CSE 331
Software Design & Implementation

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Summer 2016

Generics

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

Preface

- This lecture will get into the gritty details of generics

- In practice:
  - you will constantly need to **use** generic classes
    - e.g., the collections library
  - but you will rarely need to **write** generic classes
    - (generic methods are a little more common)
    - unless you are writing a container class, you are probably making a mistake by making it generic

- We will go through all the details so that you have seen it once
- You will need to do this in HW7

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 getting lost in details
- permit details to change later on

Give a *meaningful name* to a concept

Permit *reuse* in new contexts

- avoid duplication: error-prone, confusing
- save reimplementation effort

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

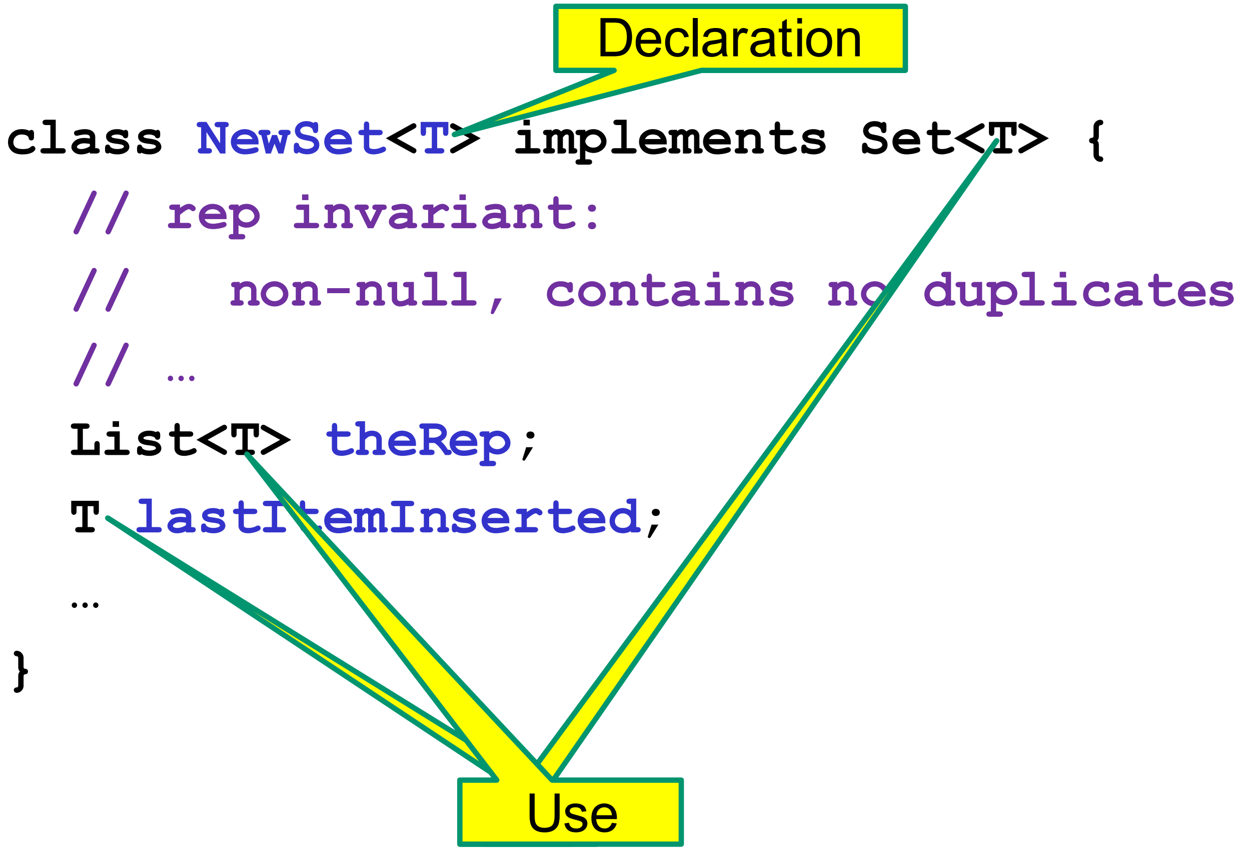
```
interface ListOfIntegers {
  boolean add(Integer elt);
  Integer get(int index);
}
```

- 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`** (allowed for backward-compatibility only)

Type variables are types



Declaration

```
class NewSet<T> implements Set<T> {
  // rep invariant:
  //    non-null, contains no duplicates
  // …
  List<T> theRep;
  T lastItemInserted;
  …
}
```

Use

Declaring and instantiating generics

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

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

- often one-letter name such as:
  `T` for **`Type`**, **`E`** for **`Element`**,
  `K` for **`Key`**, **`V`** for **`Value`**, …

To instantiate a generic class/interface, supply 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, supply 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 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
  }
}
```

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();
  …
}
```

(Note: you probably don't want to use this code in your homework.)

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
    - unchecked casts
    - **`equals`** interactions
    - creating generic arrays

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 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
    - example of *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 works but will be even more useful later with more bounds)

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

Where are we?

