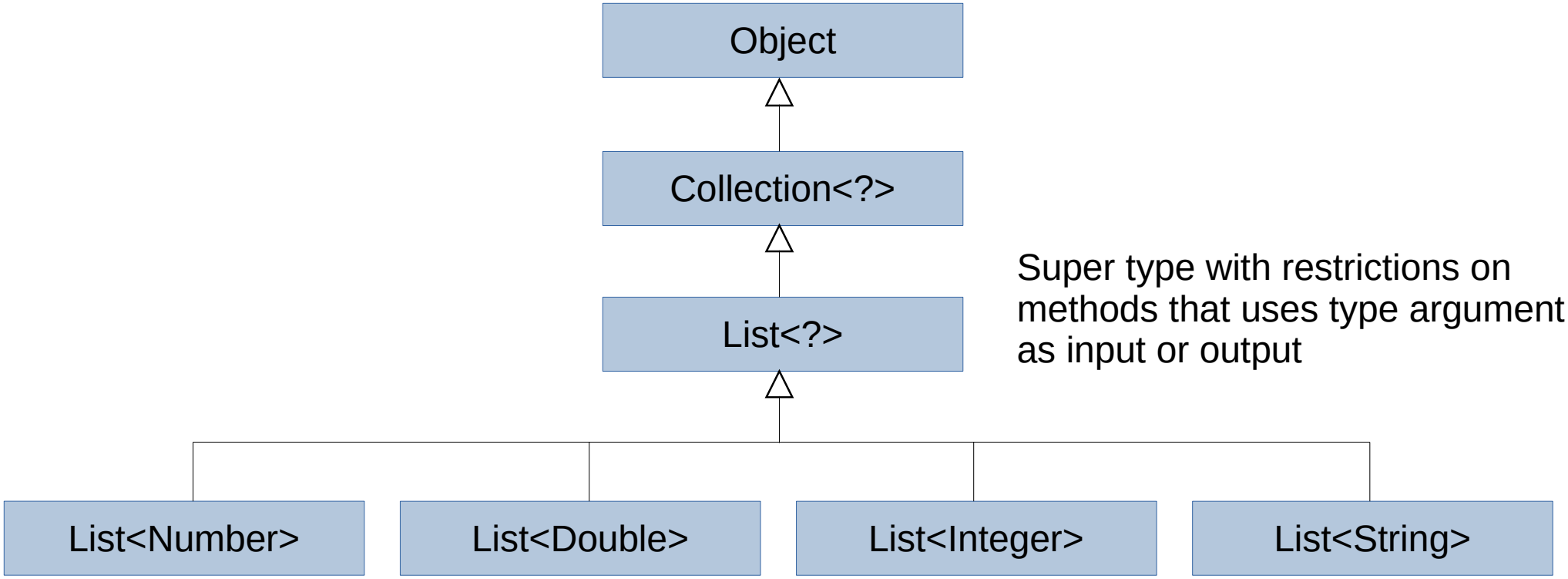
Wildcard

- **“?” is a special type parameter that ensure/control type safety of the use of generic/parameterized type.**
  - Different instantiations of generic type (List<String>, List<Double>, List<Number>) are never compatible. No inheritance relationship.
  - Wildcard “?” allows a certain amount of compatibility between various generic type instantiations.
    - Kind of inheritance with restrictions.
    - Definition of an abstract super type for any parameterized type of a given generic type.

A difficult topic

- **Joshua Bloch criticized wildcard as being too hard to understand and use.**
- **Scala (language on JVM) first uses declaration-site (“concurrent of wildcard”).**
  - Martin Odersky adds wildcard (used-site) only for Java compatibility.

