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# CSE 331

# Software Design & Implementation

Hal Perkins

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Generics

(Based on slides by Mike Ernst, Dan Grossman, David Notkin, Hal Perkins, Zach Tatlock)

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# Varieties of abstraction

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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

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## *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 reimplementing 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

*// 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);  
}
```

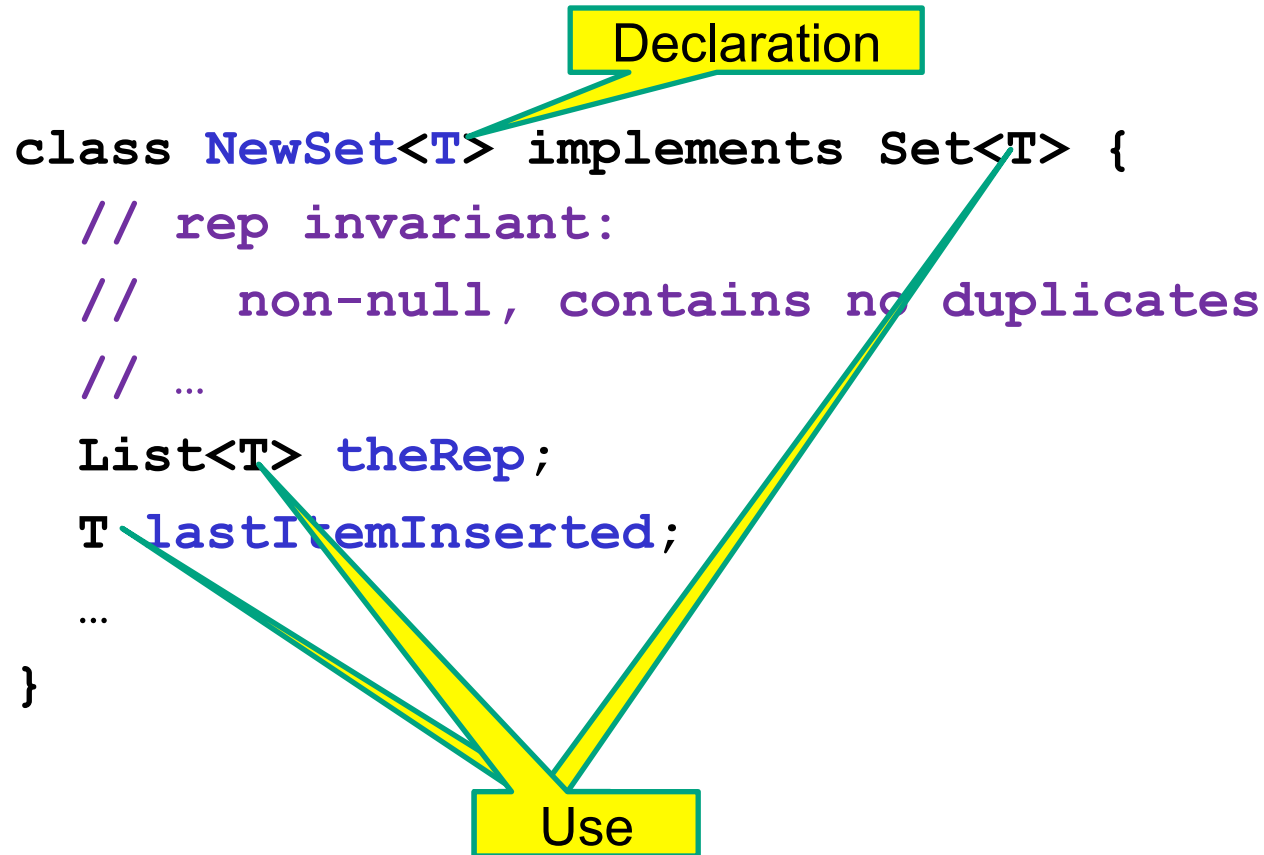
- Declares a new **variable**, called a **(formal) parameter**
- **Instantiate** with any **expression** of the right type
  - E.g., `lst.add(7)`
- **Type** of `add` is *Integer* → *boolean*

```
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* → *Type*
  - Never just use `List` (in Java for backward-compatibility)

# Type variables are types

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# 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 List1<E extends Object> {...}  
interface List2<E extends Number> {...}
```

```
List1<Date> // OK, Date is a subtype of Object
```

```
List2<Date> // compile-time error, Date is not a  
            // subtype of Number
```



# Revised 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

# 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 Fool<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  
    }  
}
```

