CSE 331
Software Design & Implementation

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Generics

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

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;
```

Why we *love* abstraction

Hide details

- avoid getting lost in details (readability)
- permit details to change later on (changeability)

Give a *meaningful name* to a concept (readability)

Permit *reuse* in new contexts

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

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>
```

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

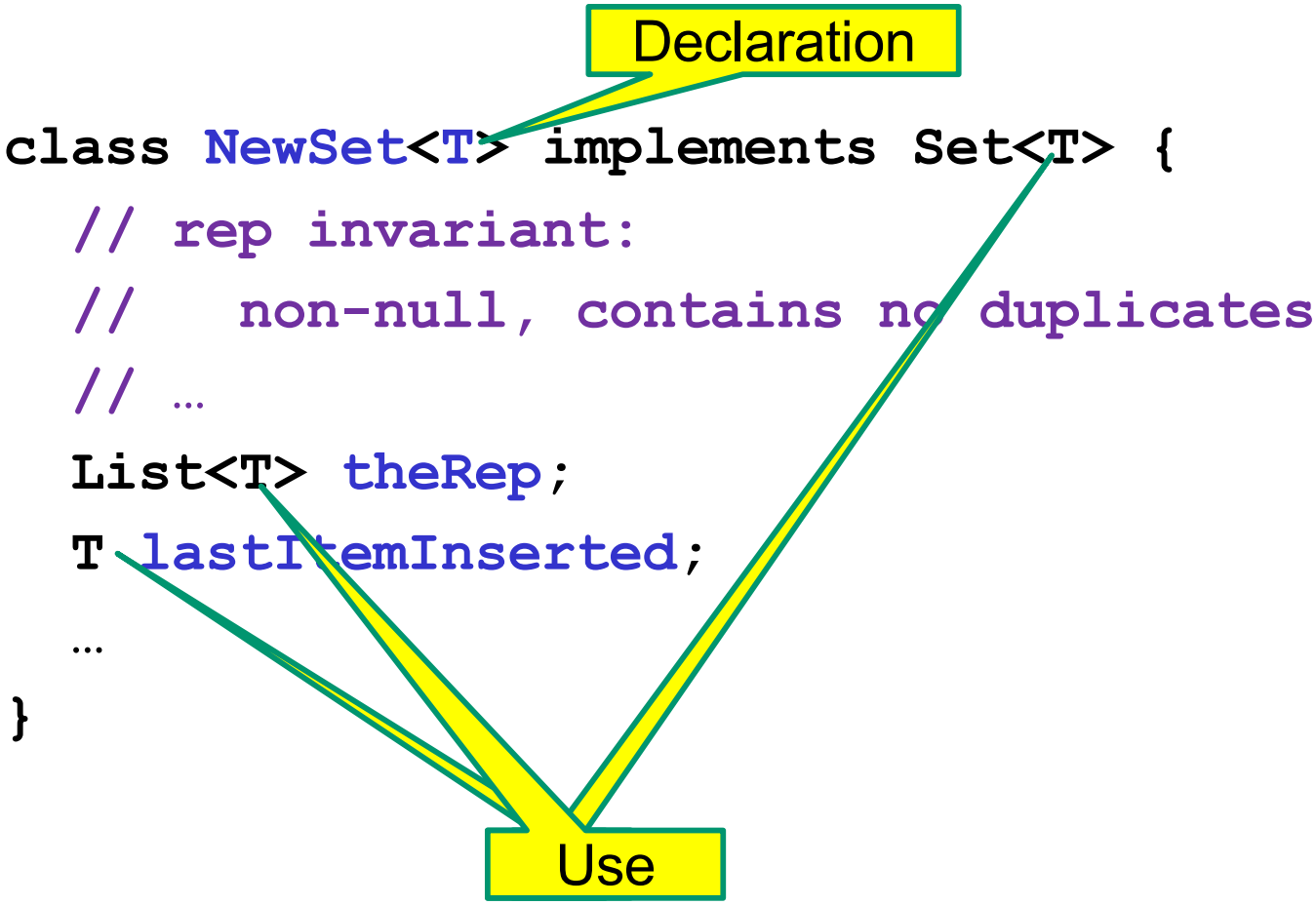
```
interface ListOfIntegers {
  boolean add(Integer elt);
  Integer get(int index);
}
```

- 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



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>
```

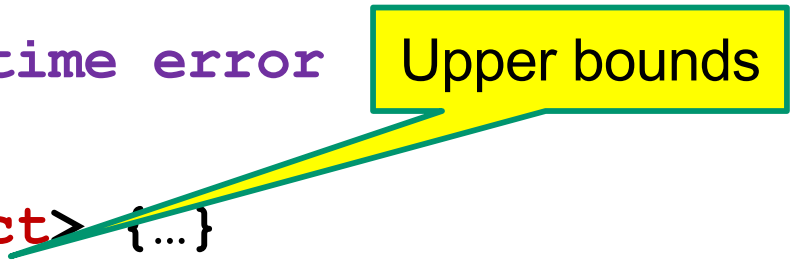
Restricting instantiations by clients

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

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.intValue();  // compiler error, E might not
                     // support intValue
  }
}

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

More examples