Inheritance and super type with wildcard

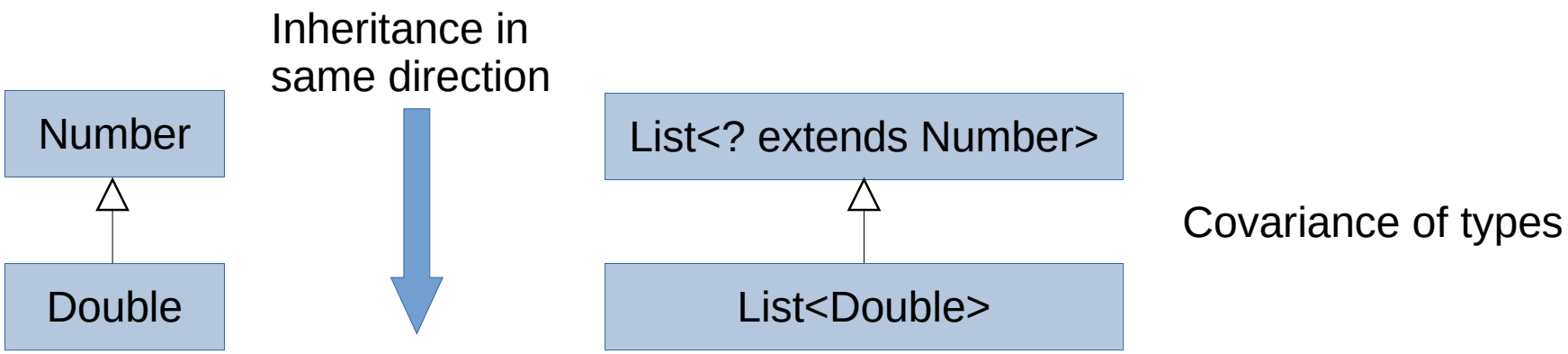


Super type with restrictions on methods that uses type argument as input or output

```
List<?> list = new ArrayList<Double>();

list.add(null);
list.add(5.0); // Error

Object x = list.get(0); // Only get Object
```

```
// Methods that does not use type argument (Double)
// Wildcard super types are less capable

list.remove(3);
list.clear();
int size = list.size();
```

Wildcard with upper bound

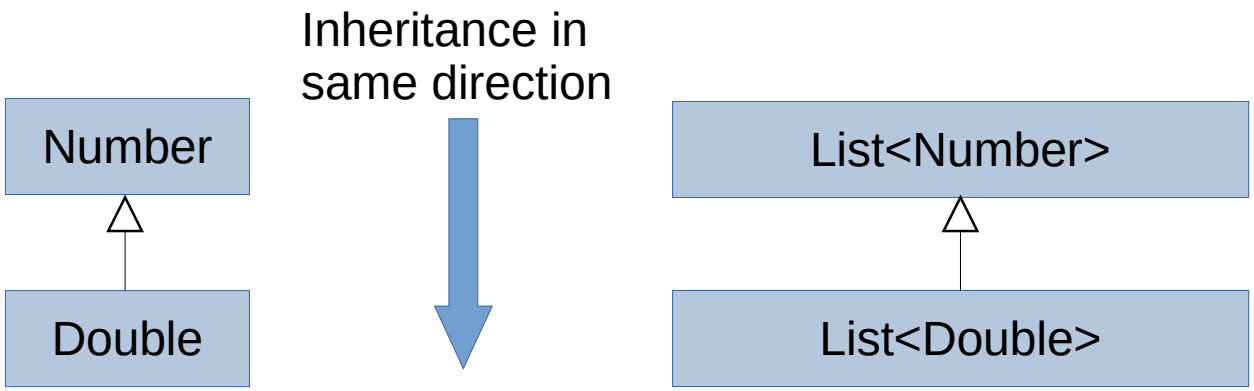


Covariance of types

```
List<? Extends Number> list = new ArrayList<Double>();

list.add(null);
list.add(5.0); // Error still not usable

Number x = list.get(0); // Known as Number
```

```
// Methods that are still usable

list.remove(3);
list.clear();
int size = list.size();
```

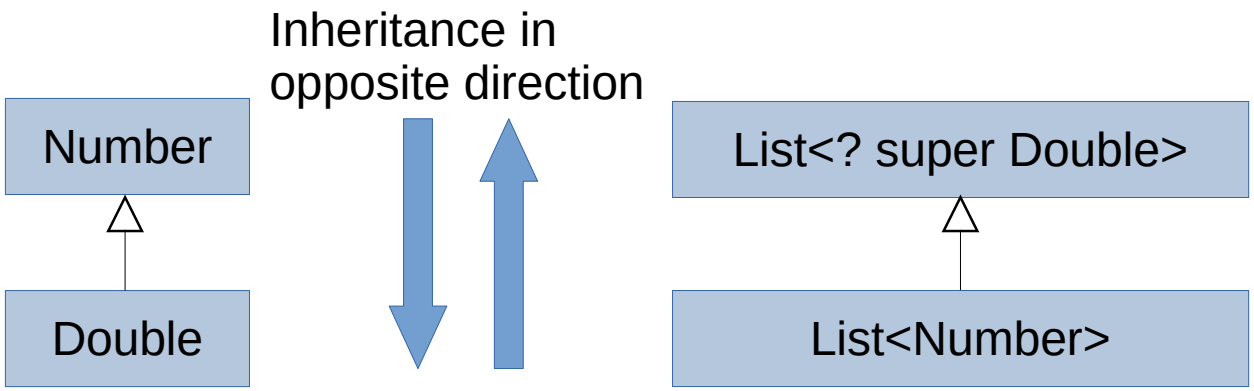
Reason of wildcard limitation (covariant case)



Wrong but assume that covariance holds

```
List<Double> doubleList = new ArrayList<Double>();
List<Number> numberList = doubleList; // Forbidden by compiler

// Possible this way but with an unchecked cast (heap pollution)
@SuppressWarnings("unchecked")
List<Number> numberList = (List<Number>) (List<?>) doubleList;

numberList.add(Integer.valueOf(3)); // Work

Double x = doubleList.get(0); // Cast error since doubleList contains an Integer
```

