CSE 331
Software Design & Implementation

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Generics

(Slides by Mike Ernst and David Notkin)

Varieties of abstraction

Abstraction over computation: procedures

```
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>
```

Applies to both computation and data

Why we ♥ abstraction

Hide details

- Avoid distraction
- Permit the details to change later

Give a meaningful name to a concept

Permit reuse in new contexts

- Avoid duplication: error-prone, confusing
- Programmers hate to repeat themselves – "lazy"

Programs include a group of abstractions

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

… and many, many more

```
interface List<E> {
  boolean add(E e);
  E get(int index);
}
```

Declares a new **variable**, called a **formal parameter**

Instantiate by passing an **Integer**:

```
lst.add(7);
aList.add(anInt);
```

The type of **add** is Integer → boolean

Declares a new **type variable**, called a **type parameter**

Instantiate by passing a type:

```
List<Float>
List<List<String>>
List<T>
```

The type of **List** is Type → Type

Type variables are types

Declaration

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

Use

Declaring and instantiating generics

```
// a parameterized (generic) class
public class Name<TypeVar,..., TypeVar> {
```

Convention: 1-letter name such as:

`T` for **`Type`**, **`E`** for **`Element`**, **`N`** for **`Number`**,

`K` for **`Key`**, **`V`** for **`Value`**, **`M`** for **`Murder`**

Class code refers to type parameter by name, e.g., **`E`**

To instantiate, client supplies type arguments

e.g., **`String`** as in **`Name<String>`**

Analogous to "constructing" a specific class from the generic definition

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
```

Using type variables

Code can perform any operation permitted by the bound

```
interface List1<E extends Object> {
  void m(E arg) {
    arg.asInt();  // compiler error, E might not
                  // support asInt
  }
}

interface List2<E extends Number> {
  void m(E arg) {
    arg.asInt();  // OK, since Number and its
                  // subtypes support asInt
  }
}
```

Another example

```
public class Graph<N> implements Iterable<N> {
  private final Map<N, Set<N>> node2neighbors;
  public Graph(Set<N> nodes, Set<Tuple<N,N>> edges) {
    ...
  }
}

public interface Path<N, P extends Path<N,P>>
  extends Iterable<N>, Comparable<Path<?, ?>> {
  public Iterator<N> iterator();
}
```

Do **NOT** cut/paste this into your project unless it is what you want (and you understand it!)

Bounded type parameters

```
<Type extends SuperType>
```

An upper bound; accepts the given supertype or any of its subtypes

Works for multiple superclass/interfaces with **&**

```
<Type extends ClassA & InterfaceB & InterfaceC & ...>
```

```
<Type super SuperType>
```

A lower bound; accepts the given supertype or any of its supertypes

Example

```
// tree set works for any comparable type
public class TreeSet<T extends Comparable<T>> {
    ...
}
```

Not all generics are for collections

```
Class Utils {
  static Number sumList(List<Number> lst) {
    Number result = 0;
    for (Number n : lst) {
      result += n;
    }
    return result;
  }
}
```

Signature of a generic method

```
Class Utils {
  static
  T sumList(Collection<T> lst) {
    // ... black magic within ...
  }
}
```

Type uses
Where is this type variable declared?

Declaring a method’s type parameter

```
class MyUtils {
  static
  <T extends Number> T sumList(Collection<T> lst){
    // ... black magic within ...
  }
}
```

How to declare a type parameter of a method

Sorting

```
public static
<T extends Comparable<T>>
void sort(List<T> list) {
  // … use list.get() and T.compareTo(T)
}
```

Actually:

```
<T extends Comparable<? super T>>
```

Generic methods

```
public static <Type> returnType name(params) {
```

When you want to make just a single (often static) method generic in a class, precede its return type by type parameter(s)

```
public class Collections {
  ...
  public static <T> void copy(List<T> dst, List<T> src) {
    for (T t : src) {
      dst.add(t);
    }
  }
}
```

Complex bounded types

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

Find max value in any collection (if the elements can be compared)

```
<T>
void copy(
    List<T2 super T> dst, List<T3 extends T> src)
```

Copy all elements from **`src`** to **`dst`**

`dst` must be able to safely store anything that could be in **`src`**

This means that all elements of **`src`** must be of **`dst`**'s element type or a subtype

