CS2030 Lecture 4

Generics and Variance of Types

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Lecture Outline

- Generics
  - Generic type, classes and methods
  - Auto-boxing and unboxing
  - Sub-typing and variance of types
    - Covariant, contravariant and invariant
  - Wildcards
    - Upper-bounded and lower-bounded
- Java Collections Framework
  - `Collection` / `List` interfaces
  - `Comparator` interface
- Type erasure

Creating a Generic Box

"Create a `Box` to store one object (of *any* type). Retrieve the object using a method `get()` so that it can be operated upon."

- E.g. `new Box("abc").get().length()` will return `3`
- How to define a "generic" `Box` class to hold any object?
  - **abstraction principle**: avoid defining similar classes with duplicate code: `StringBox`, `PointBox`, ...
  - consider declaring the internal object with type `Object` since every other object is an `Object`?
- *Keep in mind this notion of a "box", as it will come in very handy when discussing certain FP concepts later...*

A “Generic” Box using `Object`

```
class Box {
    private final Object t;

    Box(Object t) {
        this.t = t;
    }

    Object get() {
        return t;
    }

    @Override
    public String toString() {
        return "[" + t + "]";
    }
}
```

```
jshell> new Box("chocolate")
$.. ==> [chocolate]

jshell> new Box("chocolate").get()
$.. ==> "chocolate"

jshell> new Box("chocolate").get().length()
|  Error:
|  cannot find symbol
|    symbol:   method length()
|  new Box("chocolate").get().length()
|  ^--------------------------------^
```

- Calling method `get()` on a `Box` returns an `Object` type
  - requires an explicitly cast to a “known” compile-time type

```
jshell> ((String) new Box("chocolate").get()).length()
$.. ==> 9
```

Generic Type

"allows a type or method to operate on objects of various types while providing compile-time type safety"

- Since Java 5, generics has been added to eliminate the "drudgery of casting"
- Class/interface or method definitions can now include a type parameter section consisting of type parameters T_i enclosed with angle brackets (e.g. < $\mathsf{T}_1, \mathsf{T}_2, \mathsf{T}_3, \ldots$ >)
- Type parameters can then be used anywhere within the class/interface or method
- Generic typing is also known as **parametric polymorphism**
  - replace type parameters with concrete types

Generic Classes

- Declare the class `Box<T>` with a generic type parameter `T` to support parametric polymorphism, e.g. objects of type `Box<String>`, `Box<Object>`, ...

```
class Box<T> {
    private final T t;

    Box(T t) {
        this.t = t;
    }

    T get() {
        return t;
    }

    @Override
    public String toString() {
        return "[" + t + "]";
    }
}
```

```
jshell> Box<String> box = new Box<String>("abc")
box ==> [abc]

jshell> box.get()
$.. ==> "abc"

jshell> box.get().length()
$.. ==> 3
```

Generic Method

- Can also define generic methods with its own type parameter

```
jshell> <T> Box<T> of(T t) { return new Box<T>(t); }
|  created method of(T)

jshell> Box<String> box = of("abc")
box ==> [abc]
```

- The scope of type parameter T is within the method
- Use the same idea to define a static method in class Box<T>

```
class Box<T> {
    private final T t;
    ...
    static <T> Box<T> of(T t) { // can replace <T> with <U> also
        return new Box<T>(t);
    }
```

  - declaration of two type parameters T: one within the class enclosing scope, the other within an inner method scope

Generic `Box` Class

```
class Box<T> {
    private final T t;

    private Box(T t) {
        this.t = t;
    }

    T get() {
        return t;
    }

    static <T> Box<T> of(T t) {
        return new Box<T>(t);
    }

    @Override
    public String toString() {
        return "[" + t + "]";
    }
}
```

```
jshell> Box<String> box = Box.of("abc")
box ==> [abc]

jshell> box.get()
$.. ==> "abc"

jshell> box.get().length()
$.. ==> 3
```

Auto-boxing and Unboxing

- Only reference types are allowed as type arguments; primitives are auto-boxed/unboxed, e.g. in the case of `Box<Integer>`

```
jshell> Box<Integer> box = Box.of(123)
box ==> [123]

jshell> Integer x = Box.of(123).get()
x ==> 123

jshell> int y = Box.of(123).get()
y ==> 123
```

  - Placing an `int` value into `Box<Integer>` causes it to be **auto-boxed** into an `Integer` type
  - Getting an `Integer` value out of `Box<Integer>` and assigning to an `int` primitive type variable causes the `Integer` return value to be **(auto-)unboxed**

Variance of Types

- **LSP** re-defined: S is a **sub-type** of T (denoted `S <: T`) if a piece of code written for variables of type T can be used on variables of type S while ensuring type-safety
- Let `S <: T` with *simple types* `S`, `T` denoting classes/interfaces
  - **covariance**: when subtype relation is preserved in *complex types*, e.g. Java arrays are covariant `S[] <: T[]`

    ```
    Shape s = new Circle(1); Shape[] shapes = new Circle[10];
    ```
  - **contravariant**: when subtype relation is reversed for *complex types (more on this later..)*
  - **invariant**: when its neither covariant nor contravariant, e.g. Java generics are invariant

    ```
    Box<Shape> shapes = new Box<Circle>();   // error
    Box<Circle> circles = new Box<Circle>(); // ok
    ```

Wildcards

- Due to invariance in generics, the parameterized type can be inferred from the type declaration of the variable, i.e.