Wildcard with lower bound

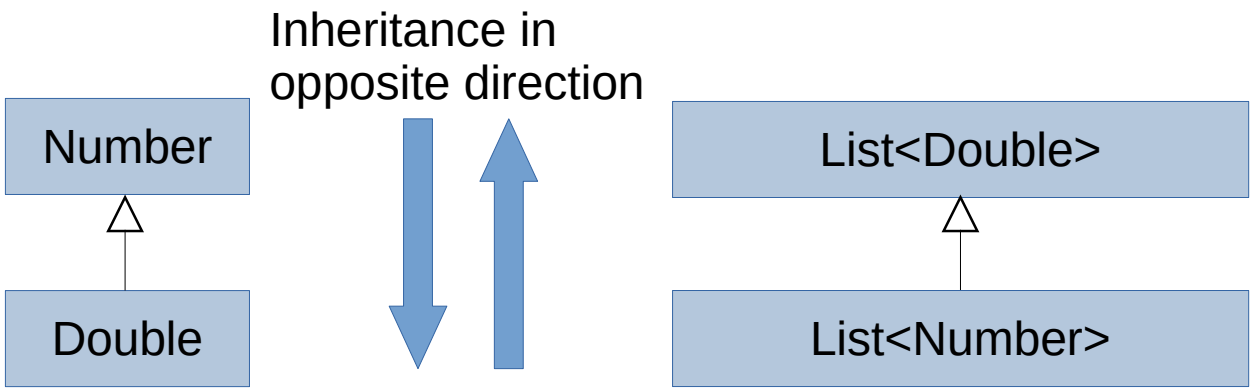


Contravariance of types

```
List<Number> nList = new ArrayList<Number>();
List<? super Double> dList = nList;

dList.add(5.0); // Only possible to add Double in Number List
dList.add(3);   // Error do not know the real List type

Object x = dList.get(0); // Only known as Object
Double d = dList.get(0); // Not necessarily a Double
                         // nList.add(3);
```

```
// Methods that are still usable

list.remove(3);
list.clear();
int size = list.size();
```

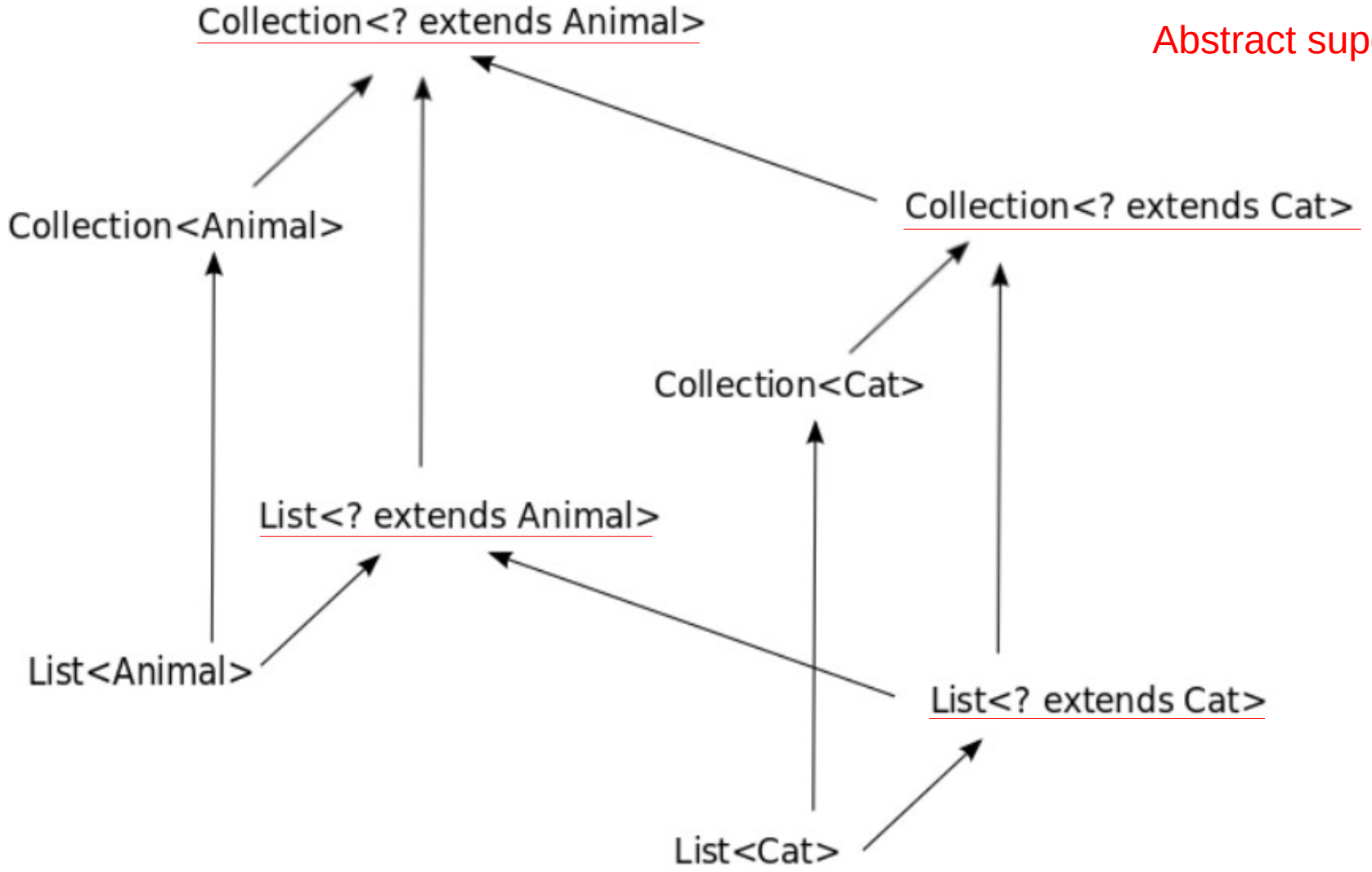
Reason of wildcard limitation (contravariant case)



