CSE 331
Software Design & Implementation

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Generics
Varieties of abstraction

Abstraction over *computation*: procedures (methods)

\[
\begin{align*}
\text{int } \ x1, \ y1, \ x2, \ y2; \\
\text{Math.sqrt}(x1*x1 + y1*y1); \\
\text{Math.sqrt}(x2*x2 + y2*y2);
\end{align*}
\]

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

\[
\text{Point } p1, \ p2;
\]

Abstraction over *types*: polymorphism (generics)

\[
\text{Point<Integer>, Point<Double>}
\]
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-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
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:

```java
Name<Typel, ..., 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
  – Convention: every type $T$ is a subtype of itself
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
    }
}
```
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

\(<\text{TypeVar extends SuperType}>\)
- An \textit{upper bound}; accepts given supertype or any of its subtypes

\(<\text{TypeVar extends ClassA }\& \text{ InterfaceB }\ & \text{ InterfaceC }\ & \text{ ...}>\)
- \textit{Multiple} upper bounds (superclass/interfaces) with &

Example:

// tree set works for any comparable type
public class TreeSet\(<T\ extends \text{Comparable}<\text{T}>\rangle \ { \ 
\ 
\ \ ... 
\}

\}
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 \texttt{sumList} for any subtype of \texttt{Number}
  – For example, \texttt{Double} or \texttt{Integer}
  – But as we will see, \texttt{List<Double>} is not a subtype of \texttt{List<Number>}

• Would like to use \texttt{choose} for any element type
  – I.e., any subclass of \texttt{Object}
  – No need to restrict to subclasses of \texttt{Number}
  – Want to tell clients more about return type than \texttt{Object}

• Class \texttt{Utils} is not generic, but the \texttt{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);
}
```
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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 *invariant* with respect to generics
    - Not covariant and not contravariant
    - Neither List<Number> nor List<Integer> subtype of other
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
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>`
  – …
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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`

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

voidaddAll(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:

\[
<T> \text{ void } \text{copyTo}(\text{List}<T> \text{ dst}, \text{ List}<T> \text{ src}) \{
\begin{align*}
& \quad \text{ for (T t : src)} \\
& \quad \quad \text{dst.add(t);}
\end{align*}
\}
\]

Now we can do this, which is more useful to clients:

\[
<T1, T2 \text{ extends } T1> \text{ void } \text{copyTo}(\text{List}<T1> \text{ dst}, \\
& \quad \text{ List}<T2> \text{ src}) \{
\begin{align*}
& \quad \text{ for (T2 t : src)} \\
& \quad \quad \text{dst.add(t);}
\end{align*}
\}
\]
Where are we?

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  – Using *bounds* for more flexible subtyping
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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

```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:
    
    \[
    \langle T \text{ super Foo} \rangle \text{ void m(Bar}<T> \text{ x);} \\
    \]
  – 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<? super Object> 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);
Where are we?

- **Done:**
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  - Using *bounds* for more flexible subtyping
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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 `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 (Java) subtype of `Type2[]`
  - Not true subtyping: the subtype does not support setting an array element 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!
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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

```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 (because it can’t!)

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());
    }
    ...
}
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());
    }

    ...

}
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

Node<? extends Object>

Node<Elephant>
Node<String>
Generics and arrays

```java
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)
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

```java
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

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