
CSE 331

Software Design & Implementation

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Generics

Where are we?

- Done:
 - basics of generic types for classes and interfaces
 - basics of *bounding* generics
- Now:
 - generic *methods* [not just using type parameters of class]
 - generics and *subtyping*
 - using *bounds* for more flexible subtyping
 - using *wildcards* for more convenient bounds
 - related digression: Java's *array subtyping*
 - Java realities: type erasure
 - unchecked casts
 - **equals** interactions
 - creating generic arrays

More verbose first

Now:

- how to use *type bounds* to write reusable code despite invariant subtyping
- elegant technique using generic methods
- general guidelines for making code as reusable as possible
 - (though not always the most important consideration)

Then: *Java wildcards*

- essentially provide the same expressiveness
- *less verbose*: No need to declare type parameters that would be used only once
- *better style* because Java programmers recognize how wildcards are used for common idioms
 - easier to read (?) once you get used to it

Best type for addAll

```
interface Set<E> {  
    // Adds all elements in c to this set  
    // (that are not already present)  
    void addAll(_____ c);  
}
```

What is the best type for `addAll`'s parameter?

- Allow as many clients as possible...
- ... while allowing correct implementations

Best type for addAll

```
interface Set<E> {  
    // Adds all elements in c to this set  
    // (that are not already present)  
    void addAll(_____ c);  
}
```

```
void addAll(Set<E> c);
```

Too restrictive:

- does not let clients pass other collections, like `List<E>`
- better: use a supertype interface with just what `addAll` needs

Best type for addAll

```
interface Set<E> {  
    // Adds all elements in c to this set  
    // (that are not already present)  
    void addAll(_____ c);  
}
```

```
void addAll(Collection<E> c);
```

Still too restrictive:

- cannot pass a `List<Integer>` to `addAll` for a `Set<Number>`
- that should be okay because `addAll` implementations only need to read from `c`, not put elements in it
- but Java does not allow it
 - this is the invariant-subtyping limitation

Best type for addAll

```
interface Set<E> {  
    // Adds all elements in c to this set  
    // (that are not already present)  
    void addAll(_____ c);  
}
```

```
<T extends E> void addAll(Collection<T> c);
```

The fix: bounded generic type parameter

- *can* pass a `List<Integer>` to `addAll` for a `Set<Number>`
- `addAll` implementations won't know what element type `T` is, but will know it is a subtype of `E`
 - it cannot add anything to collection `c` refers to
 - but this is enough to implement `addAll`

Generic methods get around invariance

You cannot pass `List<Integer>` to method expecting `List<Number>`

- Java subtyping is invariant with respect to type parameters

Get around it by making your **method** generic:

```
<T extends Number> void sumList(List<T> nums) {  
    double s = 0;  
    for (T t : nums)  
        s += t.doubleValue();  
    return s;  
}
```


Revisit copy method

Earlier we saw this:

```
<T> void copyTo(List<T> dst, List<T> src) {  
    for (T t : src)  
        dst.add(t);  
}
```

Now we can do this (which is more general):

```
<T1, T2 extends T1> void copyTo(List<T1> dst,  
                                List<T2> src) {  
    for (T2 t : src)  
        dst.add(t);  
}
```

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Examples

[Compare to earlier version]

```
interface Set<E> {  
    void addAll(Collection<? extends E> c);  
}
```

- More idiomatic (but equally powerful) compared to
 <T extends E> void addAll(Collection<T> c);
- More powerful than void addAll(Collection<E> c);

Wildcards

Syntax: for a type-parameter instantiation (inside the <...>), can write:

- ? **extends** **Type**, some unspecified subtype of **Type**
- ? is shorthand for ? **extends** **Object**
- ? **super** **Type**, some unspecified superclass of **Type**

A wildcard is essentially an ***anonymous** type variable*

- each ? stands for some possibly-different unknown type

More examples

`<T extends Comparable<T>> T max(Collection<T> c);`
– No change because `T` used more than once

Wildcards

Syntax: for a type-parameter instantiation (inside the `<...>`), can write:

- `? extends Type`, some unspecified subtype of `Type`
- `?` is shorthand for `? extends Object`
- `? super Type`, some unspecified superclass of `Type`

A wildcard is essentially an *anonymous type variable*

- each `?` stands for some possibly-different unknown type
- use a wildcard when you would use a type variable only once (no need to give it a name)
 - avoids declaring generic type variables
- communicates to readers of your code that the type's “identity” is not needed anywhere else

More examples

```
<T> void copyTo(List<? super T> dst,  
               List<? extends T> src) {  
    for (T t : src)  
        dst.add(t);  
}
```

Why this works:

- lower bound of **T** for where callee puts values
- upper bound of **T** for where callee gets values
- callers get the subtyping they want
 - Example: `copy(numberList, integerList)`
 - Example: `copy(stringList, stringList)`

PECS: Producer Extends, Consumer Super

Should you use **extends** or **super** or neither?

- use ? **extends** **T** when you *get* values (from a *producer*)
 - no problem if it's a subtype
 - (the co-variant subtyping case)
- use ? **super** **T** when you *put* values (into a *consumer*)
 - no problem if it's a supertype
 - (the contra-variant subtyping case)
- use neither (just **T**, not ?) if you both *get* and *put*
 - can't be as flexible here

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


More on lower bounds

- As we've seen, lower-bound ? **super T** is useful for “consumers”
- Upper-bound ? **extends T** could be rewritten without wildcards, but wildcards preferred style where they suffice
- But lower-bound is *only* available for wildcards in Java
 - this does not parse:

```
<T super Foo> void m(Bar<T> x) ;
```
 - no good reason for Java not to support such lower bounds except designers decided it wasn't useful enough to bother
 - $_ _ (_ _) _ _ / _ _$

? versus Object

? indicates a particular but unknown type

```
void printAll(List<?> lst) {...}
```

Difference between `List<?>` and `List<Object>`:

- can instantiate ? with any type: `Object`, `String`, ...
- `List<Object>` much more restrictive:
 - e.g., wouldn't take a `List<String>`

Difference between `List<Foo>` and `List<? extends Foo>`:

- In latter, element type is **one** unknown subtype of `Foo`
Example: `List<? extends Animal>` might store only `Giraffes` only (no `Zebras`)
- Former allows anything that is a subtype of `Foo` in the same list
Example: `List<Animal>` could store `Giraffes` and `Zebras`

Legal operations on wildcard types

```
Object o;
```

```
Number n;
```

```
Integer i;
```

```
PositiveInteger p;
```

```
List<? extends Integer> lei;
```

First, which of these is legal?

```
lei = new ArrayList<Object>();
```

```
lei = new ArrayList<Number>();
```

```
lei = new ArrayList<Integer>();
```

```
lei = new ArrayList<PositiveInteger>();
```

```
lei = new ArrayList<NegativeInteger>();
```

Legal operations on wildcard types

```
Object o;
```

```
Number n;
```

```
Integer i;
```

```
PositiveInteger p;
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List<? extends Integer> lei;
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lei = new ArrayList<Integer>();
```

```
lei = new ArrayList<PositiveInteger>();
```

```
lei = new ArrayList<NegativeInteger>();
```

Legal operations on wildcard types

Object **o**;

Number **n**;

Integer **i**;

PositiveInteger **p**;

List<? **extends Integer**> **lei**;

First, which of these is legal?

~~lei = new ArrayList<Object>();~~

~~lei = new ArrayList<Number>();~~

lei = new ArrayList<Integer>();

lei = new ArrayList<PositiveInteger>();

lei = new ArrayList<NegativeInteger>();

Which of these is legal?

lei.add(o);

lei.add(n);

lei.add(i);

lei.add(p);

lei.add(null);

o = lei.get(0);

n = lei.get(0);

i = lei.get(0);

p = lei.get(0);

Legal operations on wildcard types

Object **o**;

Number **n**;

Integer **i**;

PositiveInteger **p**;

List<? **extends Integer**> **lei**;

First, which of these is legal?