Wrong but assume that contravariance holds

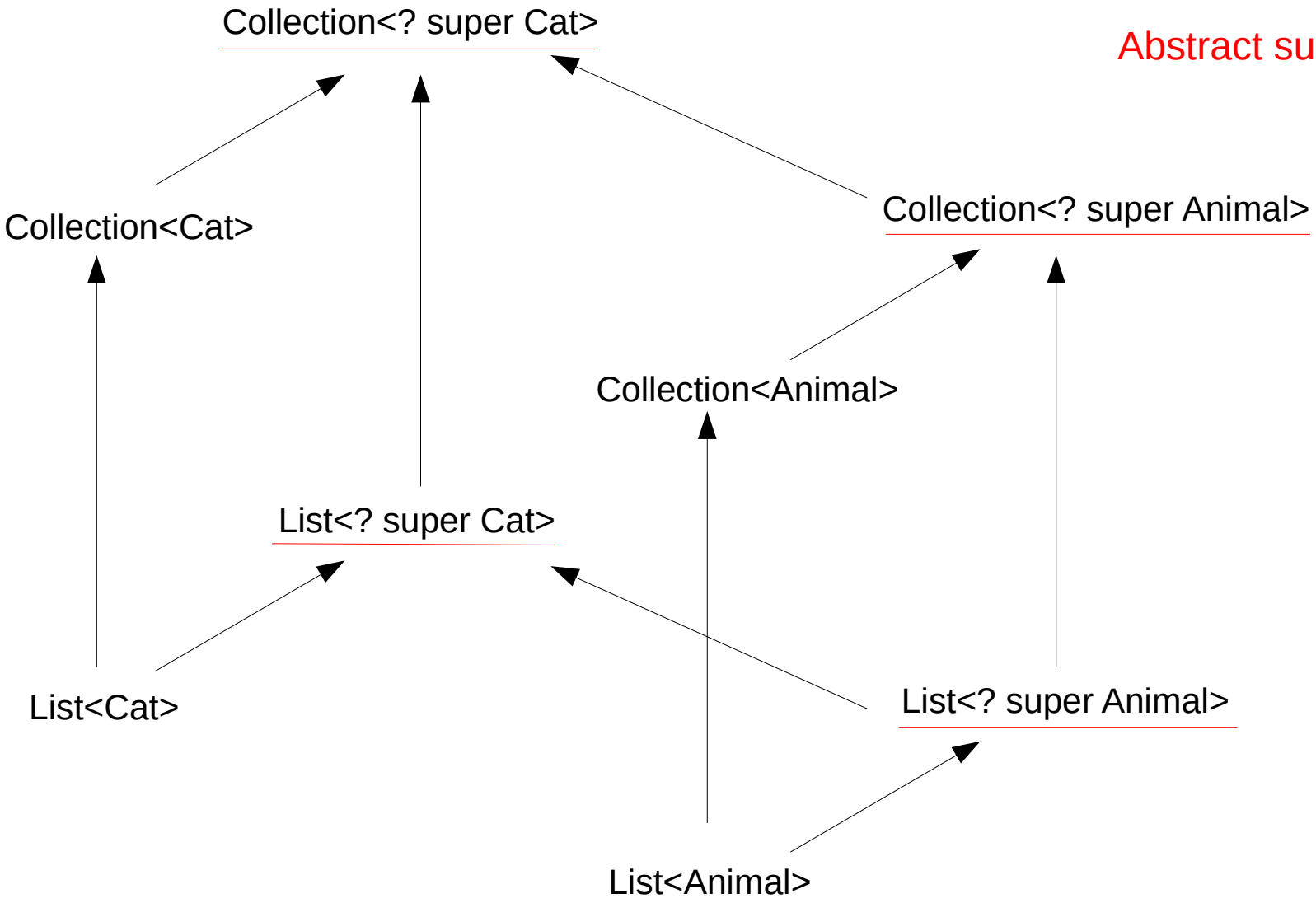
```
List<Number> numberList = new ArrayList<Number>();
List<Double> doubleList = numberList; // Forbidden by compiler

// Possible this way but with an unchecked cast (heap pollution)
@SuppressWarnings("unchecked")
List<Double> doubleList = (List<Double>) (List<?>) numberList;

numberList.add(Integer.valueOf(3));  // Normally work as expected
doubleList.add(Double.valueOf(2.0)); // Normally work as expected

Double x = doubleList.get(0); // Cast error since doubleList is a number List that contains an
                              // Integer
```