  `Box<Integer> box = new Box<Integer>(10);` can simply be

  ```
  Box<Integer> box = new Box<>(10);
  ```

- How do we then sub-type among generic types?

  ```
  jshell> Box<Integer> box = new Box<Integer>(10)
  box ==> [10]

  jshell> Box<Object> anybox = box
  |  Error:
  |  incompatible types: Box<Integer> cannot be converted to Box<Object>
  |  Box<Object> anyoox = box;
  ```

- Use the wildcard `?`, i.e. `Box<?> anyBox = new Box<Integer>(10);`
- `?` is not the `Object` type; try `new Box<?>(new Object())`
- use wildcard when specifying reference type of a variable

Wildcards

- Let's write an equals method for our `Box` class

```java
@Override
public boolean equals(Object obj) {
    if (this == obj) {
        return true;
    } else if (obj instanceof Box) {
        Box<?> anyBox = (Box<?>) obj;
        return this.get().equals(anyBox.get()); // or vice-versa
    } else {
        return false;
    }
}
```

- What happens if you cast to `(Box<T>)` instead?

```
$ javac Box.java -Xlint:unchecked
Box.java:..: warning: [unchecked] unchecked cast
            Box anyBox = (Box<T>) obj;
                                  ^
  required: Box<T>
  found:    Object
  where T is a type-variable:
    T extends Object declared in class Box
1 warning
```

Bounded Wildcards

- Suppose we have the following classes:

```
class FastFood { }
class Burger extends FastFood { }
class CheeseBurger extends Burger { }
```

- Consider the following

```
Box<Burger> box = ... // what are the possible assignments..
Burger burger = box.get(); // .. to get a Burger from a Box?
```

- Other than `Box<Burger>`, what other boxes can you get a `Burger` from, `Box<CheeseBurger>` or `Box<FastFood>`?
- `Box<CheeseBurger>`, since `CheeseBurger` is a `Burger`; however

```
jshell> Box<Burger> box = new Box<CheeseBurger>(new CheeseBurger())
|  Error:
|  incompatible types: Box<CheeseBurger> cannot be converted to Box<Burger>
|  Box<Burger> box = new Box<CheeseBurger>(new CheeseBurger());
|                    ^-----------------------------------^
```

Wildcards

- Let `Burger` form an upper bound of the wildcard — change parameterized type of the argument to `<? extends Burger>`

```
jshell> Box<? extends Burger> box = new Box<CheeseBurger>(new CheeseBurger())
box ==> [CheeseBurger@28d25987]

jshell> Burger burger = box.get()
burger ==> CheeseBurger@28d25987
```

- **Upper-bounded wildcard**: `? extends Burger`
  - any type that is the sub class of `Burger`, including itself
- How about putting a `Burger` into a box?

```
// tweak Box class to make it mutable, and include methdo: void put(Burger)
Box<something> box = ... // what are the possible assignments..
box.put(new Burger()); // .. to put a Burger into the box?
```

- Other than `Box<Burger>`, what other boxes can a `Burger` be put into, `Box<CheeseBurger>` or `Box<FastFood>`?

Wildcards

- `Box<FastFood>`, since `Burger` is a `FastFood`

```
jshell> Box<Burger> box = new Box<Burger>(new Burger())
box ==> [Burger@17d0685f]

jshell> box.put(new Burger()) // more like replace, but nevermind...

jshell> Box<FastFood> box = new Box<FastFood>(new FastFood())
box ==> [FastFood@78ac1102]

jshell> box.put(new Burger())
```

- But how to make the variable type declaration the same?
  - replace with `Box<? super Burger> box`

```
jshell> Box<? super Burger> box = new Box<Burger>(new Burger())
box ==> [Burger@365185bd]

jshell> box.put(new Burger())

jshell> box = new Box<FastFood>(new FastFood())
box ==> [FastFood@42607a4f]

jshell> box.put(new Burger())
```

