CSE 331
Software Design & Implementation

James Wilcox & Kevin Zatloukal

Fall 2022

Generics

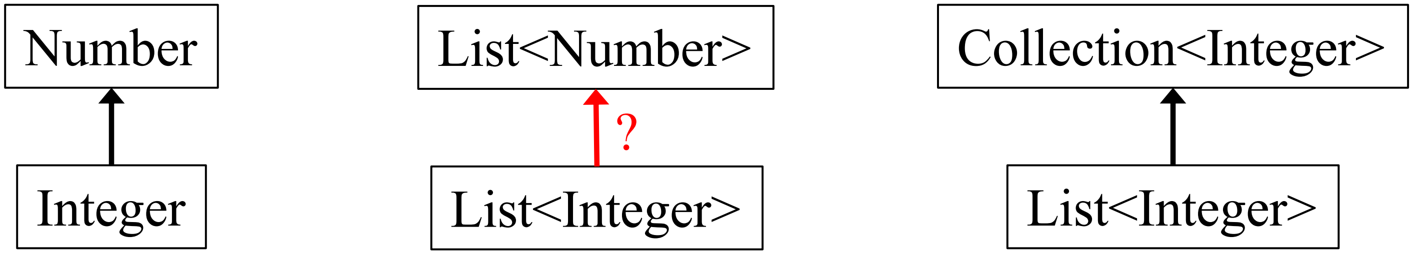
Generic Classes

```
class NewSet<T> implements Set<T> {

  // rep invariant:
  //   non-null, contains no duplicates
  // …
  List<T> theRep;
  T lastItemInserted;
  …

}
```

Generics and subtyping



Number

Integer

List<Number>

?

List<Integer>

Collection<Integer>

List<Integer>

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

Consequences of invariant subtyping

```
class Utils {
  static double sumList(List<Number> lst) {
      double result = 0.0;
      for (Number n : lst) {
        result += n.doubleValue();
      }
      return result;
  }
}
```

Cannot pass **`List<Double>`** to this method!

- **`List<Double>`** is not a subtype of **`List<Number>`**

Generic Methods

```
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;
  }
}
```

Can now pass `List<Double>` to this method

- Java can see that this is safe by checking the method body
- generic methods work around limitations of generic classes

Where are we?

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

- Now:
  - generics and *subtyping*
  - generic *methods* [not just using type parameters of class]
  - 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

More verbose first

Last Time:

- 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)

Today: *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);
}
```

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

Can pass a **`List<Integer>`** to **`addAll`** for a **`Set<Number>`**

- **`List<Integer>`** is a subtype of **`Collection<Integer>`**
- **`Collection<Integer>`** is allowed above
  - have **`T`** = **`Integer`** and **`E`** = **`Number`**

Where are we?

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

- Now:
  - generics and *subtyping*
  - generic *methods* [not just using type parameters of class]
  - using *bounds* for more flexible subtyping
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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`**

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

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

`?` 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<Number>` and `List<? extends Number>`:

- can instantiate `?` with `Number`, `Integer`, `Double`, …
- first version is much more restrictive

Non-example

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

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

- must choose a name to say that two types must match

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
- use a wildcard when you would use a type variable only once (no need to give it a name)
- communicates to readers of your code that the type's "identity" is not needed anywhere else

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`

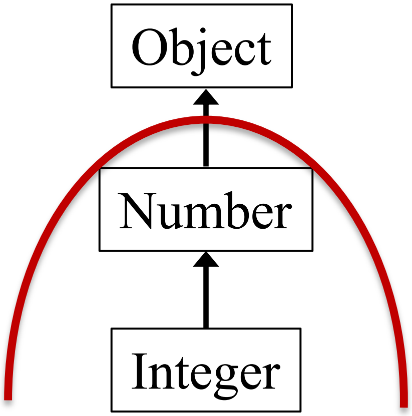
Wildcard can have lower bounds instead of upper bounds!

- says that `?` must be `Type` or a superclass of `Type`

Type Bounds

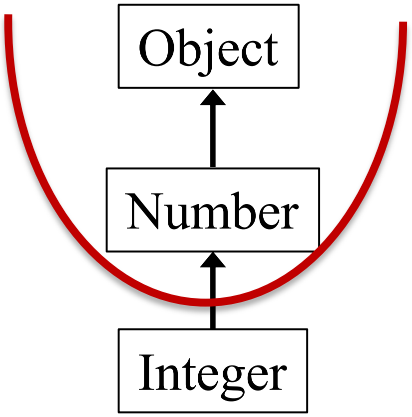
Upper Bound

`? extends Number`



Lower bound

`? super Number`



Revisit copy method

First version:

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

More general version:

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

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)_/¯

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

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Legal operations on wildcard types

```
Object o;
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Which of these is legal?

```
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>();
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Which of these is legal?

```
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>();
```

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Which of these is legal?

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o = lei.get(0);
n = lei.get(0);
i = lei.get(0);
```

~~`p = lei.get(0);`~~

```
lei.add(o);
lei.add(n);
lei.add(i);
lei.add(p);
lei.add(null);
```

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`lei.add(null);`

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

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Object o;
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`lsi.add(i);`
`lsi.add(p);`
`lsi.add(null);`
`o = lsi.get(0);`
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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);`~~

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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
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  - related digression: Java's *array subtyping*
  - Java realities: type erasure
    - unchecked casts
    - **`equals`** interactions
    - creating generic arrays

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

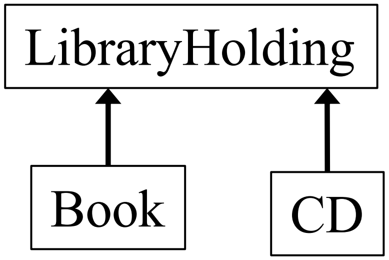
Surprise!