Wildcard subtyping in Java can be visualized as a cube (covariant)

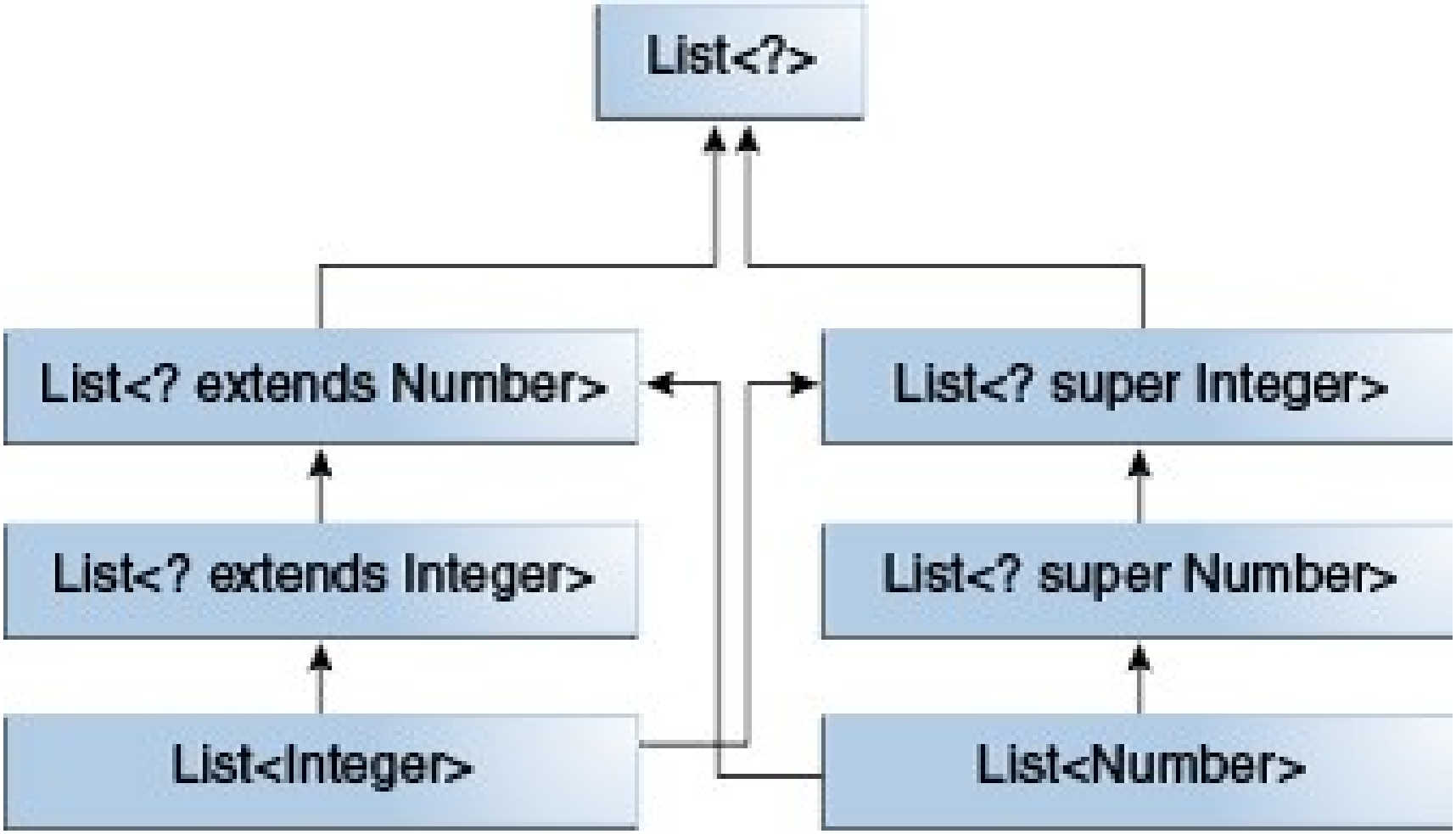


Source: wikipedia

Wildcard subtyping in Java can be visualized as a cube (contravariant)