Wildcards

- `Burger` now forms a lower bound of the wildcard — change parameterized type of the argument to `<? super Burger>`
- **Lower-bounded wildcard**: `? super Burger`
  - any type that is the super class of `Burger`, including itself
- **Get and Put Principle:**
  - Use an extends wildcard to get values out of a structure; use a super wildcard to put values into a structure.
- What about getting and putting into a `Box<Burger>`?

```
jshell> Box<Burger> box = new Box<Burger>(new Burger()) // any other way?
box ==> [Burger@28d25987]

jshell> Burger oldBurger = box.get()
oldBurger ==> Burger@28d25987

jshell> box.put(new Burger())
```

Covariance versus Contravariance

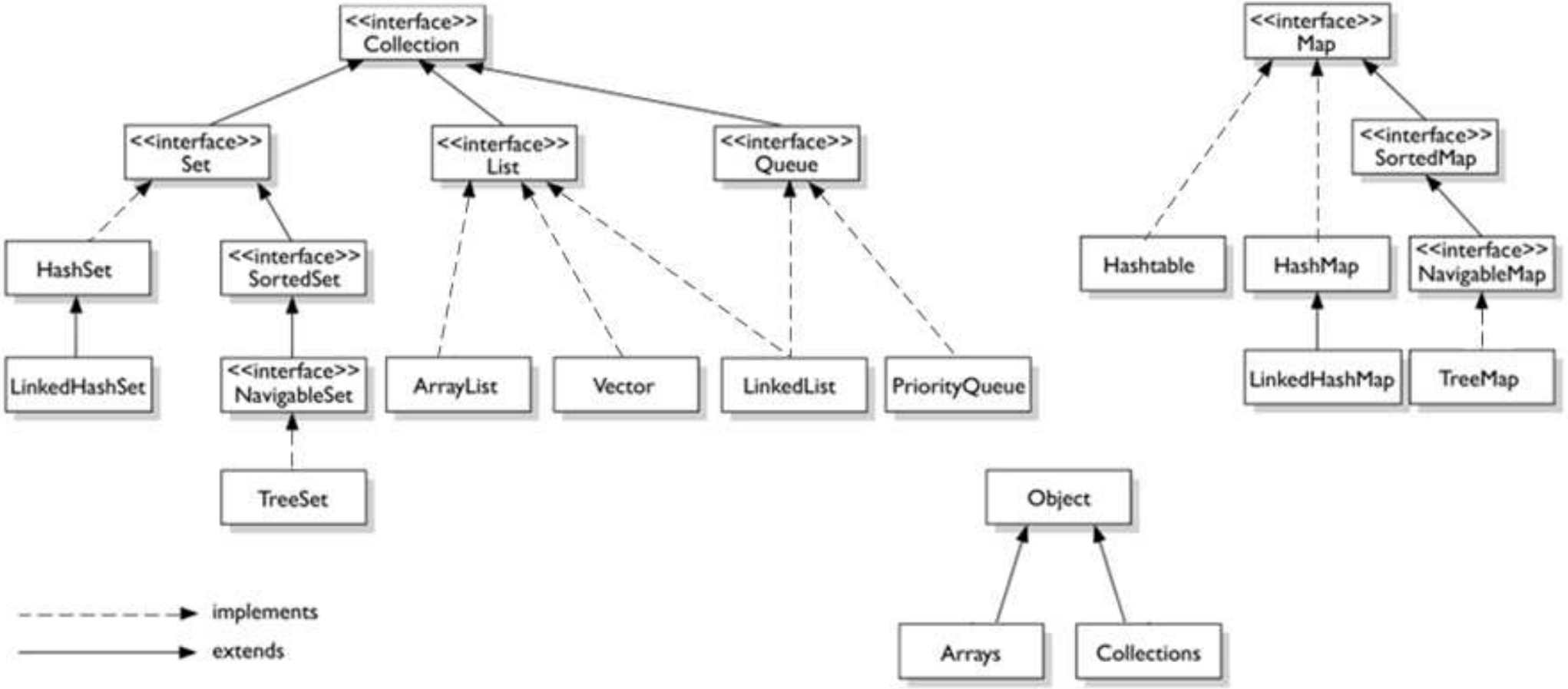
- Let the complex-type `C<T>` be a class/interface having a simple-type parameter `T`
- Covariance — supports get:
  - `? extends` is covariant since sub-type relation is **preserved** between simple and complex types
  - if `S <: T`, then `C<S> <: C<? extends T>`

    `CheeseBurger <: Burger` $\implies$ `Box<CheeseBurger> <: Box<? extends Burger>`
- Contravariance — supports put:
  - `? super` is contravariant since the sub-type relation is **reversed** between simple and complex types
  - if `S <: T`, then `C<T> <: C<? super S>`

    `Burger <: FastFood` $\implies$ `Box<FastFood> <: Box<? super Burger>`

Java Collections Framework

- JCF specifies interfaces with common operations that can be performed *generically* on various type of collections



