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>
```

Pre-generic Collection Use

Checking types were correct was done at run-time.

```
Hashtable h = new Hashtable();
h.put("abc", new Integer(3));
...
Integer val = (Integer) h.get("abc");
```

No compiler help to ensure type constraints are satisfied

Alternative: Many, Many Classes

```
interface ListOfNumbers {
  boolean add(Number elt);
  Number get(int index);
}

interface ListOfStrings {
  boolean add(String elt);
  String get(int index);
}
```

… and many, many more

Related abstractions

```
interface ListOfNumbers {
  boolean add(Number elt);
  Number get(int index);
}
interface ListOfStrings {
  boolean add(String elt);
  String 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

Declaration

```
class NewSet<T> implements Set<T> {
  // rep invariant:
  //   non-null, contains no duplicates
  // …
  List<T> theRep;
  T lastItemInserted;
  …
}
```

Use

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
```

Upper bounds

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?

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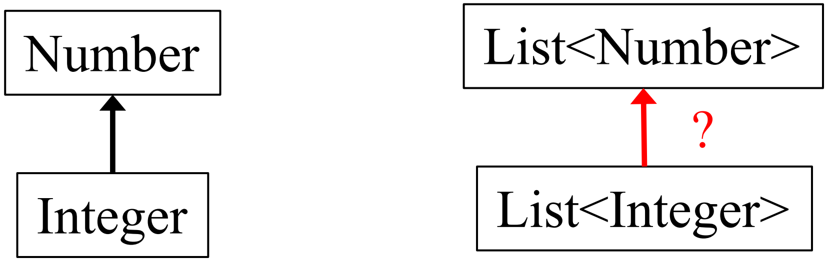
Generics and subtyping



- **`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?

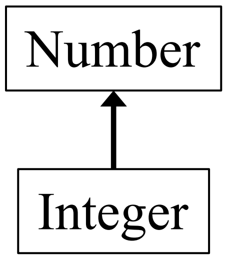
Generics and subtyping

```
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:

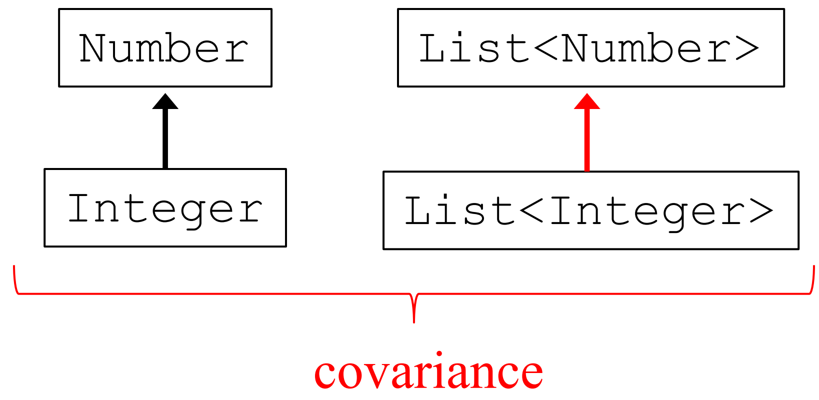
- Observer method prevents “one direction”
- Mutator/producer method prevents “the other direction”

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:

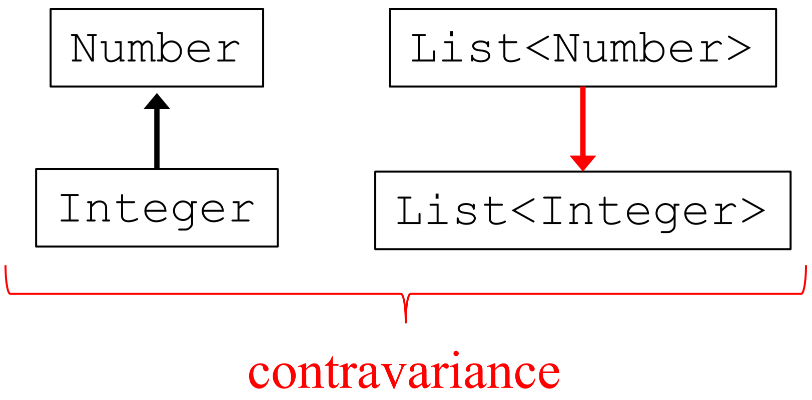
- **List<Integer>** a subtype of **List<Number>**

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>`**
  - …

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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**