CSE 331
Software Design and Implementation

Lecture 14
Generics 2

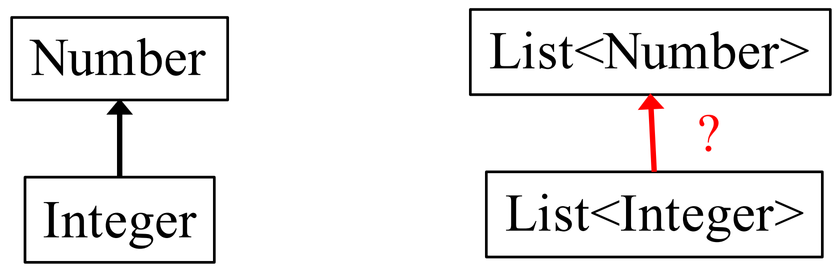
James Wilcox / Winter 2016

Hi, I’m James!

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*

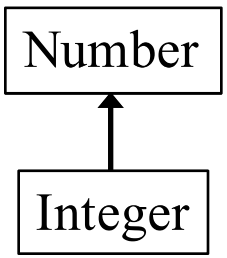
Generics and subtyping



- **`Integer`** is a subtype of **`Number`**
- Is **`List<Integer>`** a subtype of **`List<Number>`**?
- Use subtyping rules (stronger, weaker) to find out…

`List<Number>` and `List<Integer>`

```java
interface List<T> {
  boolean add(T elt);
  T get(int index);
}
```



So type **`List<Number>`** has:

```java
  boolean add(Number elt);
  Number get(int index);
```

So type **`List<Integer>`** has:

```java
  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

Invariance of Java's subtyping

If **`Type2`** and **`Type3`** are different,

then **`Type1<Type2>`** is *not* a subtype of **`Type1<Type3>`**

Previous example shows why:

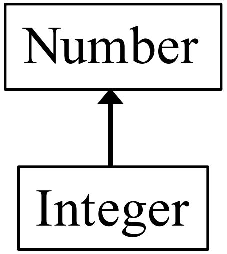
- Observer method prevents "one direction"
- Mutator/producer method prevents "the other direction"

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:

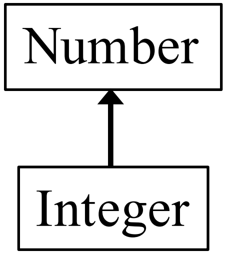
- **`List<Integer>`** a subtype of **`List<Number>`**

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

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*

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

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
- 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);
}
```

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*

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 **`? sub 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

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>();`

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

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

List<? super Integer> lsi;
```

First, which of these is legal?

```java
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);`~~

```java
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);`~~

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*

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

Two unsoundnesses in Java

- One well-known and intentional
  - array subtyping
- One discovered this week(!!!)
  - a subtle interaction between generic bounds and null

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

Demos

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*

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<?> 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 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

- Most common real need is creating arrays with generic element types (discussed shortly), when doing things like implementing **`ArrayList`**.

`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
- So, two reasons not to 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());
  }
  …
}
```

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());
  }
  …
}
```

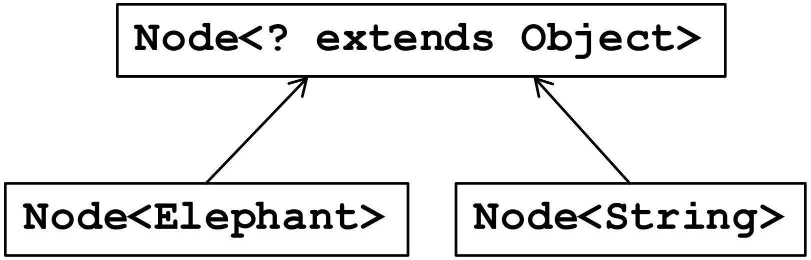
More erasure: At run time, do not know what **E** is and will not be checked, so don't indicate otherwise

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

(Actual type info 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, so it generates a warning
- Rare to need an array of a generic type (e.g., use **`ArrayList`**)

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 ugly: wildcards, arrays, instantiation
- Generics always make the client code prettier and safer

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