```
<T extends Comparable<T2 super T>>
void sort(List<T> list)
```

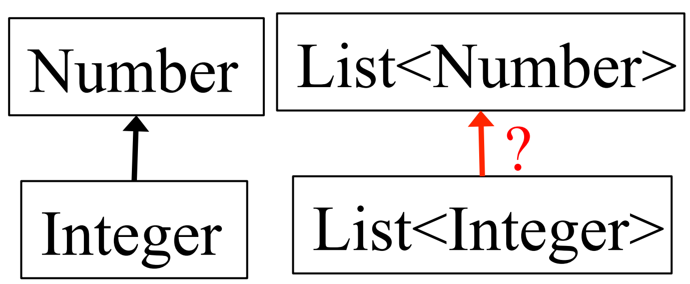
Sort any list whose elements can be compared to the same type or a broader type

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>`

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

Java subtyping is invariant with respect to generics

i.e, not covariant, not contravariant

Invariant subtyping is restrictive
Solution: wildcards

`interface Set<E> {`

`// Adds all of the elements in c to this set`

`// if they're not already present.`

~~`void addAll(Set<E> c);`~~

~~`void addAll(Collection<E> c);`~~

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

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

`}`

Unrelated to invariant subtyping

Problem 1:

```
Set<Number> s;
List<Number> l;
s.addAll(l);
```

Caused by invariant subtyping

Problem 2:

```
Set<Number> s;
List<Integer> l;
s.addAll(l);
```

A wildcard is essentially an anonymous type variable

Use it when you would use a type variable exactly once

It appears at the use site; nothing appears at the declaration site

Using wildcards

```
class HashSet<E> implements Set<E> {
  void addAll(Collection<? extends E> c) {
    // What can this code assume about c?
    // What operations can this code invoke on c?
    ...
  }
}
```

A wildcard is essentially an anonymous type variable

Wildcards are written at type argument uses

- Within a parameter declaration

A missing extends clause means "**`extends Object`**"

There is also "**`? super E`**"

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

```
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);`~~

Wildcards

? indicates a wild-card type parameter, one that can be any type

```
List<?> list = new List<?>();  // anything
```

Difference between **List**<?> and **List<Object**>

- **?** can become any particular type; **Object** is just one such type
- **List<Object>** is restrictive; wouldn't take a **List<String**>

Difference between **List<Foo>** and **List<? extends Foo>**

- The latter binds to a particular **Foo** subtype and allows ONLY that
  - Ex: **List<? extends Animal>** might store only **Giraffes** but not **Zebras**
- The former allows anything that is a subtype of **Foo** in the same list
  - Ex: **List<Animal**> could store both **Giraffes** and **Zebras**

Equals for a parameterized class

```
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: at run time, the JVM has no knowledge of type arguments

Equals for a parameterized class

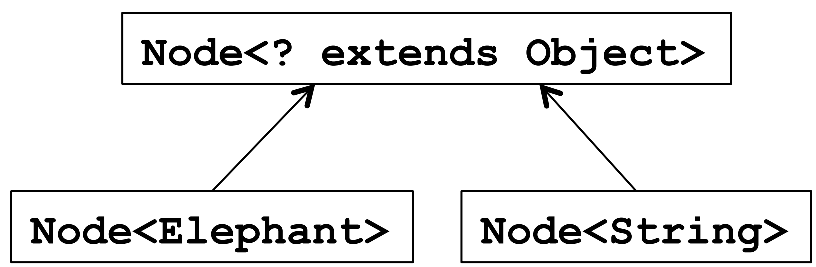
```
class Node<E> {
  …
  @Override
  public boolean equals(Object obj) {
    if (!(obj instanceof Node<?>)) {
      return false;
    }
    Node<E> n = (Node<E>) obj;
    return this.data().equals(n.data());
  }
  …
}
```

Erasure again.
At run time, equivalent to
`Node<Elephant> type = (Node<String>) obj;`

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 …



no subtyping relationship

Get/Put Principle

Should you insert wildcards everywhere, and if so, **`extends`** or **`super`** or neither?

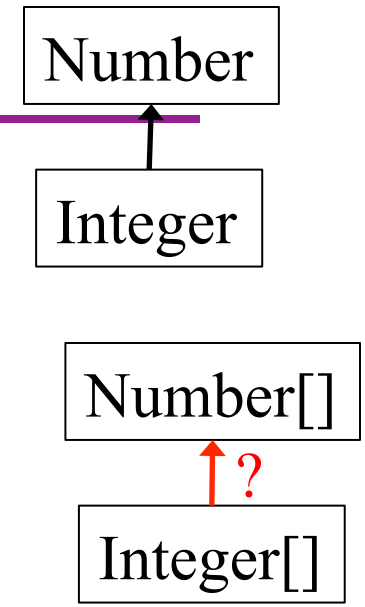
Get/Put principle

- Use **`? extends T`** when you *get* values from a producer
- Use **`? super T`** when you *put* values into a consumer
- Use neither (just **`T`**, not **`?`**) if you do both

Example:

