CSE 331
Software Design & Implementation

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Generics

(Based on slides by Mike Ernst, Dan Grossman, David Notkin, Hal Perkins)

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>
```

Why we *love* abstraction

Hide details

- Avoid distraction
- Permit details to change later

Give a *meaningful name* to a concept

Permit *reuse* in new contexts

- Avoid duplication: error-prone, confusing
- Save reimplementation effort
- Helps to "Don't Repeat Yourself"

Related 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

// 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* $\rightarrow$ *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* $\rightarrow$ *Type*
  - Never just use **`List`** (in Java for backward-compatiblity)

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> {…}`

- Convention: One-letter name such as:
  `T` for **`Type`**, **`E`** for **`Element`**,
  `K` for **`Key`**, **`V`** for **`Value`**, …

To instantiate a generic class/interface, client supplies 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, client supplies 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.asInt();  // compiler error, E might not
                  // support asInt
  }
}

class Foo2<E extends Number> {
  void m(E arg) {
    arg.asInt();  // OK, since Number and its
                  // subtypes support asInt
  }
}
```

More examples

```
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*** copy/paste this stuff into your project unless it is what you want

- *And* you understand it!

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 **`&`**

`<TypeVar super SubType>`

– A *lower bound*; accepts the given subtype or any of its supertypes

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 and static 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
  - *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 one "works" but will make it even more useful later by adding 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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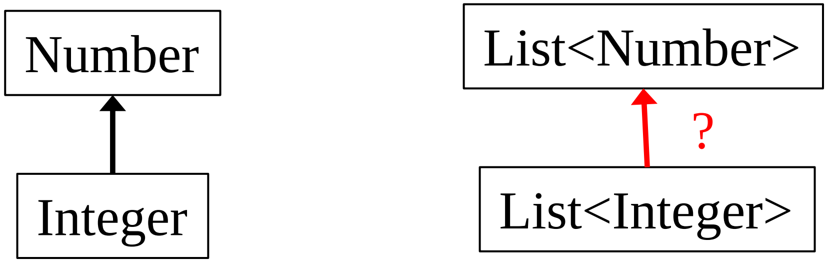
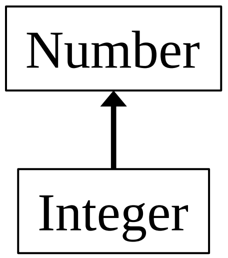
Generics and subtyping



- `Integer` 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<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>`

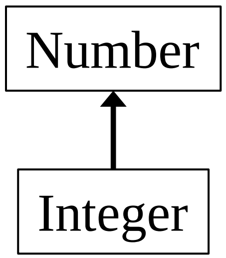
Previous example shows why:

- 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:

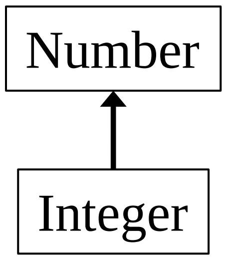
- `List<Integer>` a subtype of `List<Number>`

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

About the parameters

- So we have seen **List<Integer>** and **List<Number>** are not subtype-related

- But there is subtyping "as expected" 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>**
  - …

Where are we?

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  - Using *bounds* for more flexible subtyping
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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);
}
```

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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 (but equally powerful) compared 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);
```

`?` 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

```
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);
```

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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??

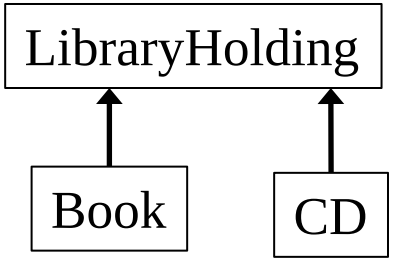
Surprise!

- 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.
  – Now programmers are used to this too-lenient subtyping

What can happen: the good

Programmers can use this subtyping to “do okay stuff”

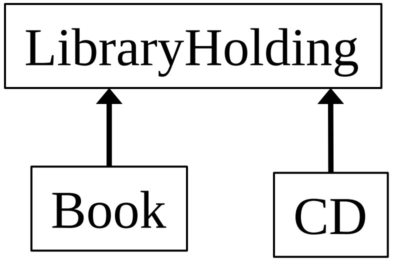



```
void maybeSwap(LibraryHolding[] arr) {
    if(arr[17].dueDate() < arr[34].dueDate())
        // … swap arr[17] and arr[34]
}

// client with subtype
Book[] books = …;
maybeSwap(books); // relies on covariant
                  // array subtyping
```

What can happen: the bad

Something in here must go wrong!




```
void replace17(LibraryHolding[] arr,
               LibraryHolding h) {
  arr[17] = h;
}

// client with subtype
Book[] books = …;
LibraryHolding theWall = new CD("Pink Floyd",
                                "The Wall", …);
replace17(books, theWall);
Book b = books[17]; // would hold a CD
b.getChapters(); // so this would fail
```

Java's choice

- Recall Java's guarantee: Run-time type is a subtype of the compile-time type
  - This was violated for the **`Book b`** variable
- To preserve the guarantee, Java would never get that far:
  - Each array "knows" its actual run-time type (e.g., **`Book []`**)
  - Trying to store a (run-time) supertype into an index causes **`ArrayStoreException`**
- So the body of **`replace17`** would raise an exception
  - Even though **`replace17`** is entirely reasonable
    - And fine for plenty of "careful" clients
  - *Every Java array-update includes this run-time check*
    - (Array-reads never fail this way – why?)
  - Beware array subtyping!

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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());
  }
  …
}
```

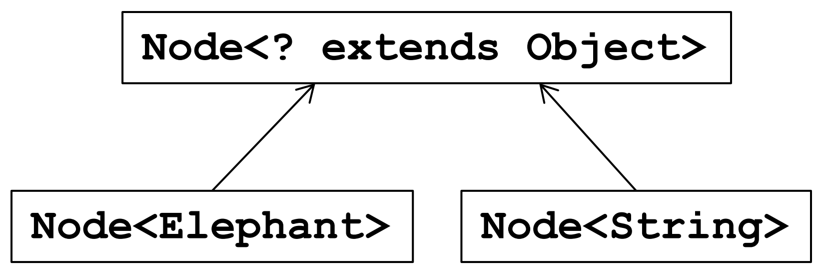
More erasure: At run time, do not know what **E** is and will not be checked, so don't indicate otherwise

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 create 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