~~lei = new ArrayList<Object>();~~

~~lei = new ArrayList<Number>();~~

lei = new ArrayList<Integer>();

lei = new ArrayList<PositiveInteger>();

lei = new ArrayList<NegativeInteger>();

Which of these is legal?

~~lei.add(o);~~

~~lei.add(n);~~

~~lei.add(i);~~

~~lei.add(p);~~

lei.add(null);

o = lei.get(0);

n = lei.get(0);

i = lei.get(0);

~~p = lei.get(0);~~

Legal operations on wildcard types

Object **o**;

Number **n**;

Integer **i**;

PositiveInteger **p**;

List<? **super Integer**> **lsi**;

First, which of these is legal?

lsi = new ArrayList<Object>;

lsi = new ArrayList<Number>;

lsi = new ArrayList<Integer>;

lsi = new ArrayList<PositiveInteger>;

lsi = new ArrayList<NegativeInteger>;

Legal operations on wildcard types

```
Object o;
```

```
Number n;
```

```
Integer i;
```

```
PositiveInteger p;
```

```
List<? super Integer> lsi;
```

First, which of these is legal?

```
lsi = new ArrayList<Object>;
```

```
lsi = new ArrayList<Number>;
```

```
lsi = new ArrayList<Integer>;
```

```
lsi = new ArrayList<PositiveInteger>;
```

```
lsi = new ArrayList<NegativeInteger>;
```


Legal operations on wildcard types

Object `o`;

Number `n`;

Integer `i`;

PositiveInteger `p`;

List<? **super Integer**> `lsi`;

First, which of these is legal?

`lsi = new ArrayList<Object>;`

`lsi = new ArrayList<Number>;`

`lsi = new ArrayList<Integer>;`

~~`lsi = new ArrayList<PositiveInteger>;`~~

~~`lsi = new ArrayList<NegativeInteger>;`~~

Which of these is legal?

`lsi.add(o);`

`lsi.add(n);`

`lsi.add(i);`

`lsi.add(p);`

`lsi.add(null);`

`o = lsi.get(0);`

`n = lsi.get(0);`

`i = lsi.get(0);`

`p = lsi.get(0);`

Legal operations on wildcard types

Object `o`;

Number `n`;

Integer `i`;

PositiveInteger `p`;

List<? **super Integer**> `lsi`;

First, which of these is legal?

`lsi = new ArrayList<Object>;`

`lsi = new ArrayList<Number>;`

`lsi = new ArrayList<Integer>;`

~~`lsi = new ArrayList<PositiveInteger>;`~~

~~`lsi = new ArrayList<NegativeInteger>;`~~

Which of these is legal?

~~`lsi.add(o);`~~

~~`lsi.add(n);`~~

`lsi.add(i);`

`lsi.add(p);`

`lsi.add(null);`

`o = lsi.get(0);`

~~`n = lsi.get(0);`~~

~~`i = lsi.get(0);`~~

~~`p = lsi.get(0);`~~

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Java arrays

We know how to use arrays:

- declare an array holding **Type** elements: **Type []**
- get an element: **x[i]**
- set an element **x[i] = e;**

Java included the syntax above because it's common and concise

But can reason about how it should work the same as this:

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

So: If **Type1** is a subtype of **Type2**, how should **Type1 []** and **Type2 []** be related??

Java Arrays

- Given everything we have learned, if **Type1** is a subtype of **Type2**, then **Type1 []** and **Type2 []** should be unrelated
 - invariant subtyping for generics
 - because arrays are mutable

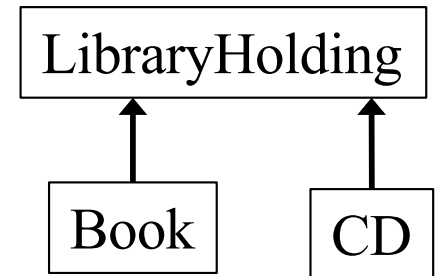


Surprise!