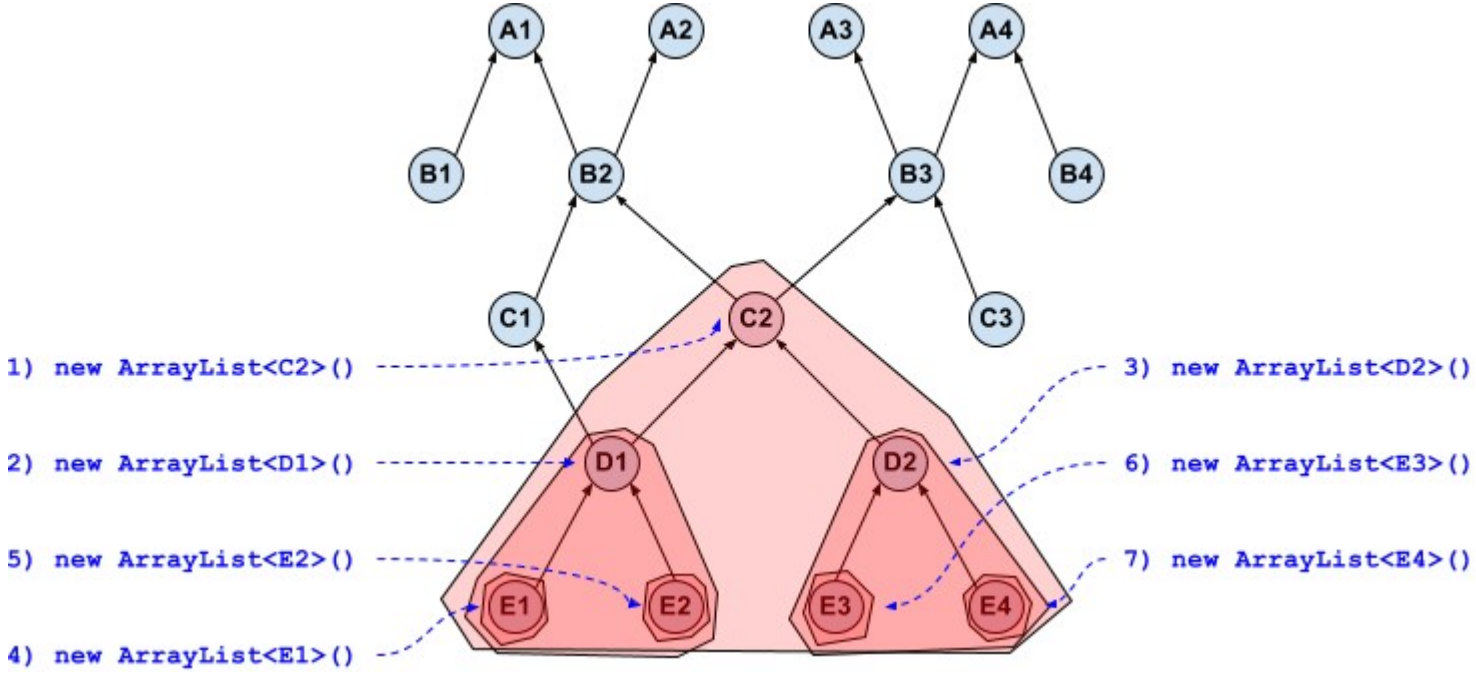


A hierarchy of several generic List class declarations



Source: Oracle

Hierarchy for “? extends” super type

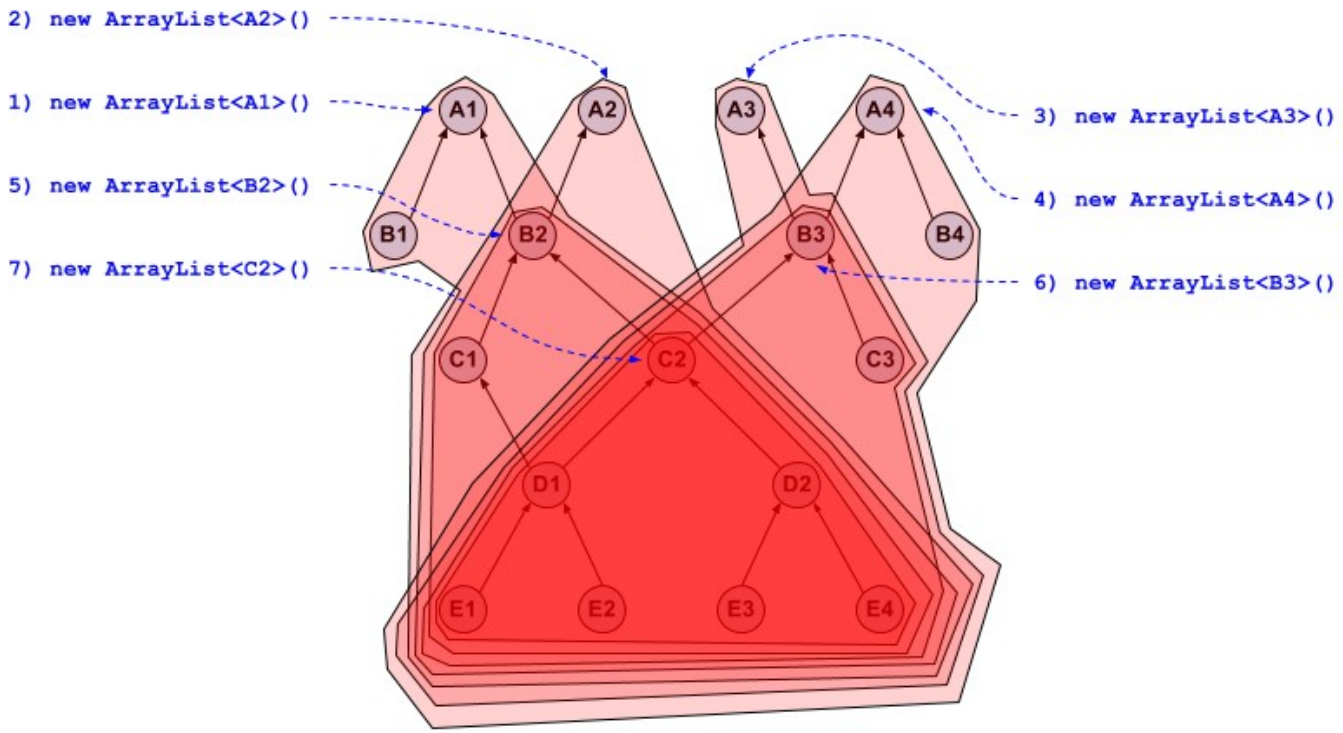



```
Possible concrete types for List<? extends C2>:

1) new ArrayList<C2>(): can store C2 D1 D2 E1 E2 E3 E4
2) new ArrayList<D1>(): can store    D1    E1 E2
3) new ArrayList<D2>(): can store       D2       E3 E4
4) new ArrayList<E1>(): can store          E1
5) new ArrayList<E2>(): can store             E2
6) new ArrayList<E3>(): can store                E3
7) new ArrayList<E4>(): can store                   E4
```

No common parameter type:

- Impossible to write
- Only common super type: C2
  - Could only be read as C2

Hierarchy for “? super” super type



Common parameter types:
C2, D1, D2, E1, E2, E3, E4

- Can write safely all common parameter types (possible input)
- No common super type
  - Could only be read as Object

Possible concrete types for List<? super C2>:

```
1) new ArrayList<A1>(): can store A1          B1 B2       C1 C2    D1 D2 E1 E2 E3 E4
2) new ArrayList<A2>(): can store    A2          B2       C1 C2    D1 D2 E1 E2 E3 E4
3) new ArrayList<A3>(): can store       A3          B3       C2 C3 D1 D2 E1 E2 E3 E4
4) new ArrayList<A4>(): can store          A4       B3 B4    C2 C3 D1 D2 E1 E2 E3 E4