```
<T> void copy(
    List<? super T> dst,
    List<? extends T> src)
```

Arrays and subtyping



Integer is a subtype of Number

Is **`Integer[]`** a subtype of **`Number[]`**?

Use our subtyping rules to find out

(Same question as with Lists)

Same answer with respect to true subtyping

Different answer in Java!

- **`Integer[]`** is a Java subtype of **`Number[]`**
- Java subtyping disagrees with true subtyping

Integer[] is a Java subtype of Number[]

```
Number n;
Number[] na;
Integer i;
Integer[] ia;

na[0] = n;
na[1] = i;
n = na[0];
i = na[1];
ia[0] = n;
ia[1] = i;
n = ia[0];
i = ia[1];
```

```
ia = na;

Double d = 3.14;

na = ia;
na[2] = d;
i = ia[2];
```

Why did the Java designers do this?

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 & different
- Not all ints are the same, nor are all Strings
- The compiler will help you find errors

Eventually, it will be easier to write the code generically from the start

- but ~~maybe~~ probably not yet

Parametric polymorphism

"Parametric polymorphism" means: identical code and behavior, regardless of the type of the input

- Applies to procedures and types
- One copy of the code, many instantiations
- Utilizes dynamic dispatch

Types of parametric polymorphism

- Dynamic (e.g., Lisp)
- static (e.g., ML, Haskell, Java, C#, Delphi)
- C++ templates are similar; both more and less expressive

In Java, called "generics"

- Most commonly used in Java with collections
- Also used in reflection and elsewhere

Lets you write flexible, general, type-safe code

Generics clarify your code

```
interface Map {
  Object put(Object key, Object value);
  equals(Object other);
}
```

plus casts in client code
→ possibility of run-time errors

```
interface Map<Key,Value> {
  Value put(Key key, Value value);
  equals(Object other);
}
```

Cost: More complicated declarations and instantiations, added compile-time checking

Generics usually clarify the implementation

sometimes ugly: wildcards, arrays, instantiation

Generics always make the client code prettier and safer

JAVA PRACTICALITIES

Type erasure

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

- Big reason: backward compatibility with ~~old~~ ancient byte code
- So, at runtime, all generic instantiations have the same type

```
List<String>  lst1 = new ArrayList<String>();
List<Integer> lst2 = new ArrayList<Integer>();
lst1.getClass() == lst2.getClass()  // true
```

You 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 a warning

```
List<?> lg = new ArrayList<String>();  // ok
List<String> ls = (List<String>) lg;   // warn
```

The compiler gives an unchecked warning, since this isn't something the runtime system is going to check for you

Usually, if you think you need to do this, you're wrong

(Unless you're implementing things like **`ArrayList`** – and then be sure you understand why you're getting the warning)

The same is true of type variables:

```
public static <T> T badCast(T t, Object o) {
  return (T) o;   // unchecked warning
}
```

Generics and arrays

```
public class Foo<T> {
    private T aField;                          // ok
    private T[] anArray;                       // ok


    public Foo(T param) {
        aField = new T();                      // error
        anArray = new T[10];                   // error
    }
}
```

You cannot create objects or arrays of a parameterized type

(Actual type info not available at runtime)

Generics/arrays: a hack

```
public class Foo<T> {
    private T aField;                          // ok
    private T[] anArray;                       // ok

    @SuppressWarnings("unchecked")
    public Foo(T param) {
        aField = param;                        // ok
        T[] anArray = (T[])(new Object[10]); // ok
    }
}
```

You *can* create variables of that type, 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
- You almost surely don't need this in common situations!

Comparing generic objects

```
public class ArrayList<E> {
    ...
    public int indexOf(E value) {
        for (int i = 0; i < size; i++) {
        // if (elementData[i] == value) {
            if (elementData[i].equals(value)) {
                return i;
            }
        }
        return -1;
    }
}
```

When testing objects of type **`E`** for equality, must use **`equals`**