CSE 331
Software Design & Implementation

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Generics
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
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
  - (though not always the most important consideration)

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
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`

```java
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
interface Set<E> {
    // Adds all elements in c to this set
    // (that are not already 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`

```java
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`
Generic methods get around invariance

You cannot pass List<Integer> to method expecting List<Number>
- Java subtyping is invariant with respect to type parameters

Get around it by making your method generic:

```java
<T extends Number> double sumList(List<T> nums) {
    double s = 0;
    for (T t : nums)
        s += t.doubleValue();
    return s;
}
```
Revisit copy method

Earlier we saw this:

```java
<T> void copyTo(List<T> dst, List<T> src) {
    for (T t : src)
        dst.add(t);
}
```

Now we can do this (which is more general):

```java
<T1, T2 extends T1> void copyTo(List<T1> dst,
                                           List<T2> src) {
    for (T2 t : src)
        dst.add(t);
}
```
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  – 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
Examples

[Compare to earlier version]

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

- More idiomatic (but equally powerful) compared to
  ```java
  <T extends E> void addAll(Collection<T> c);
  ```
- More powerful than
  ```java
  void addAll(Collection<E> c);
  ```
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 superclass of `Type`

A wildcard is essentially an *anonymous type variable*

- each `?` stands for some possibly-different unknown type
More examples

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

- No change because T used more than once
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 superclass 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 only once (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
More examples

\[
<T> \text{ void } \text{copyTo}(\text{List}<\text{ super } T> \text{ dst, }) \text{ List}<\text{ extends } T> \text{ src) } \{
    \text{ for (T t : src) }
        \text{ dst.add(t); }
\}
\]

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: \text{copy(numberList, integerList)}
  - Example: \text{copy(stringList, stringList)}
PECS: Producer Extends, Consumer Super

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
  - (the co-variant subtyping case)
- use `<? super T>` when you put values (into a consumer)
  - no problem if it’s a supertype
  - (the contra-variant subtyping case)
- use neither (just `T`, not `?`) if you both get and put
  - can’t be as flexible here

```java
<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”

• Upper-bound ? extends T could be rewritten without 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
    • ¯\_(ツ)_¯
? versus Object

? indicates a particular but unknown type

```java
void printAll(List<?>
``` lst

Difference between List<?> and List<Object>:
  – can instantiate ? with any type: Object, String, ...
  – List<Object> much more restrictive:
    • e.g., 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 Giraffes only (no Zebras)
  – Former allows anything that is a subtype of Foo in the same list
    Example: List<Animal> could store Giraffes and Zebras
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>();
Legal operations on wildcard types

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

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Legal operations on wildcard types

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

List<? extends Integer> lei;

Which of these is legal?
o = lei.get(0);
n = lei.get(0);
i = lei.get(0);
p = lei.get(0);

First, which of these is legal?
lei = new ArrayList<Object>();
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lei = new ArrayList<Number>();
lei = new ArrayList<Integer>();
lei = new ArrayList<PositiveInteger>();
lei = new ArrayList<NegativeInteger>();

Which of these is legal?
o = lei.get(0);
n = lei.get(0);
i = lei.get(0);
p = lei.get(0);
lei.add(o);
lei.add(n);
lei.add(i);
lei.add(p);
lei.add(null);
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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>();
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Which of these is legal?
o = lei.get(0);
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i = lei.get(0);
p = lei.get(0);
lei.add(o);
lei.add(n);
lei.add(i);
lei.add(p);
lei.add(null);
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>;

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>;
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lsi = new ArrayList<Object>;
lsi = new ArrayList<Number>;
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lsi = new ArrayList<PositiveInteger>;
lsi = new ArrayList<NegativeInteger>;

lsi.add(o);
lsi.add(n);
lsi.add(i);
lsi.add(p);
lsi.add(null);

First, which of these is legal?
lsi = new ArrayList<Object>;
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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>;
\[\text{\underline{lsi = new ArrayList<PositiveInteger>};}\]
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);
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lsi.add(i);
lsi.add(p);
lsi.add(null);
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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:
```java
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??
Java Arrays

- Given everything we have learned, if \texttt{Type1} is a subtype of \texttt{Type2}, then \texttt{Type1[]} and \texttt{Type2[]} should be unrelated
  - invariant subtyping for generics
  - because arrays are mutable
Surprise!

• Given everything we have learned, if \texttt{Type1} is a subtype of \texttt{Type2}, then \texttt{Type1[]} and \texttt{Type2[]} should be unrelated
  – invariant subtyping for generics
  – because arrays are mutable

• But in Java, if \texttt{Type1} is a subtype of \texttt{Type2}, then \texttt{Type1[]} \textit{is a subtype of} \texttt{Type2[]} (covariant subtyping)
  – not true subtyping: the subtype does not support setting an array element to hold a \texttt{Type2} (spoiler: throws an exception)
  – Java (and C#) made this decision in pre Generics days
    • needed to write reusable sorting routines, etc.
    • also \_\_(ツ)_/\_
What can happen: the good

Programmers can use this subtyping to “do okay stuff”

```java
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!

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

// client with subtype

```java
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

• Java normally guarantees run-time type is a subtype of the compile-time type
  – this was violated for the Book b variable

• To preserve the guarantee, Java must never get that far:
  – each array “knows” its actual run-time type (e.g., Book [])
  – trying to store a supertype into an index causes ArrayStoreException (at run time)

• 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?)
  – be careful with array subtyping
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Type erasure

All generic types become type `Object` once compiled

```java
List<String> lst = new ArrayList<String>();
```

at runtime, becomes

```java
List<Object> lst = new ArrayList<Object>();
```
Type erasure

All generic types become type `Object` once compiled
- gives backward compatibility (a selling point at time of adoption)
- at run-time, all generic instantiations have the same type

Cannot use `instanceof` to discover a type parameter

```java
Collection<?> cs = new ArrayList<String>();
if (cs instanceof Collection<String>) { // illegal
    ...
} else {
    ...
}
```
Generics and casting

Casting to generic type results in an important warning

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

Compiler gives a warning because this is something the runtime system will not check for you

Usually, if you think you need to do this, you're wrong
– a real need to do this is extremely rare

Object can also be cast to any generic type 😞

```java
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 if no unchecked cast warnings are shown
  - 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:
  1. You’re violating good style/design/subtyping/generics
  2. 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());
    }
    ...
}
equals for a parameterized class

```java
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());
  }
  ...
}

Leave it to here to “do the right thing” if this and n differ on element type

Works if the type of obj is Node<Elephant> or Node<String> or...

Node<? extends Object>
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
  – type info is not available at runtime
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 (hence the warning)
- Effective Java: use ArrayList instead
FINAL THOUGHTS
Generics clarify your code

interface Map {
    Object put(Object key, Object value);
    ...
}

interface Map<Key, Value> {
    Value put(Key key, Value value);
    ...
}

- Generics always make the client code prettier and safer
- Generics usually clarify the implementation
  - (but sometimes uglify: wildcards, arrays, instantiation)

plus casts in client code
→ possibility of run-time errors
Tips when writing a generic class

• Think through whether you **really need** to make it generic
  – if it’s not really a container, most likely a **mistake**

• 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

• It will become easier with practice to write generic from the start