- Done:
  - basics of generic types for classes and interfaces
  - basics of *bounding* generics
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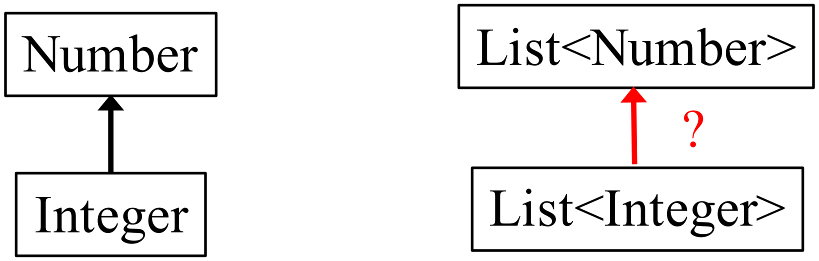
Generics and subtyping



Number

Integer

List<Number>

?

List<Integer>

- **`Integer`** can be used wherever **`Number`** is expected
  - this is the notion of a subtype (see Fri lecture)
    - (specifically, the Liskov substitutability principle)
  - i.e, **`Integer`** satisfies a *stronger spec* than **`Number`**
    - only adds methods and strengthens existing methods

- Can you safely substitute **`List<Integer>`** wherever a **`List<Number>`** is used without possibility of error?

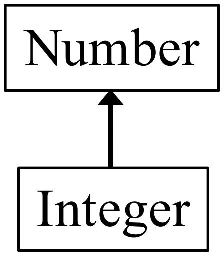
Generics and subtyping

```
List<Number> numList = new List<Number>();
List<Integer> intList = new List<Integer>();

intList.add(new Integer(3));
 -> numList.add(new Integer(3));   // okay
numList.add(new Double(3.0));
 -> intList.add(new Double(3.0));  // not legal

Number n = numList.get(0);
 -> Number n = intList.get(0);     // okay
Integer n = intList.get(0);
 -> Integer n = numList.get(0);    // illegal
```

Neither type can be substituted for the other legally in all situations!

`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?

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

Previous example shows why:

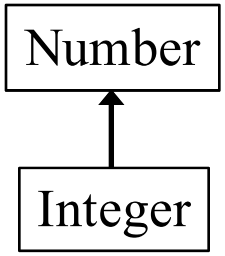
- Observer method prevents "one direction"
- Mutator/producer method prevents "the other direction"

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:

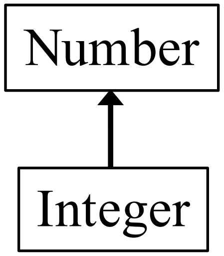
- **`List<Integer>`** a subtype of **`List<Number>`**

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

Co- and Contra-variance

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

In general, `List<T>` should be

- covariant if `T` only appears as a return value
- contravariant if `T` only appears as an argument

Some languages (e.g., Scala and C#) allow this
Java does not:

- cannot substitute `List<T1>` for `List<T2>` unless `T1` = `T2`

About the parameters

- So we have seen **`List<Integer>`** and **`List<Number>`** are not subtype-related
- There is “as expected” subtyping 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>`**
  - …

Where are we?

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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
  - (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`**

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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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

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);`

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

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 subtypting 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
    - ¯_(ツ)_/¯

`?` 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>();`

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);`~~

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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??

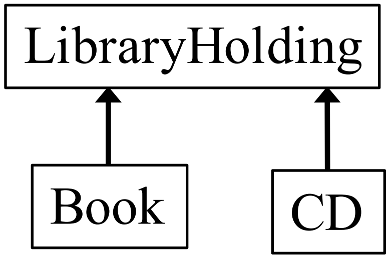
Surprise!

- 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[]`** (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”


LibraryHolding

Book

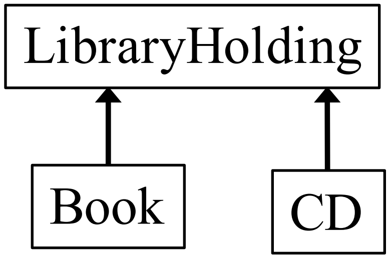
CD

```
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

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

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
     - "a world of pain, Dude" — Walter

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());
  }
  …
}
```

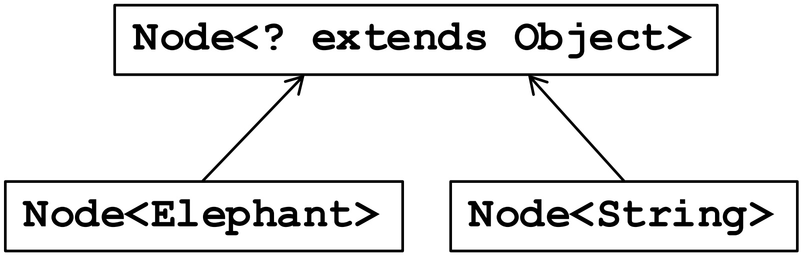
More erasure: At run time, do not know what **`E`** is and will not be checked, so don't indicate otherwise

`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