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

Review

- `List<Number>` is a subtype of `Collection<Number>`
- `Set<Number>` is a subtype of `Collection<Number>`

- `Integer` is a subtype of `Number`

- `List<Integer>` is not a subtype of `List<Number>`
- `Set<Integer>` is not a subtype of `Set<Number>`

- Summary:
  - subtyping works in the type if the parameters are the same
  - changing the parameters removes any subtype relationships

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>`**

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`**

More examples

```
<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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Wildcards

[Compare to earlier version]

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

- Equivalent to

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

- Idiomatic Java

Wildcards

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

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

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);
```

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
    - ¯_(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 `Giraffe`s only (no `Zebra`s)
- Former allows anything that is a subtype of `Foo` in the same list

  Example: `List<Animal>` could store `Giraffe`s and `Zebra`s

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;

List<? extends Integer> lei;
```

First, which of these is legal?

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

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

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

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

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`o = lei.get(0);`

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~~`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>;`
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Legal operations on wildcard types

```
Object o;
Number n;
Integer i;
PositiveInteger p;

List<? super Integer> lsi;
```

First, which of these is legal?

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

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

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lsi.add(o);
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o = lsi.get(0);
n = lsi.get(0);
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Object o;
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`lsi.add(i);`

`lsi.add(p);`

`lsi.add(null);`

`o = lsi.get(0);`

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

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~~`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

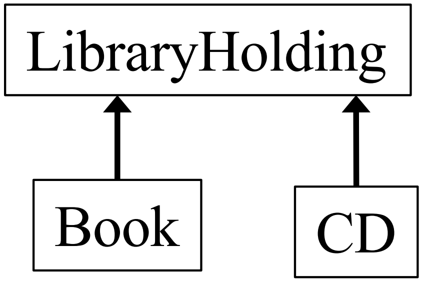
Surprise!

- 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

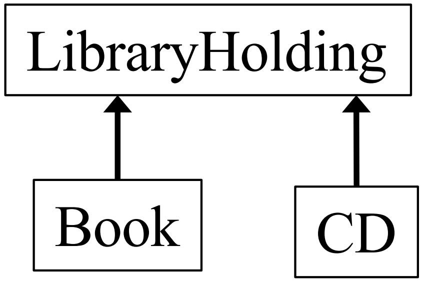
Programmers can use this subtyping to “do okay stuff”



```
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
```

DEMO

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*

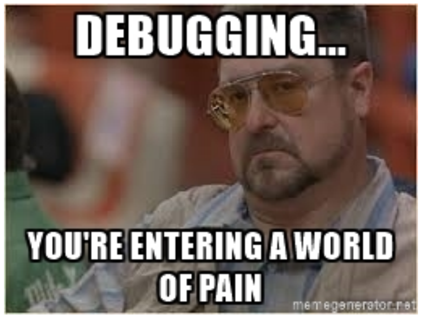
Usually, if you think you need to do this, you're wrong
  - a real need to do this is extremely rare

`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());
  }
  …
}
```

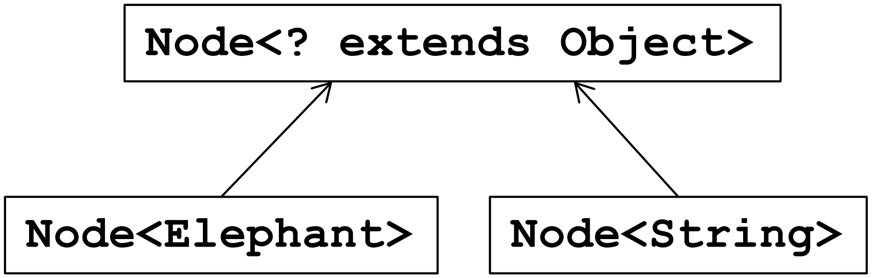
More erasure: At run time, do not know what `E` is and will not be checked, so don’t indicate otherwise

`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