```
public class Graph<N> implements Iterable<N> {
  private final Map<N, Set<N>> node2neighbors;
  public Graph(Set<N> nodes, Set<Pair<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
- Now:
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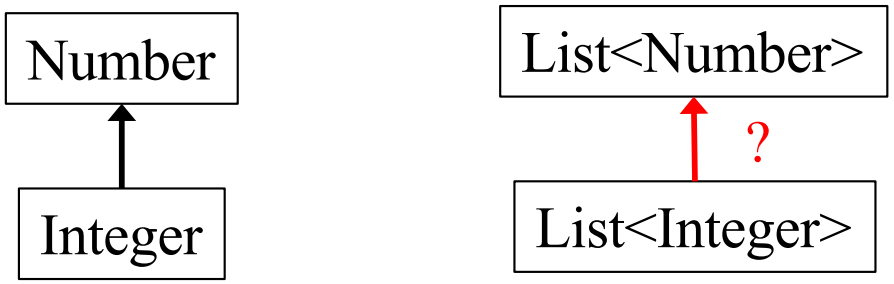
Generics and subtyping



- **`Integer`** can be used wherever **`Number`** is expected
  - this is the notion of a subtype
    - (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?

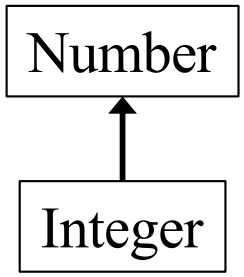
Generics and subtyping

```
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

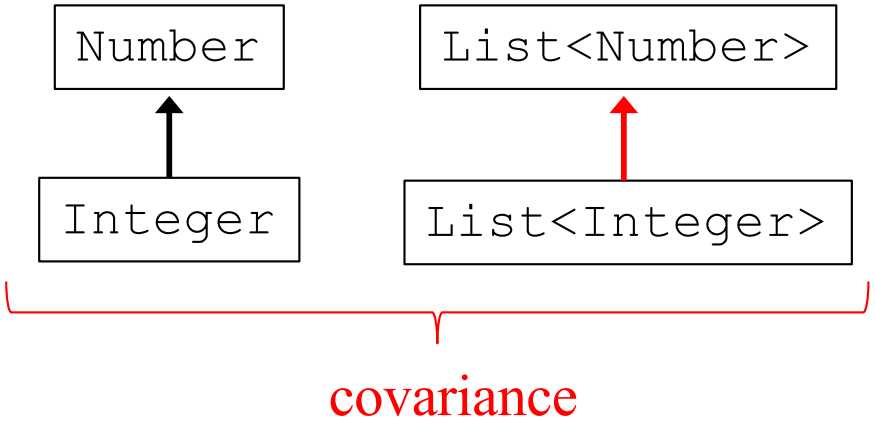
```
interface List<T> {
  T get(int index);
}
```

So type `List<Number>` has:

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

So type `List<Integer>` has:

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



So *covariant* subtyping would be correct:

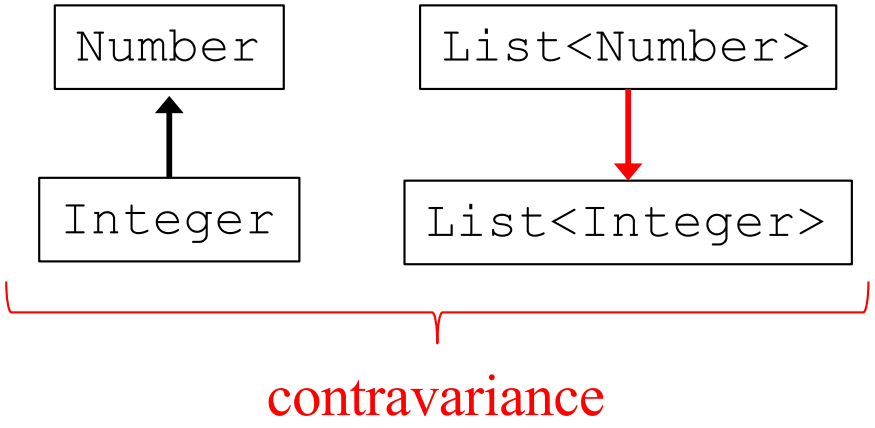
- `List<Integer>` a subtype of `List<Number>`

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?

- Done:
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  - using *bounds* for more flexible subtyping
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  - related digression: Java's *array subtyping*
  - Java realities: type erasure
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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`

Generic methods get around invariance

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

- Java subtyping is invariant with respect to type parameters

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

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

Revisit copy method

Earlier we saw this:

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

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

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

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Examples

[Compare to earlier version]

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

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

Wildcards

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

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

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

- each **`?`** stands for some possibly-different unknown type

More examples

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

- No change because `T` used more than once

Wildcards

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

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

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

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

More examples

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

Why this works:

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

PECS: Producer Extends, Consumer Super

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

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

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

More on lower bounds

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

```
<T super Foo> void m(Bar<T> x);
```

  - no good reason for Java not to support such lower bounds except designers decided it wasn't useful enough to bother
    - ¯_(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