CSE 331
Software Design & Implementation

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Generics
(Based on slides by Mike Ernst, Dan Grossman, David Notkin, Hal Perkins, Zach Tatlock)
Varieties of abstraction

Abstraction over *computation*: procedures (methods)

```java
int x1, y1, x2, y2;
Math.sqrt(x1*x1 + y1*y1);
Math.sqrt(x2*x2 + y2*y2);
```

Abstraction over *data*: ADTs (classes, interfaces)

```java
Point p1, p2;
```

Abstraction over *types*: polymorphism (generics)

```java
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>>
...

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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 (in Java for backward-compatibility)
Type variables are types

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

Declaration

Use

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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
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

```java
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
    }
}
```

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More examples

```java
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 &

Example:

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

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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
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
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);
    }
}
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

```java
<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 \textit{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
  – Using wildcards for more convenient bounds
  – Related digression: Java’s array subtyping
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    • 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

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`

```java
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
- This is not related to invariant subtyping [yet]
Best type for `addAll`

```java
interface Set<E> {
    // Adds all elements in c to this set
    // (that are not already present)
    voidaddAll(_______ c);
}

voidaddAll(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`

```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: 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:

```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 useful to clients:

```java
<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]

```java
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

```java
<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

```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”

- For upper-bound ? extends T, we could always rewrite it not to use wildcards, but wildcards preferred style where they suffice

- But lower-bound is only available for wildcards in Java
  - This does not parse:
    ```java
    <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
? 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>` 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 Giraffes but not 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>();

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:

```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??
Surprise!

• Given everything we have learned, if \texttt{Type1} is a subtype of \texttt{Type2}, then \texttt{Type1[\texttt{]} \texttt{]} \texttt{and \texttt{Type2[\texttt{]} \texttt{]} \texttt{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[\texttt{]} \texttt{is a subtype of Type2[\texttt{]} \texttt{]}}
  – Not true subtyping: the subtype does not support setting an array element to hold a \texttt{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”

```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
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

```java
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

```java
Collections<?< cs = new ArrayList<String>();
    if (cs instanceof Collections<String>) { // illegal
        ...
    }
```
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 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 😞

```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 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 runtime, 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>

Node<Elephant>    Node<String>
Generics and arrays

```java
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

```java
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, 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);
...
}

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