CSE 331
Software Design & Implementation

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

```java
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);
}
```

Let's use types

- List<Integer>
- List<Number>
- List<String>
- List<List<String>>

...
interface ListOfIntegers {
    boolean add(Integer elt);
    Integer get(int index);
}

interface List<E> {
    boolean add(E e);
    E get(int index);
}
Type variables are types

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

Declaration

Use
Declaring and instantiating generics

```java
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

```java
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:

```java
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
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
  }
}
```
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 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
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`

• `Utils` is not generic, 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) {
    ...
}
```

```java
<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)

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

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  – Using bounds for more flexible subtyping
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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
If \texttt{Type2} and \texttt{Type3} are different, then \texttt{Type1<Type2>} is \textit{not} a subtype of \texttt{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
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

```java
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>`
  – ...
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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
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)
    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
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 see this 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`
- `?`, 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) 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 copy(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 copy(List<? super T> dst,
             List<? extends T> src);
```
? 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?
\( lei = \text{new ArrayList<Object>}; \)
\( lei = \text{new ArrayList<Number>}; \)
\( lei = \text{new ArrayList<Integer>}; \)
\( lei = \text{new ArrayList<PositiveInteger>}; \)
\( lei = \text{new ArrayList<NegativeInteger>}; \)

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;

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>;

First, 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);
Where are we?

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Java arrays

We know how to use arrays:

- Declare an array holding Type elements: Type[]
- Get an element: \texttt{x[i]}
- Set an element \texttt{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 `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”

```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!
Where are we?

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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
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 due, 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());
    }

    ...

}
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>
Generics and arrays

```java
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
(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 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

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

```java
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

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