Polymorphism (generics)

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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>
```

  - Type abstraction 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

A collection of 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

```
// Type abstraction
// abstracts over element type E
interface List<E> {
  boolean add(E n);
  E get(int index);
}
```

`add` declares a new **variable**, called a **formal parameter**

Instantiate by passing an `Integer` argument:
`l.add(7);`
`myList.add(myInt);`

The type of `add` is
Integer → boolean

`List` declares a new **type variable**, called a **type parameter**

use types

Instantiate by passing a type argument:
`List<Float>`
`List<List<String>>`
`List<T>`

The kind of `List` is
Type → Type

(Never use `List` on its own.
Only instantiate it with a type.)

Declaring generics

```
class MyClass<TypeVar1, …, TypeVarN> {…}
interface MyInterface<TypeVar1, …, TypeVarN> {…}
```

Convention: Type variable has a one-letter name such as:

`E` for **`Element`**

`K` for **`Key`**

`V` for **`Value`**

Avoid **`T`** for **`Type`** which is uninformative

Type variables are types

Declaration

```
class MySet<E> implements Set<E> {
  // rep invariant:
  //   non-null, contains no duplicates
  // …
  List<E> theRep;
  E lastLookedUp;
}
```

Use

Restricting instantiation by clients

```
boolean add1(Object elt);
boolean add2(Number elt);
add1(new Date());  // OK
add2(new Date());  // compile-time error
```

"Upper bound"
Default is `Object`

```
interface MyOList<E extends Object> {…}
interface MyNList<E extends Number> {…}
MyOList<Date>      // OK
MyNList<Date>      // compile-time error
```

Using type variables

Code can perform any operation permitted by the bound

```
class Foo<T extends Object> {
  void m(T arg) {
    arg.asInt();    // compiler error:  T might not support asInt
  }
}

class Bar<N extends Number> {
  void m(N arg) {
    arg.asInt();    // OK:  Number and its subtypes support asInt
  }
}
```

More generic classes

```
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** paste into your project unless you understand it *and* it is what you want

Outline

- Basics of generic types for classes and interfaces
- Basics of *bounding* generics
- 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 Util {
  public static
  Object choose(List<Object> lst) {
    int i = new Random().nextInt(lst.size());
    return lst.get(i);
  }
}
```

Poor approximation to return value

Cannot pass **`List<String>`**

Invariant collection typing:
`List<String>`
is not a subtype of
`List<Object>`

Class **`Utils`** is not generic, but the *method* should be generic

(**`Utils`** is a collection of static methods, not an ADT that represents something. 😕)

Signature of a generic method

```
class Util {
  public static
  E choose(List<E> lst) {
    int i = new Random().nextInt(lst.size());
    return lst.get(i);
  }
}
```

These are type uses. Where is this type variable declared for use in the method?

Declaring a method's type parameter

Declare a type parameter before the method

```
class Util {
  public static
  <E> E choose(List<E> lst) {
    int i = new Random().nextInt(lst.size());
    return lst.get(i);
  }
}
```

modifiers… <TypeVar> *returnType* name(*params*) {…}

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

Using generic methods

- Instance methods can use type parameters of the class
- Methods can have their own type parameters
  - If so, called a “generic method”
- Callers to generic methods need not explicitly instantiate the method’s type parameters
  - Compiler usually figures it out for you
  - *Type inference*

Generic method with type bound

```
class Util {
  public static
  double sumList(List<Number> lst) {
    double result = 0;
    for (Number n : lst) {
      result += n.doubleValue();
    }
    return result;
  }
}
```

Cannot pass `List<Double>`

Invariant collection typing:
`List<Double>`
is not a subtype of
`List<Number>`

Signature of a generic method

Type use.
Intention:
only for numbers.