- Given everything we have learned, if **Type1** is a subtype of **Type2**, then **Type1 []** and **Type2 []** should be unrelated
 - invariant subtyping for generics
 - because arrays are mutable
- But in Java, if **Type1** is a subtype of **Type2**, then **Type1 []** *is a subtype* of **Type2 []** (covariant subtyping)
 - not true subtyping: the subtype does not support setting an array element to hold a **Type2** (spoiler: throws an exception)
 - Java (and C#) made this decision in pre-generics days
 - needed to write reusable sorting routines, etc.
 - also `_(ツ)_/`

What can happen: the good

Programmers can use this subtyping to “do okay stuff”



```
void maybeSwap(LibraryHolding[] arr) {
    if(arr[17].dueDate() < arr[34].dueDate())
        // ... swap arr[17] and arr[34]
}
```

```
// client with subtype
```

```
Book[] books = ...;
```

```
maybeSwap(books); // relies on covariant
                   // array subtyping
```

What can happen: the bad

Something in here must go wrong!

```
void replace17(LibraryHolding[] arr,  
              LibraryHolding h) {  
    arr[17] = h;  
}
```

```
// client with subtype
```

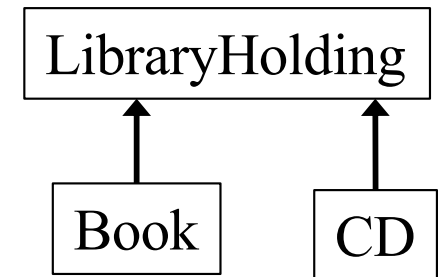
```
Book[] books = ...;
```

```
LibraryHolding theWall = new CD("Pink Floyd",  
                                "The Wall", ...);
```

```
replace17(books, theWall);
```

```
Book b = books[17]; // would hold a CD
```

```
b.getChapters(); // so this would fail
```



Java's choice

- Java normally guarantees run-time type is a subtype of the compile-time type
 - this was violated for the **Book b** variable
- To preserve the guarantee, Java must never get that far:
 - each array “knows” its actual run-time type (e.g., **Book []**)
 - trying to store a supertype into an index causes **ArrayStoreException** (at run time)
- So the body of **replace17** would raise an exception
 - even though **replace17** is entirely reasonable
 - and fine for plenty of “careful” clients
 - *every Java array-update includes this run-time check*
 - (array-reads never fail this way – why?)
 - **beware careful with array subtyping**

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Type erasure

All generic types become type `Object` once compiled

- gives backward compatibility (a selling point at time of adoption)
- at run-time, all generic instantiations have the same type

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

Cannot use `instanceof` to discover a type parameter

```
Collection<?> cs = new ArrayList<String>();  
if (cs instanceof Collection<String>) { // illegal  
    ...  
}
```

Generics and casting

Casting to generic type results in an important warning

```
List<?> lg = new ArrayList<String>(); // ok
List<String> ls = (List<String>) lg; // warn
```

Compiler gives a warning because this is something the runtime system *will not check for you*

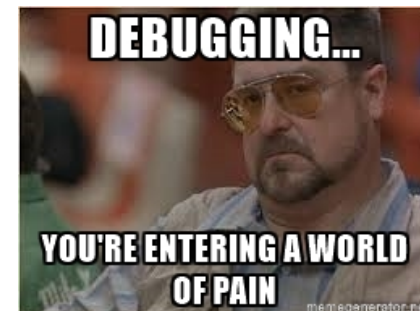
Usually, if you think you need to do this, you're wrong
– a real need to do this is extremely rare

Object can also be cast to any generic type ☹

```
public static <T> T badCast(T t, Object o) {
    return (T) o; // unchecked warning
}
```

The bottom-line

- Java guarantees a `List<String>` variable always holds a (subtype of) the *raw type* `List`
- Java does not guarantee a `List<String>` variable always has only `String` elements at run-time
 - will be true if no unchecked cast warnings are shown
 - compiler inserts casts to/from `Object` for generics
 - if these casts fail, ***hard-to-debug errors result:*** often far from where conceptual mistake occurred
- So, two reasons not to ignore warnings:
 1. You're violating good style/design/subtyping/generics
 2. You're risking difficult debugging