JCF: `interface Collection<E>`

- *Generic interface* parameterized with a type parameter `E`
- `toArray(T[])` is a generic method; the caller is responsible for passing the right type*
- `containsAll`, `removeAll`, and `retainAll` has parameter type `Collection<?>`, we can pass in a Collection of any reference type to check for equality
- `addAll` has parameter declared as `Collection <? extends E>`; we can only add elements that are upper-bounded by `E`

```
public interface Collection<E>
        extends Iterable<E> {
    boolean add(E e);

    boolean contains(Object o);

    boolean remove(Object o);

    void clear();

    boolean isEmpty();

    int size();

    Object[] toArray();

    <T> T[] toArray(T[] a);

    boolean addAll(Collection<? extends E> c);

    boolean containsAll(Collection<?> c);

    boolean removeAll(Collection<?> c);

    boolean retainAll(Collection<?> c);
    :
}
```

**otherwise, an `ArrayStoreException` will be thrown*

JCF: class ArrayList<E>

void	add(int index, E element)	Inserts the specified element at the specified position in this list.
boolean	add(E e)	Appends the specified element to the end of this list.
void	clear()	Removes all of the elements from this list.
boolean	contains(Object o)	Returns true if this list contains the specified element.
E	get(int index)	Returns the element at the specified position in this list.
int	indexOf(Object o)	Returns the index of the first occurrence of the specified element in this list, or -1 if this list does not contain the element.
boolean	isEmpty()	Returns true if this list contains no elements.
E	remove(int index)	Removes the element at the specified position in this list.
boolean	remove(Object o)	Removes the first occurrence of the specified element from this list, if it is present.
E	set(int index, E element)	Replaces the element at the specified position in this list with the specified element.
int	size()	Returns the number of elements in this list.
void	trimToSize()	Trims the capacity of this ArrayList instance to be the list's current size.

- Examples of methods specified in interface `Collection<E>`:
  - `size()`, `isEmpty()`, `contains(Object)`, `add(E)`, `remove(Object)`, `clear`
- Examples of methods specified in interface `List<E>`:
  - `indexOf(Object)`, `get(int)`, `set(int, E)`, `add(int, E)`, `remove(int)`,

JCF: `interface List<E>`

- `List<E>` interface extends `Collection<E>`
  - for ordered collections of possibly duplicate objects
  - classes that implement `List<E>` include `ArrayList`, `Vector` and `LinkedList`, e.g.

```
List<Integer> ints = new ArrayList<Integer>();
```

    - **covariance**: `S <: T` $\Longrightarrow$ `S<E> <: T<E>`

- `List<E>` specifies a sort method with a default implementation

```
default void sort(Comparator<? super E> c)
```

- `sort` method takes as argument an object with a generic interface `Comparator<? super E>` (*why super?*)

The `Comparator<T>` Interface

```
public interface Comparator<T> {
    int compare(T o1, T o2);
    ...
}
```

- `compare(o1, o2)` returns 0 if the two elements are equal, < 0 if `o1` is "less than" `o2`, or > 0 otherwise

```
import java.util.Comparator;

class NumberComparator implements Comparator<Integer> {
    @Override
    public int compare(Integer s1, Integer s2) {
        return s1 - s2;
    }
}
```

```
jshell> List<Integer> nums = Arrays.asList(3, 1, 2);
nums ==> [3, 1, 2]

jshell> nums.sort(new NumberComparator())

jshell> nums
nums ==> [1, 2, 3]
```

Type Erasure

- Compiler performs type checking/inference, and generates non-generic bytecode (erasure) for backward compatibility
  - type parameters are replaced with either `Object` if it is unbounded, or the bound if it is bounded

```
class Box { // bytecode generated from this "type-erased" version
    private final Object t;
    private Box(Object t) { this.t = t; }
    Object get() { return t; }
    static Box of(Object t) { return new Box(t); }
```

  - type arguments are erased during compile time; generics allow the creation of raw types (should be avoided)

```
jshell> Box raw = Box.of("abc")  // possible, but bad practice
raw ==> [abc]

jshell> Box<Integer> box = raw   // erasure becomes: Box box = raw
|  Warning: unchecked conversion // warning ensues but still compilable
|    required: Box<java.lang.Integer>
|    found:    Box
box ==> [abc]                    // still runs
```

Lecture Summary

- Appreciate the use of Java generics in classes and methods
- Understand autoboxing and unboxing involving primitives and its wrapper classes
- Understand parametric polymorphism and the sub-typing mechanism, e.g. given `Burger <: FastFood`
  - covariant: `Burger[] <: FastFood[]`
  - covariant: `ArrayList<Burger> <: List<Burger>`
  - covariant: `Box<Burger> <: Box<? extends FastFood>`
  - contravariant: `Box<FastFood> <: Box<? super Burger>`
  - invariant: Neither `Box<Burger> <: Box<FastFood>` nor `Box<FastFood> <: Box<Burger>`
- Familiarity with usage of the Java Collections Framework