```
class Util {
  public static
  double sumList(List<N> lst) {
    double result = 0;
    for (Number n : lst) {
      result += n.doubleValue();
    }
    return result;
  }
}
```

Declaring a method’s type parameter

A type parameter may have a *bound*

```
class Util {
  public static <N extends Number>
  double sumList(List<N> lst) {
    double result = 0;
    for (Number n : lst) {
      result += n.doubleValue();
    }
    return result;
  }
}
```

modifiers… <TypeVar* **[super/extends]** ***Bound>
returnType **name(*params*) {…}**

Sorting needs type bounds

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

Actually:

`<E extends Comparable<? super E>>`

which we will learn about shortly.

More bounded type examples

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

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

```
<E extends Object, E2 extends E>
void copy(List<E> dst, List<E2> src)
```

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

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

All elements of **`src`** must be of **`dst`**'s element type or a subtype

Equivalently: **`<E, E2 extends E>`**

```
<E extends Comparable<E2 super E>>
void sort(List<E> list)
```

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

Actually: **`<E extends Comparable<? super E>>`**

Bounds with type qualifiers

```
<E extends @NonNull Object>
void foo(List<E> arg) { … }

<E extends @Nullable Object>
void bar(List<E> arg) { … }

Set<@NonNull Object> sNnO;
Set<@Nullable Object> sNbleO;

Set<@NonNull Date> sNnD;
Set<@Nullable Date> sNbleD;
```

Which calls are legal?

1. `foo(sNnO)`
2. `foo(sNbleO)`
3. `bar(sNnO)`
4. `bar(sNbleO)`
5. `foo(sNnD)`
6. `foo(sNbleD)`
7. `bar(sNnD)`
8. `bar(sNbleD)`

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- ➡ 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
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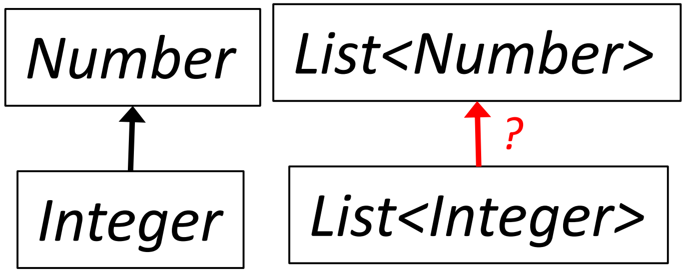
Generics and subtyping

Integer is a subtype of Number

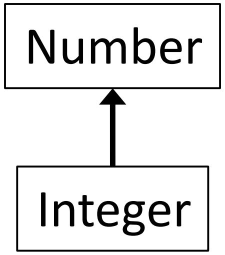
Is **`List<Integer>`** a subtype of **`List<Number>`**?

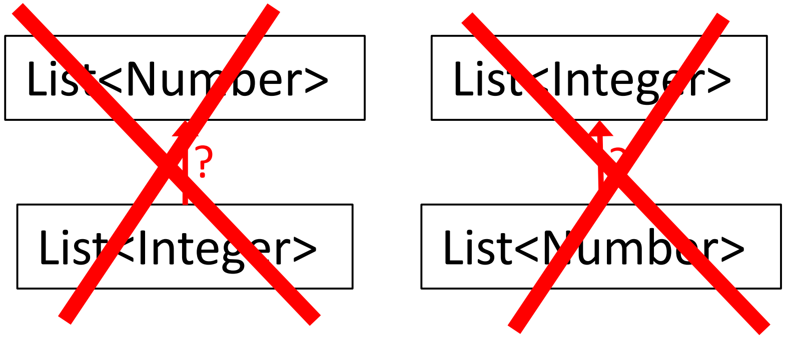
Use our subtyping rules to find out



What is the subtyping relationship between `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);
}
```



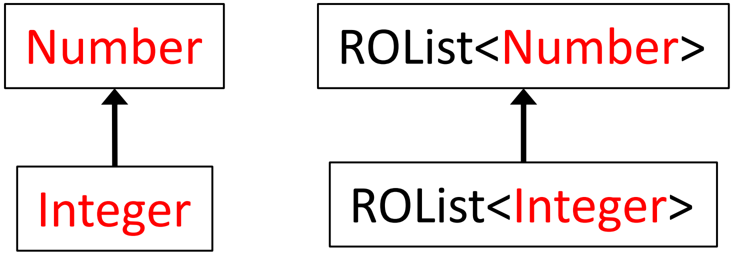


Java subtyping is invariant with respect to generics

If A≠B, then C<A> has no subtyping relationship to C'<B>

Immutable lists

```
interface ReadOnlyList<Number> {
  Number get(int index);
}
interface ReadOnlyList<Integer> {
  Integer get(int index);
}
```



