
CSE 331

Software Design & Implementation

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Winter 2020
Generics (Polymorphism)

Varieties of abstraction

Abstraction over *computation*: procedures (methods)

```
int x1, y1, x2, y2;  
Math.sqrt(x1*x1 + y1*y1) ;  
Math.sqrt(x2*x2 + y2*y2) ;
```

Abstraction over *data*: ADTs (classes, interfaces)

```
Point p1, p2;
```

Abstraction over *types*: polymorphism (generics)

```
Point<Integer>, Point<Double>
```

Why we *love* abstraction

Hide details

- Avoid distraction
- Permit details to change later

Give a *meaningful name* to a concept

Permit *reuse* in new contexts

- Avoid duplication: error-prone, confusing
- Save reimplementation effort
- Helps to “Don’t Repeat Yourself”

Related abstractions

```
interface ListOfNumbers {
    boolean add(Number elt);
    Number get(int index);
}
interface ListOfIntegers {
    boolean add(Integer elt);
    Integer get(int index);
}
```

... and many, many more

// Type abstraction

// abstracts over element type

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

Lets us use types

List<Integer>

List<Number>

List<String>

List<List<String>>

...

An analogous parameter

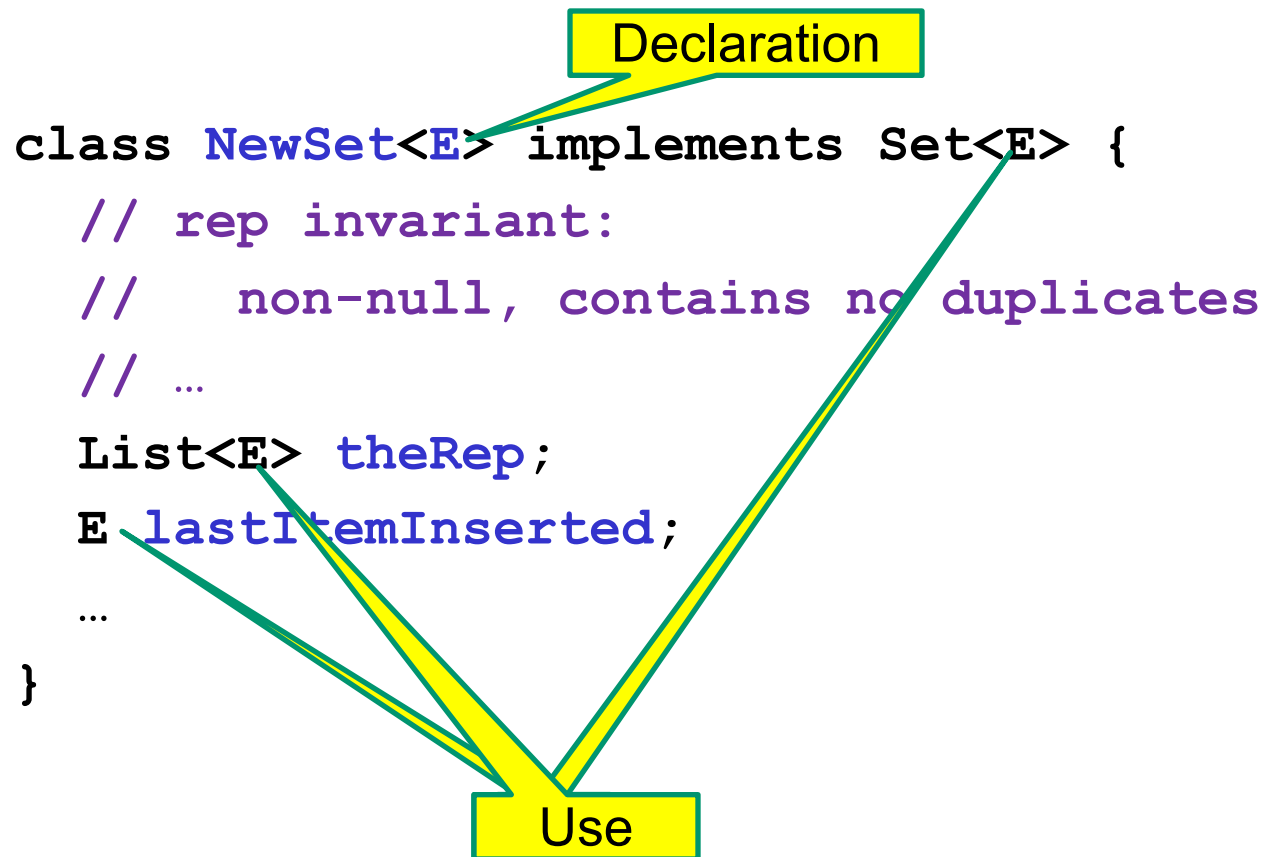
```
interface ListOfIntegers {  
    boolean add(Integer elt);  
    Integer get(int index);  
}
```