Recall equals

```
class Node {
    ...
    @Override
    public boolean equals(Object obj) {
        if (!(obj instanceof Node)) {
            return false;
        }
        Node n = (Node) obj;
        return this.data().equals(n.data());
    }
    ...
}
```

equals for a parameterized class

```
class Node<E> {  
    ...  
    @Override  
    public boolean equals (Object obj) {  
        if (!(obj instanceof Node<E>)) {  
            return false;  
        }  
        Node<E> n = (Node<E>) obj;  
        return this.data().equals(n.data());  
    }  
    ...  
}
```

Erasure: Type arguments do not exist at runtime

equals for a parameterized class

```
class Node<E> {  
    ...  
    @Override  
    public boolean equals(Object obj) {  
        if (!(obj instanceof Node<?>)) {  
            return false;  
        }  
        Node<E> n = (Node<E>) obj;  
        return this.data().equals(n.data());  
    }  
    ...  
}
```

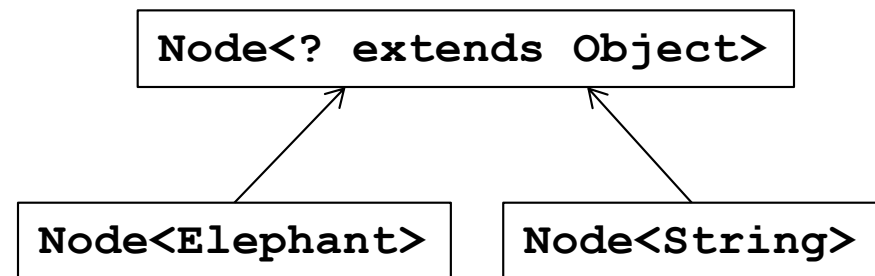
More erasure: At run time, do not know what **E** is and will not be checked, so don't indicate otherwise

equals for a parameterized class

```
class Node<E> {  
    ...  
    @Override  
    public boolean equals(Object obj) {  
        if (!(obj instanceof Node<?>)) {  
            return false;  
        }  
        Node<?> n = (Node<?>) obj;  
        return this.data().equals(n.data());  
    }  
    ...  
}
```

Works if the type of obj is Node<Elephant> or Node<String> or ...

Leave it to here to “do the right thing” if this and n differ on element type



Generics and arrays

```
public class Foo<T> {  
    private T aField;           // ok  
    private T[] anArray;       // ok  
  
    public Foo() {  
        aField = new T();      // compile-time error  
        anArray = new T[10];  // compile-time error  
    }  
}
```

- You cannot create objects or arrays of a parameterized type
 - type info is not available at runtime

Necessary array cast

```
public class Foo<T> {
    private T aField;
    private T[] anArray;

    @SuppressWarnings("unchecked")
    public Foo(T param) {
        aField = param;
        anArray = (T[]) new Object[10];
    }
}
```

You *can* declare variables of type **T**, accept them as parameters, return them, or create arrays by casting **Object[]**

- casting to generic types is not type-safe (hence the warning)
- Effective Java: use **ArrayList** instead

Some final thoughts...

Generics clarify your code

```
interface Map {  
    Object put(Object key, Object value);  
    ...  
}
```

plus casts in client code
→ possibility of run-time errors

```
interface Map<Key, Value> {  
    Value put(Key key, Value value);  
    ...  
}
```

- Generics usually clarify the *implementation*
 - (but sometimes uglify: wildcards, arrays, instantiation)
- Generics always make the client code prettier and safer

Tips when writing a generic class

- Think through whether you **really need** to make it generic
 - if it's not really a container, most likely a *mistake*
- Start by writing a concrete instantiation
 - get it correct (testing, reasoning, etc.)
 - consider writing a second concrete version
- Generalize it by adding type parameters
 - think about which types are the same or different
 - the compiler will help you find errors
- It will become easier with practice to write generic from the start