# 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!

# 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<T extends Comparable<T>> {
    ...
}
```

# 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 <T extends Number>
    double sumList(List<T> lst) {
        double result = 0.0;
        for (Number n : lst) { // T also works
            result += n.doubleValue();
        }
        return result;
    }
    static <T>
    T choose(List<T> 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
- 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

---

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

```
<T extends Comparable<T>>  
void sort(List<T> list) {  
    // ... use list.get() and T's compareTo  
}
```

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

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

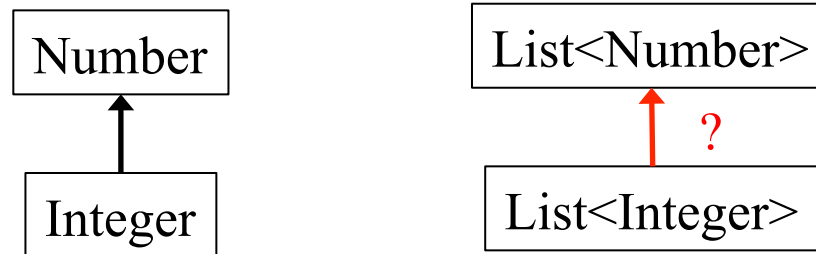
# Where are we?

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  - **Generics and *subtyping***
  - Using *bounds* for more flexible subtyping
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# Generics and subtyping

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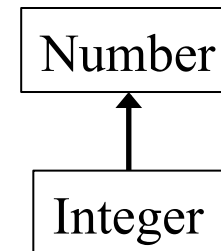


- **Integer** is a subtype of **Number**
- Is **List<Integer>** a subtype of **List<Number>**?
- Use subtyping rules (stronger, weaker) to find out...

# List<Number> and List<Integer>

---

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

# Hard to remember?

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If **Type2** and **Type3** are different,  
then **Type1<Type2>** is *not* a subtype of **Type1<Type3>**

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

So type `List<Number>` has:

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

So type `List<Integer>` has:

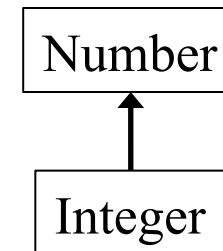
```
    Integer get(int index);
```

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

So type `List<Number>` has:

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

So type `List<Integer>` has:

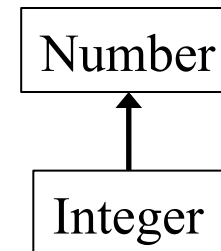
```
boolean add(Integer elt);
```

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:

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

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

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



# Where are we?

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# 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 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 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

# Examples

---

[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

---

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

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

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

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

---

Where should you insert wildcards?

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

```
<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”
- For upper-bound ? **extends T**, 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:  

```
<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>` 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**;

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>;~~

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);**~~

# Where are we?

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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??

# Surprise!

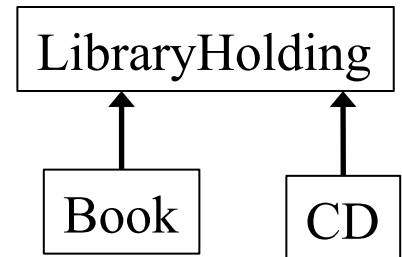
---

- 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 []**
  - 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 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
```

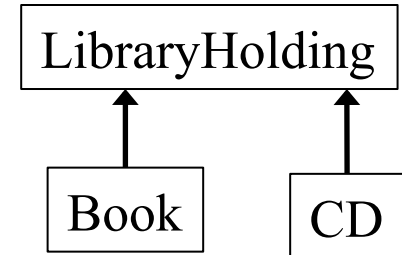
```
Book[] books = ...;
```

```
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

---

- 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 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

```
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 an unchecked warning, since this is something the runtime system *will not check for you*

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
}
```

# 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 unless unchecked casts involving generics are used
  - 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

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

Erasement: 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());  
    }  
    ...  
}
```

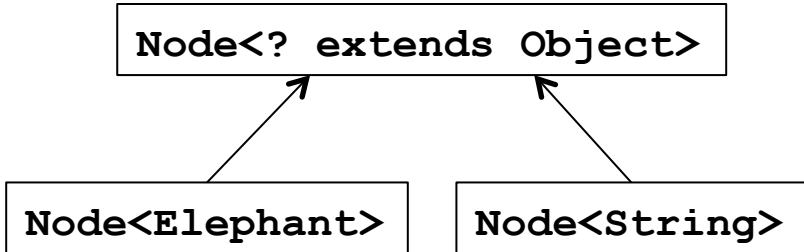
More erasure: At run time, do not know what **E** is and will not be checked, so don't indicate otherwise

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

---

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 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