- 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

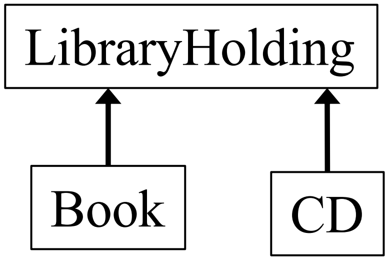
Programmers can use this subtyping to “do okay stuff”



```
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

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*
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  - related digression: Java's *array subtyping*
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Type erasure

All generic types become type **`Object`** once compiled

```
List<String> lst = new ArrayList<String>();
```

at runtime, becomes

```
List<Object> lst = new ArrayList<Object>();
```

Generics are purely a ***compiler*** feature!

Type erasure example

```
import java.util.*;

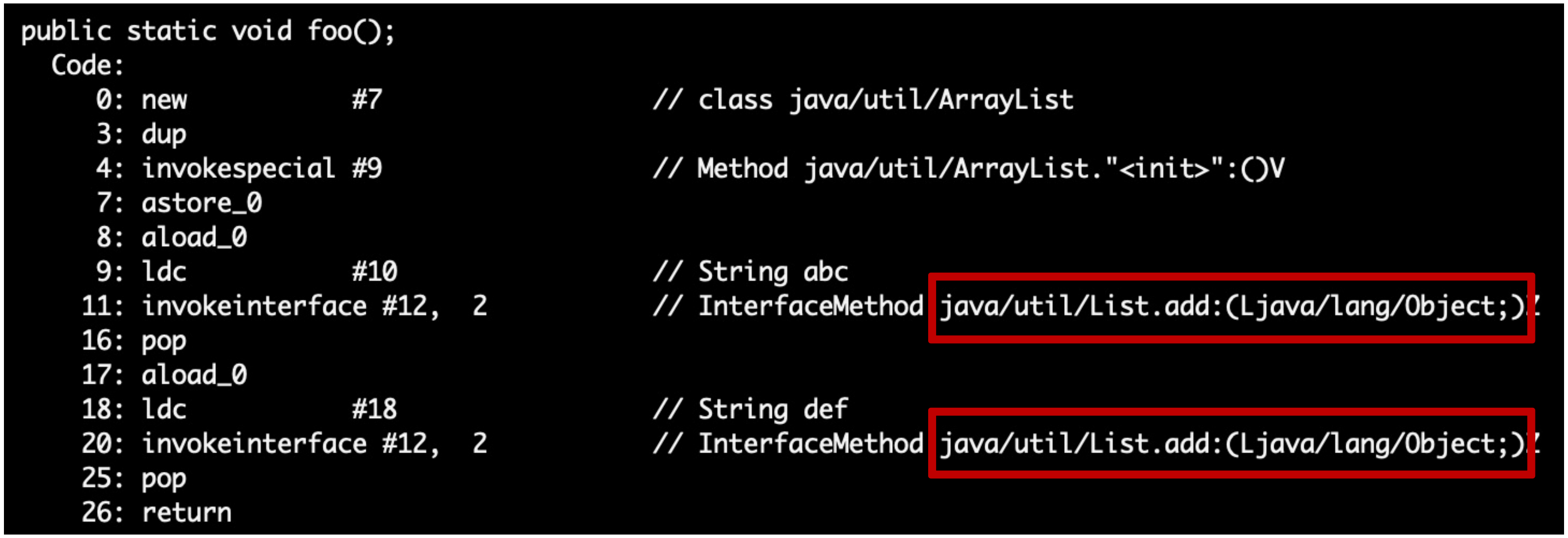
public class Erasure {

  public static void foo() {
    List<String> lst = new ArrayList<String>();
    lst.add("abc");
    lst.add("def");
  }

}
```

Type erasure example

Compile-time signature is **`add(String)`** but the bytecodes say…



```
public static void foo();
  Code:
     0: new           #7                  // class java/util/ArrayList
     3: dup
     4: invokespecial #9                  // Method java/util/ArrayList."<init>":()V
     7: astore_0
     8: aload_0
     9: ldc           #10                 // String abc
    11: invokeinterface #12,  2           // InterfaceMethod java/util/List.add:(Ljava/lang/Object;)Z
    16: pop
    17: aload_0
    18: ldc           #18                 // String def
    20: invokeinterface #12,  2           // InterfaceMethod java/util/List.add:(Ljava/lang/Object;)Z
    25: pop
    26: return
```

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

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<E>)) {
      return false;
    }
    Node<E> n = (Node<E>) obj;
    return this.data.equals(n.data);
  }
  …
}
```

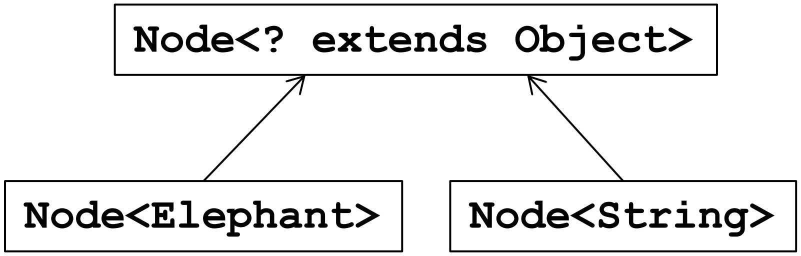
More erasure: At run time, do not know what **`E`** is and will not be checked, so don't indicate otherwise

`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

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 always make the client code prettier and safer
- Generics usually clarify the *implementation*
  - (but sometimes uglify: wildcards, arrays, instantiation)

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