- Declares a new **variable**, called a **(formal) parameter**
- **Instantiate** with any **expression** of the right type
 - E.g., `lst.add(7)`
- **Type** of `add` is *Integer* $\rightarrow$ *boolean*

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

- Declares a new **type variable**, called a **type parameter**
- **Instantiate** with any (reference) type
 - E.g., `List<String>`
- **“Type”** of `List` is *Type* $\rightarrow$ *Type*
 - Never just use `List` (in Java for backward-compatibility)

Type variables are types



Declaring and instantiating generics

```
class Name<TypeVar1, ..., TypeVarN> {...}
```

```
interface Name<TypeVar1, ..., TypeVarN> {...}
```

- Convention: One-letter name such as:
T for **T**ype, E for **E**lement,
K for **K**ey, V for **V**alue, ...

To instantiate a generic class/interface, client supplies type arguments:

```
Name<Type1, ..., TypeN>
```

Restricting instantiations by clients

```
boolean add1(Object elt);
boolean add2(Number elt);
add1(new Date()); // OK
add2(new Date()); // compile-time error
```

Upper bounds

```
interface ObjList<E extends Object> {...}
interface NumList<E extends Number> {...}
```

```
ObjList<Date> // OK, Date is a subtype of Object
```

```
NumList<Date> // compile-time error, Date is not
               // a subtype of Number
```

Using type variables

Code can perform any operation permitted by the bound

- Because we know all instantiations will be subtypes!
- An enforced precondition on type instantiations

```
class Foo1<E extends Object> {  
    void m(E arg) {  
        arg.asInt(); // compiler error, E might not  
                     // support asInt  
    }  
}
```

```
class Foo2<E extends Number> {  
    void m(E arg) {  
        arg.asInt(); // OK, since Number and its  
                     // subtypes support asInt  
    }  
}
```

Generalized definition

```
class Name<TypeVar1 extends Type1,  
    ...,  
    TypeVarN extends TypeN> {...}
```

- (same for interface definitions)
- (default upper bound is `Object`)

To instantiate a generic class/interface, client supplies type arguments:

```
Name<Type1, ..., TypeN>
```

- Compile-time error if type is not a subtype of the upper bound
 - Convention: *every type T is a subtype of itself*

More bounds

`<TypeVar extends SuperType>`

- An *upper bound*; accepts given supertype or any of its subtypes

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

- *Multiple* upper bounds (superclass/interfaces) with &

Example:

```
// tree set works for any comparable type
public class TreeSet<E extends Comparable<E>> {
    ...
}
```

More examples

```
public class Graph<N> implements Iterable<N> {  
    private final Map<N, Set<N>> node2neighbors;  
    public Graph(Set<N> nodes, Set<Tuple<N,N>> edges) {  
        ...  
    }  
}
```

```
public interface Path<N, P> extends Path<N, P>>  
    extends Iterable<N>, Comparable<Path<?, ?>> {  
    public Iterator<N> iterator();  
    ...  
}
```

Do **NOT** copy/paste this stuff into your project unless it is what you want
– And you understand it!