Covariance

(True subtyping, but Java forbids)

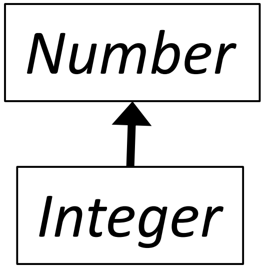
Write-only lists

```
interface WriteOnlyList<Number> {
  boolean add(Number elt);
}
interface WriteOnlyList<Integer> {
  boolean add(Integer elt);
}
WriteOnlyList<Eagle> hotelCalifornia;
```

Contravariance

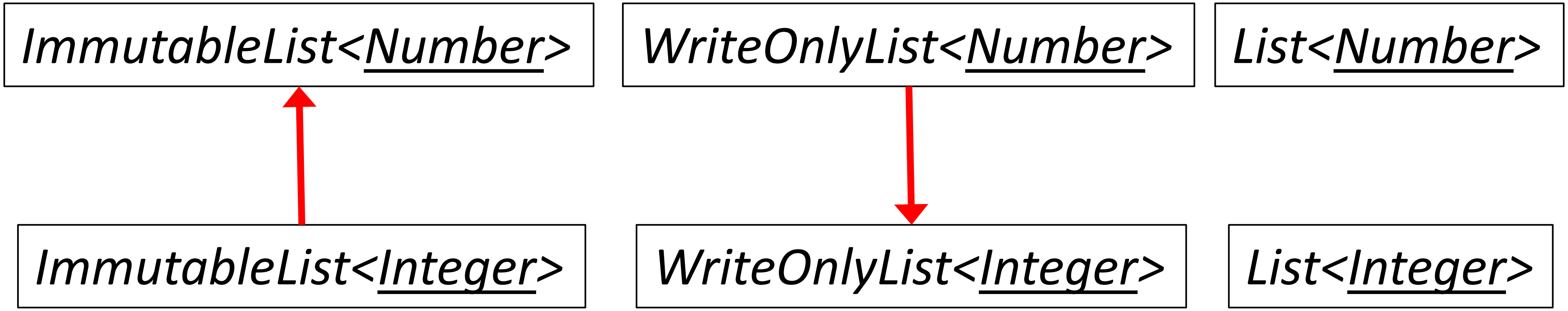
(True subtyping, but Java forbids)

{In,Co,Contra}variant subtyping


Number

Integer

If $X \sqsubseteq Y$, then what is the relationship between C<X> and C<Y>?


Covariant subtyping

ImmutableList<Number>

ImmutableList<Integer>

Contravariant subtyping

WriteOnlyList<Number>

WriteOnlyList<Integer>

Invariant subtyping

List<Number>

List<Integer>

Generic types and subtyping

`List<Integer>` and **`List<Number>`** are not subtype-related

Generic types can have subtyping relationships

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>`**
- …
- But **`HeftyBag<Integer>`** is unrelated to **`Bag<Number>`**

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Invariant subtyping is restrictive
Solution: wildcards

```
interface Set<E> {
  // Add each element of collection c
  // to this set, if not already present.
  ~~void addAll(Set<E> c);~~
  ~~void addAll(Collection<E> c);~~
  <E2 extends E> void addAll(Collection<E2> c);
  void addAll(Collection<? extends E> c);
}
```

same

`Collection<? extends Number>` means:

At run time, the value is a collection of some concrete type

`new List<Number>()`, `new Set<Integer>()`, `new Queue<Double>()`

At compile time, we don't know which one it was

Code must accommodate all possibilities

Unrelated to invariant subtyping

Problem 1:

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

Caused by invariant subtyping

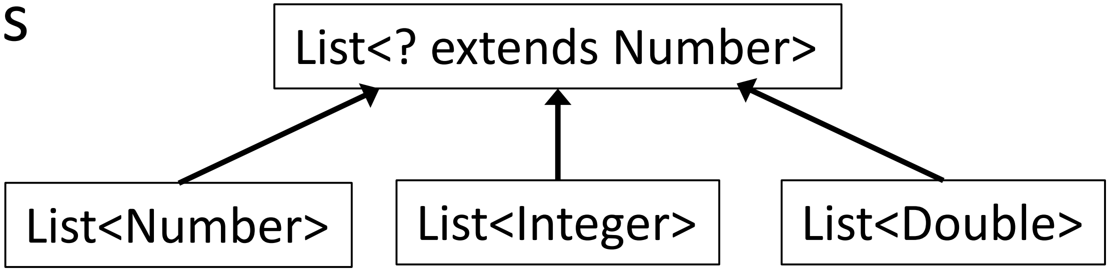
Problem 2:

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

What a wildcard represents

A type is a set of values

Wildcards increase flexibility, usability



```
double sum(Collection<? extends Number> lst) {…}

List<Number> ln;          sum(ln);
List<Integer> li;         sum(li);
List<Double> ld;          sum(ld);
Set<Number> sn;           sum(sn);
Set<Integer> si;          sum(si);
Set<Double> sd;           sum(sd);
LinkedList<BigDecimal> llbd;      sum(llbd);
```

Wildcard = anonymous type variable

Use a wildcard when you would use a type variable *once*

```
interface Set<E> extends Collection<E> {
       void addAll(Collection<? extends E> c);
same
       <E2 extends E> void addAll(Collection<E2> c);
}
```

Wildcards are written at type argument use sites

- within a parameter declaration
- Nothing appears at the declaration site

Missing extends clause: “`<?>`” = “`<? extends Object>`”

There is also “`? super E`”

- Expressible *only* as a wildcard; no equivalent syntax

Copying a collection

Lower bound for a producer

```
class Collections {
  ~~<E> void copy(List<E> dest, List<E> src) {~~
  <E> void copy(List<? super E> dest,
                List<? extends E> src) {
    for (E elt : src) {
      dst.add(t);
    }
  }
}
```

Upper bound for a consumer

```
Collections.copy(stringList, stringList);    ✓
Collections.copy(numberList, integerList);   ✗✓
```

Version with wildcards permits more clients

Legal operations on wildcard types

```
Object o;
Number n;
Integer i;
@Positive Integer 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<@Positive Integer>;`

`lei = new ArrayList<@Negative Integer>;`

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;
@Positive Integer 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<@Positive Integer`~~`>;`
~~`lsi = new ArrayList<@Negative Integer`~~`>;`

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);`~~

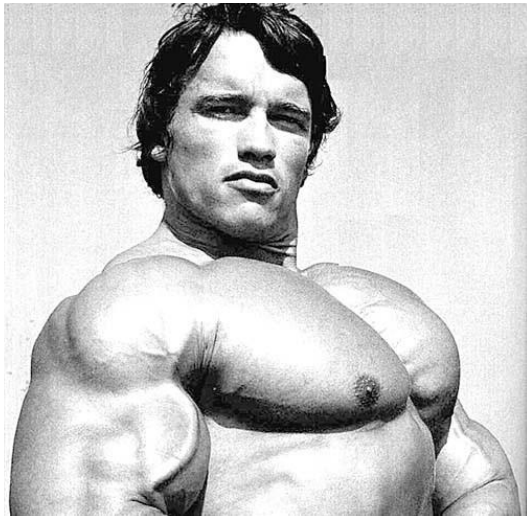
PECS: Producer Extends, Consumer Super

Where should you insert wildcards?
Should you use **`extends`** or **`super`** or neither?

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

Example:

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



Subtyping for generics

Object

Number

List<?>

List

List<Object>

Integer

List<? extends Number>

List<Number>

List<Integer>

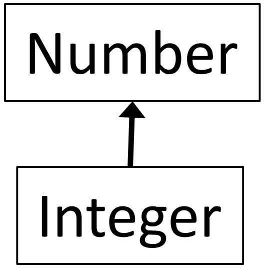
List<Double>

ArrayList<Integer>

LinkedList<Integer>

Subtyping requires invariant type arguments
Exception: `super` wildcard is a supertype of what it matches
Don’t use raw types like `List`! (CSE 331 forbids it)

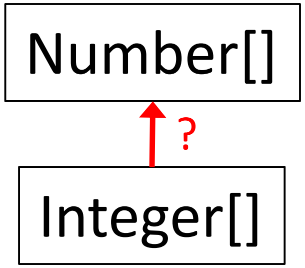
Arrays and subtyping



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

Think of **`Array`** as an ADT with **`get`** and **`set`** ops:

```
class Array<E> {
  public E get(int i) { … }
  public E set(E newVal, int i) { … }
}
```



Same answer as Lists with respect to true subtyping

  `Integer[]` and **`Number[]`** are unrelated

Different answer in Java!

  `Integer[]` *is* a Java subtype of **`Number[]`**

  Java subtyping disagrees with true subtyping

  Unsound: a program that type-checks can crash

  Rationale: enabled code reuse (e.g., sorting routines) before generics

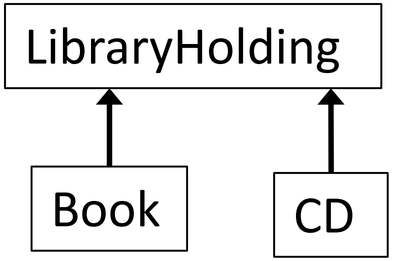
  Backwards compatibility means it's here to stay ☹

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];
```

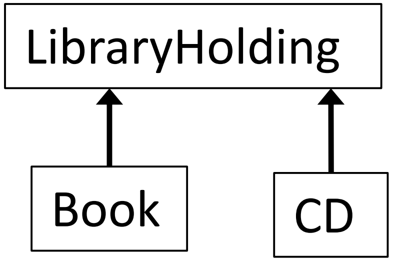
```
ia = na;

Double d = 3.14;

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

What can happen: the good



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

// client with array that is a Java subtype
Book[] books = …;
maybeSwap(books);
```

What can happen: the bad



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

// client with array that is a Java subtype
Book[] books = …;
LibraryHolding theWall = new CD("Pink Floyd",
                                "The Wall", …);
replace17(books, theWall);
Book b = books[17]; // holds a
b.getChapters();    // fails, vi
```

ArrayStoreException in **replace17** at run time.
The exception prevents execution of the following code.

Every Java array-update includes this run-time check

Reads don't have to (why?)

Tips when writing a generic class

1. Start by writing a concrete instantiation
2. Get it correct (testing, reasoning, etc.)
3. Consider writing a second concrete version
4. Generalize it by adding type parameters
   - Think about which types are the same & different
   - Not all **`int`**s are the same, nor are all **`String`**s
   - The compiler will help you find errors

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

- but maybe 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

- But 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 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!
```

You cannot use `instanceof` to discover a type parameter

```
Collection<?> cs = new ArrayList<String>();
if (cs instanceof Collection<String>) // illegal
...
```

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: 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());
  }
  …
}
```

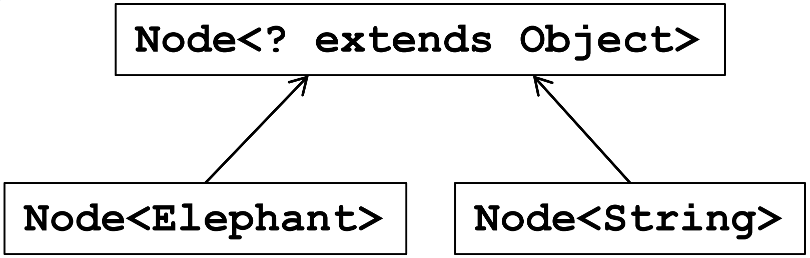
More erasure.
At run time, cannot check.
Equivalent to
`Node<Elephant> type =`
`(Node<String>) obj;`

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 …

This test should distinguish **`Node<Elephant>`** from **`Node<String>`**.



no subtyping relationship between **`Node<Elephant>`** and **`Node<String>`**

Generics and casting

- Casting to generic type results in a compiler warning

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

- The compiler gives an unchecked warning, since the runtime system *cannot* check this
- If you think you need to do this, you are probably wrong

  (Unless you're implementing `ArrayList` – and then be sure you understand the warning.)

- `Object` can also be cast to any generic type ☹

```
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();              // compile-time error
    anArray = new T[10];           // compile-time error
  }
}
```

- You cannot create objects or arrays of a parameterized type (type info not available at run time)

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
    anArray = (T[]) (new Object[10]); // ok
  }
}
```

- You cannot create objects or arrays of a parameterized type (type info not available at run time)
- 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
  - Rare to need an array of a generic type (e.g., use **`ArrayList`**)

Comparing generic objects

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

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

Guarantees and lack of guarantees

- 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