5) new ArrayList<B2>(): can store                B2       C1 C2    D1 D2 E1 E2 E3 E4
6) new ArrayList<B3>(): can store                   B3       C2 C3 D1 D2 E1 E2 E3 E4
7) new ArrayList<C2>(): can store                            C2    D1 D2 E1 E2 E3 E4
```

Usage of abstract super types

```
class Triangle implements Ishape {…}
class Circle implements Ishape {…}

class Canvas {
    List<IShape> shapes;

    void addShape(IShape shape) {
        shapes.add(shape);
    }

    void draw() {
        for (Ishape shape : Shapes) {
            shape.draw();
        }
    }
}
```

- **Writing code that depends on abstraction and is independent of concrete things**

Usage of generic abstract super type (covariant case)

```
interface IBlinkingShape extends IShape {...}

class Canvas {
    List<IShape> shapes;
    //…
    void addAll(List<? Extends IShape> shapes) {
        this.shapes.addAll(shapes);
    }
}

List<IBlinkingShape> blinkingShapes = …
List<IShape> shapes = …

canvas.addAll(blinkingShapes);
canvas.addAll(shapes);
```

- **Writing code that depends on abstraction and is independent of concrete things**
  - `List<? extends IShape>` is an abstraction of `IShape` provider/producer
  - `List<IShape>`, `List<IBlinkingShape>` are concrete `IShape` provider/producer

