CSE 331
Software Design and Implementation

Lecture 15
Generics⟨2⟩

Leah Perlmutter / Summer 2018

Announcements

Announcements

- Quiz 5 is due tomorrow
- Homework 6 due tomorrow
- Section tomorrow!
  - Subtyping – now with worksheet!
  - HW7 (Dijkstra's algorithm)

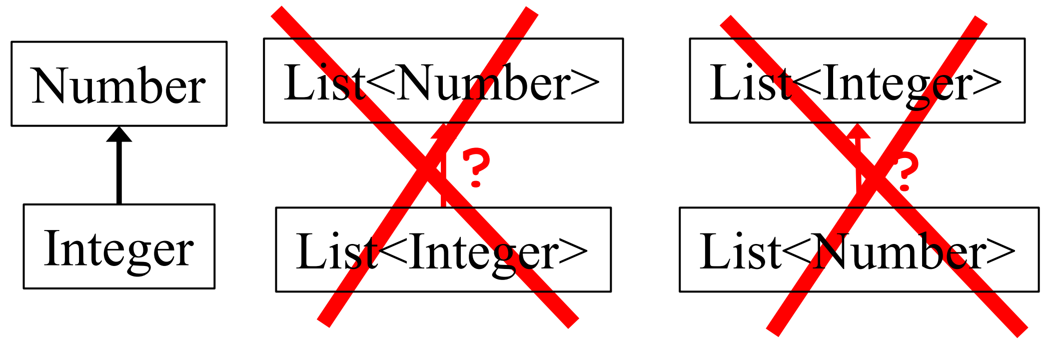
Big picture

- Last time: Generics intro
- *Subtyping* and Generics
- Using *bounds* for more flexible subtyping
- Using *wildcards* for more convenient bounds
- Digression: Java's *unsoundness*(es)
- Java realities: *type erasure*

Review

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);
```

- Subtype needs stronger spec than super

- Stronger method spec has:
   - weaker precondition
   - stronger postcondition

Java subtyping is *invariant* with respect to generics

- Neither **List<Number>** nor **List<Integer>** subtype of other
- Not covariant and not contravariant

Generic types and subtyping

- **`List<Integer>`** and **`List<Number>`** are not subtype-related
  - No subtyping relationships based on the type argument

- Generic types can have subtyping relationships relying on the "base" type

- 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>`**
  - …

Overview

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Overview: Bounds and Wildcards

Now: *Type bounds* e.g. **`<T extends Number>`**

- 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

Next: *Java wildcards* e.g. **`<? extends Number>`**

- 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

Bounds

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
- This is not related to invariant subtyping [yet]

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);
```

Too restrictive:

- Client cannot pass a **List<Integer>** to **addAll** for a **Set<Number>**
- Should be okay because **addAll** implementations only need to read from **c**, not put elements in 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: A bounded generic type parameter

- Now client *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`**
  - So 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 useful to clients:

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

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Wildcards

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 supertype 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 exactly once, so 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 versions using explicit generic types]

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

- More flexible than `void addAll(Collection<E> c);`
- More idiomatic than (but semantically identical to) `<T extends E> void addAll(Collection<T> 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

Where should you insert wildcards?

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
- Use **`? super T`** when you *put* values (into a *consumer*)
  - No problem if it's a supertype
- Use neither (just **`T`**, not **`?`**) if you both *get* and *put*

```
<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"
- For upper-bound **`? exends T`**, we could always rewrite it not to use 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

`?` 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>`** is restrictive; 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 but not **`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

Reasoning about wildcard types

Consider all possible instantiations of the wildcard type!

Reasoning about 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);~~

Reasoning about 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);`~~

Summary: Wildcards

`? extends Type`, some unspecified subtype of **`Type`**

`? super Type`, some unspecified supertype 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 exactly once, so no need to give it a name

Reasoning about Wildcards

- Consider all possible instantiations of the wildcard type!

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Type Unsoundness

Type systems

- Prove absence of certain run-time errors
- In Java:
  - methods/fields guaranteed to exist
    - compare to, eg, python
  - programs without casts don't throw ClassCastExceptions
- Type system *unsound* if it fails to provide its stated guarantees

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??

Array subtyping

- 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[]`**
  - Not true subtyping: the subtype does not support setting an array index to hold a **`Type2`**
  - Java (and C#) made this decision in pre-generics days
    - Else cannot write reusable sorting routines, etc.
  - Backwards compatibility means it's here to stay

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Type Erasure

Type erasure

All generic types become type `Object` once compiled

- Big reason: backward compatibility with ancient byte code
- So, 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<String> cs = new ArrayList<String>();
  if (cs instanceof Collection<String>) { // illegal
  ...
}
```

Type Erasure: Consequences

```
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

(Actual type info not available at runtime)

Generics and casting

Casting to generic type results in an important warning

NEVER DO THIS!

```
List<Cat> cats = new ArrayList<Cat>();  // ok
List<?> mystery = cats;
List<String> ls = (List<String>) mystery; // warn
ls.add("not a cat"); // undetected error
...
Cat c = cats.remove(0); // ClassCastException
```

- Compiler gives an unchecked warning, since this is something the runtime system *will not check for you*
- Usually, if you think you need to do this, you're wrong

`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 unless unchecked casts involving generics are used
  - Compiler inserts casts to/from **`Object`** for generics
    - If these casts fail, hard-to-debug errors result: Often far from where conceptual mistake occurred
- Don't ignore warnings!
  - You're violating good style/design/subtyping/generics
  - 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());
  }
  …
}
```

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

`Node<? extends Object>`

`Node<Elephant>` `Node<String>`

Summary: Type Erasure

- At runtime, Java does not know the exact types of generics
- Sort of awkward but required for backward compatibility

Wrapup

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);
  …
}
```

Tips when writing a generic class

- 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

- As you gain experience, it will be easier to write generic code from the start

Summary

Type bounds e.g. **`<T extends Number>`**

- Make code more flexible!

Java wildcards

- Anonymous type variables (used only once)
- **`? extends Type`**, some unspecified subtype of **`Type`**
- **`? super Type`**, some unspecified supertype of **`Type`**

Type Erasure

- Java doesn’t know generic types at runtime
  - necessary for backward compatibility

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- Section tomorrow!
  - Subtyping – now with worksheet!
  - HW7 (Dijkstra's algorithm)