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
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Not all generics are for collections

```
class Utils {
    static double sumList(List<Number> lst) {
        double result = 0.0;
        for (Number n : lst) {
            result += n.doubleValue();
        }
        return result;
    }
    static Number choose(List<Number> lst) {
        int i = ... // random number < lst.size
        return lst.get(i);
    }
}
```

Weaknesses

- Would like to use `sumList` for any subtype of `Number`
 - For example, `Double` or `Integer`
 - But as we will see, `List<Double>` is not a subtype of `List<Number>`
- Would like to use `choose` for any element type
 - I.e., any subclass of `Object`
 - No need to restrict to subclasses of `Number`
 - Want to tell clients more about return type than `Object`
- Class `Utils` is not generic, but the *methods* should be generic

Much better

```
class Utils {
    static <E extends Number>
    double sumList(List<E> lst) {
        double result = 0.0;
        for (Number n : lst) { // E also works
            result += n.doubleValue();
        }
        return result;
    }
    static <E>
    E choose(List<E> lst) {
        int i = ... // random number < lst.size
        return lst.get(i);
    }
}
```

Have to declare type
parameter(s)

Have to declare type
parameter(s)

Using generics in methods

- Instance methods can use type parameters of the class
 - (if the enclosing class has type parameters, of course)
- Instance methods and static methods can have their own type parameters
 - Generic methods
- Callers to generic methods need not explicitly instantiate the methods' type parameters
 - Compiler just figures it out for you
 - *Type inference*

More examples

```
<E extends Comparable<E>> E max(Collection<E> c) {  
    ...  
}
```

```
<E extends Comparable<E>>  
void sort(List<E> list) {  
    // ... use list.get() and E's compareTo  
}
```

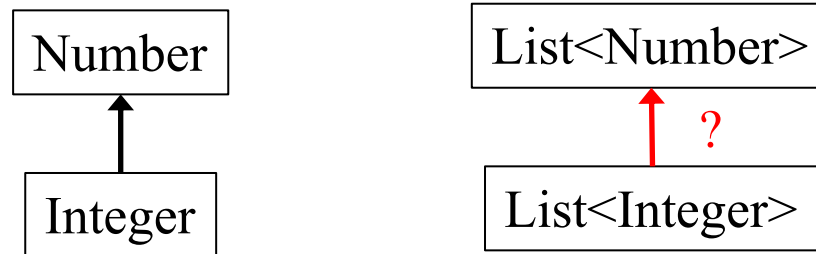
(This one “works” but we will make it even more useful later by adding more type bounds)

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

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 - **Generics and subtyping**
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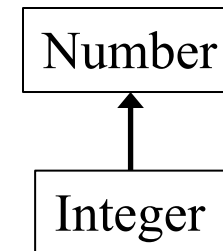
Generics and subtyping



- **Integer** is a subtype of **Number**
- Is **List<Integer>** a subtype of **List<Number>**?
- Use subtyping rules (stronger, weaker) to find out...

List<Number> and List<Integer>

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



So type List<Number> has:

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

So type List<Integer> has:

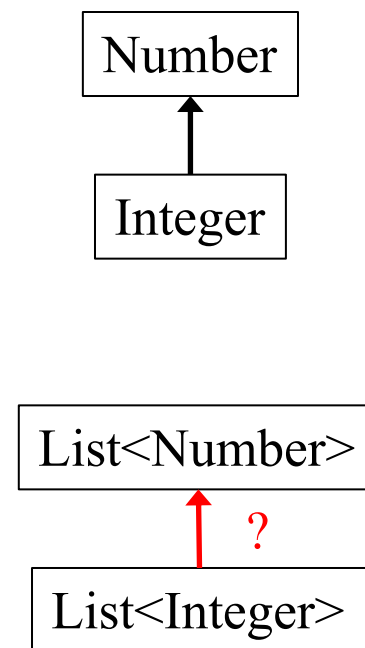
```
boolean add(Integer elt);  
Integer get(int index);
```

Java subtyping is *invariant* with respect to generics

- Not covariant and not contravariant
- Neither List<Number> nor List<Integer> subtype of other

Aside: covariant/contravariant

- These are fancy ways of saying whether one typing relationship “goes the same direction” as another
- We know Integer is a subtype of Number
- If List<Integer> were a subtype of List<Number> we would say that the type relationship is **covariant** (same direction)
- If List<Number> were a subtype of List<Integer> it would be **contravariant** (type relationship opposite of parameter type relationship)
- But in this case the relationship is **invariant**: it’s neither of the above



Hard to remember?