Usage of generic abstract super type (contravariant case)

```
interface IShape extends IDrawable // Image, text, shape...
interface ITransformer<T> {
    void transform(T t) {// Translation, rotation…}
}

class Canvas {
    List<IShape> shapes;
    //…
    void transformShapes(ITransformer<? super IShape> transformer) {
        this.shapes.foreach(transformer::transform);
    }
}

ITransformer<IDrawable> drawableTransformer = …
ITransformer<IShape> shapeTransformer = …

canvas.transformShapes(drawableTransformer);
canvas.transformShapes(shapeTransformer);
```

- **Writing code that depends on abstraction and is independent of concrete things**
  - `ITransformer<? super IShape>` is an abstraction of `IShape` consumer
  - `ITransformer<IShape>`, `ITransformer<IDrawable>` are concrete `IShape` consumer

Usage of wildcards

- **For maximum flexibility, use wildcard types on input parameters that represent producers (output) or consumers (input parameter).**
- **PECS stands for producer-extends, consumer-super.**
- **For both producer and consumer**
  - Use exact type (no wildcard)
- **Do not use bounded wildcard as return types.**

Generic methods

- **Not seen here, but easy to find information in reference**

Another approach to generic types: C#

IEnumerator<T>
T get(); Bool MoveNext();

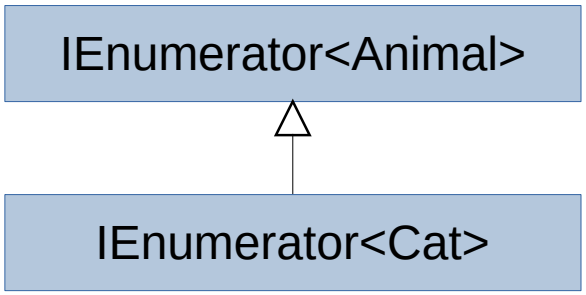
public interface IEnumerable<out T>

“out” keyword means:
T will only be used as return value

⇨

Covariant type

So:



IComparable<T>
int compareTo(T other);

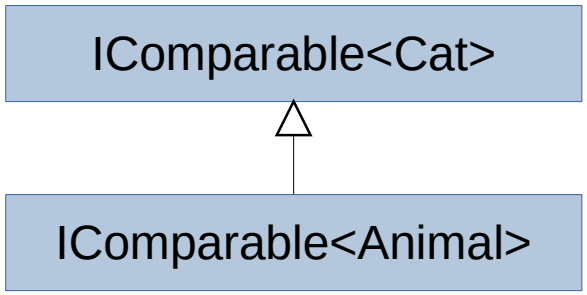
public interface IComparable<in T>

‘in’ keyword means:
T will only be used as input parameter

⇨

Contravariant type

So:

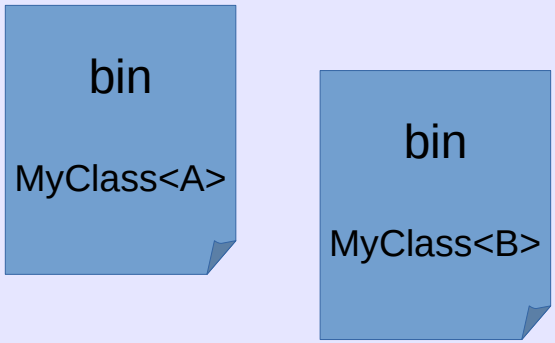


Declaration-site (vs used-site in Java): Easier to use a component but harder to write its API

Generic programming implementations

C++ Template	Java Generics type erasure	C# Generics reification

`template <typename T>`
`class MyClass {`
`  T get() {...}`
`}`
 	
`MyClass<A> ma;`
`MyClass<B> mb;`
 	
`A a = ma.get();`
	`class MyClass<T> {`
	`  T get() {...}`
	`}`
	
	`MyClass<A> ma;`
	`MyClass<B> mb;`
	
	`// Compiler implicitly add cast`
	`A a = (A) ma.get();`
		`class MyClass<T> {`
		`  T get() {...}`
		`}`
		
		`MyClass<A> ma;`
		`MyClass<B> mb;`
		
		`A a = ma.get();`

Generated at compile time 	Only one class compiled 	Generated at runtime  Different binaries with primitive types

Reference

- http://www.angelikalanger.com/GenericsFAQ/FAQSections/ParameterizedTypes.html
- A Conversation with Anders Hejlsberg (part VII)
  by Bill Venners with Bruce Eckel

  https://www.artima.com/intv/anders.html
- https://docs.oracle.com/javase/tutorial/java/generics/index.html
- Effective Java - Joshua Bloch
- https://stackoverflow.com/questions/4343202/difference-between-super-t-and-extends-t-in-java

Abstract super types hierarchy