If **A** and **B** are different,
then **Type1<A>** is *not* a subtype of **Type1**

Previous example shows why:

- Observer method prevents “one direction”
- Mutator/producer method prevents “the other direction”

If our types have only observers or only mutators, then one direction of subtyping would be sound

- But Java’s type system does not “notice this” so such subtyping is never allowed in Java

Read-only allows covariance

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

So type `List<Number>` has:

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

So type `List<Integer>` has:

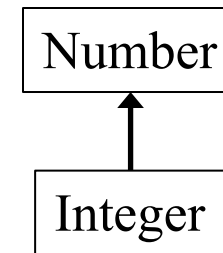
```
Integer get(int index);
```

So *covariant* subtyping would be correct:

- `List<Integer>` a subtype of `List<Number>`

But Java does not analyze interface definitions like this

- Conservatively disallows this subtyping



Write-only allows contravariance

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

So type `List<Number>` has:

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

So type `List<Integer>` has:

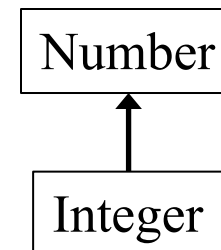
```
boolean add(Integer elt) ;
```

So *contravariant* subtyping would be correct:

- `List<Number>` a subtype of `List<Integer>`

But Java does not analyze interface definitions like this

- Conservatively disallows this subtyping



About the parameters

- So we have seen `List<Integer>` and `List<Number>` are not subtype-related
- But there is subtyping “as expected” on the generic types themselves
- Example: If `HeftyBag` extends `Bag`, then
 - `HeftyBag<Integer>` is a subtype of `Bag<Integer>`
 - `HeftyBag<Number>` is a subtype of `Bag<Number>`
 - `HeftyBag<String>` is a subtype of `Bag<String>`
 - ...

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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

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
- This is not related to invariant subtyping [yet]

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);
```

Too restrictive:

- Client cannot pass a `List<Integer>` to `addAll` for a `Set<Number>`
- Should be okay because `addAll` implementations only need to read from `c`, not put elements in 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: A bounded generic type parameter

- Now client *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`
 - So it cannot add anything to collection `c` refers to
 - But this is enough to implement `addAll`

Revisit copy method

Earlier we saw this:

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

Now we can do this, which is more useful to clients:

```
<E1, E2 extends E1> void copyTo(List<E1> dst,  
                                List<E2> src) {  
    for (E2 e : src)  
        dst.add(e);  
}
```

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Wildcards - anonymous type variables

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 supertype 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 exactly once, so there's no need to give it a name
- Avoids declaring generic type variables when not needed
- Communicates to readers of your code that the type's "identity" is not needed anywhere else

Wildcard for addAll collection type

[Compare to earlier versions using explicit generic types]

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

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

More examples: max, copyTo

```
<E extends Comparable<E>> E max(Collection<E> c);
```

- No change because **E** used more than once

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

Why this “works”?

- Lower bound of **E** for where callee puts values
- Upper bound of **E** for where callee gets values
- Callers get the subtyping they want
 - Example: `copy(numberList, integerList)`
 - Example: `copy(stringList, stringList)`

PECS: Producer Extends, Consumer Super

Where should you insert wildcards?

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

- Use ? **extends** **E** when you *get* values (from a *producer*)
 - No problem if it's a subtype
- Use ? **super** **E** when you *put* values (into a *consumer*)
 - No problem if it's a supertype
- Use neither (just **E**, not ?) if you both *get* and *put*

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

More on lower bounds

- As we've seen, lower-bound `<? super E>` is useful for “consumers”
- For upper-bound `<? extends E>`, we could always rewrite it not to use wildcards, but wildcards preferred style where they suffice
- But lower-bound is *only* available for wildcards in Java
 - This does not parse:

```
<E super Foo> void m(Bar<E> 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>` is restrictive; 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` but not `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**;

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);~~

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**;

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

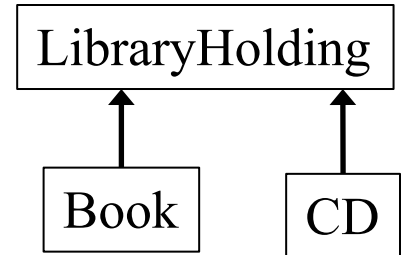
So: If **Type1** is a subtype of **Type2**, how should **Type1 []** and **Type2 []** be related??

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 (Java) subtype of **Type2 []**
 - Not true subtyping: the subtype does not support setting an array element to hold a **Type2**
 - Java (and C#) made this decision in pre-generics days
 - Else cannot write reusable sorting routines, etc.
 - Now programmers are used to this too-lenient subtyping

What can happen: the good

Programmers can use this subtyping to “do okay stuff”



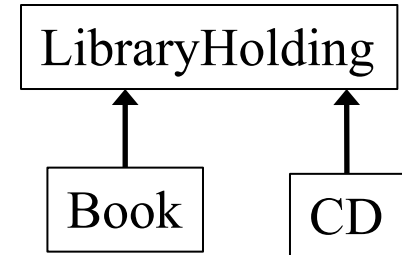
```
void maybeSwap(LibraryHolding[] arr) {  
    if(arr[17].dueDate() < arr[34].dueDate())  
        // ... swap arr[17] and arr[34]  
}
```

```
// client with array that is a Java 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 array that is a Java 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

- Recall Java's guarantee: Run-time type is a subtype of the compile-time type
 - This was violated for the **Book b** variable
- To preserve the guarantee, Java would never get that far:
 - Each array “knows” its actual run-time type (e.g., **Book []**)
 - Trying to store a (run-time) supertype into an array element (index) causes **ArrayStoreException**
- 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 array subtyping!**

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Type erasure

All generic types become type `Object` once compiled

- Big reason: backward compatibility with ancient byte code
- So, at run-time, all generic instantiations have the same type
 - (See `TypeErasure.java` for demo/example)

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

Cannot use `instanceof` to discover a generic 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 an unchecked warning, since this is something the runtime system *will not check for you* (because it can't!)

Usually, if you think you need to do this, you're wrong

- Most common real need is creating arrays with generic element types (discussed shortly), when doing things like implementing **ArrayList**.

Object can also be cast to any generic type ☹

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

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());  
    }  
    ...  
}
```

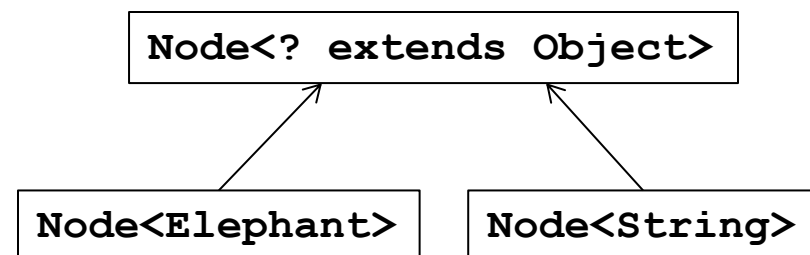
More erasure: At run time, do not know what **E** is and cannot be checked

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
...

If classes implement
equals properly this
should distinguish
Elephants from Strings



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
(Actual type info not available at runtime – can't allocate /
construct new objects since we don't know what **T** really is)

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, so it generates a warning
- Rare to need an array of a generic type (e.g., use **ArrayList**)

Some final thoughts...

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
 - But will be true unless unchecked casts involving generics are used (i.e., type checks work if you don't bypass them)
 - 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:
 - You're violating good style/design/subtyping/generics
 - You're risking difficult debugging

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 ugly: wildcards, arrays, instantiation
- Generics always make the client code prettier and safer

Tips when writing a generic class

- 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
- As you gain experience, it will be easier to write generic code from the start
- Read *Effective Java* Ch. 5