CMSC 433: Programming Paradigms and Technologies
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Java and Java Generics

(slides partially developed by Jeff Foster for CS330)

Java

- Developed in 1995 by Sun Microsystems
  – Started off as Oak, a language aimed at software for consumer electronics
  – Then the web came along...
- Java incorporated into web browsers
  – Java source code compiled into Java byte code
  – Executed (interpreted) on Java Virtual Machine
    - Portability to different platforms
    - Safety and security much easier, because code is not directly executing on hardware
- These days, Java used for a lot of purposes
  – Server side programming, general platform, etc.

Java Versions

- Java has evolved over the years
  – Virtual machine quite stable, but source language has been getting new features

- Will use Java 1.5 (a.k.a Java 5.0) for this class
  – We *will* be using 1.5-specific features, so if you've got a different version, you will want to upgrade
  – Some of the new features in Java 1.5 came as a response to pressure from Microsoft's C#

Object-Orientation

- Java is a class-based, object-oriented language
- Classes extend other classes to inherit
  - The root of the inheritance hierarchy is Object
  - Why have a root of the hierarchy?
- Classes also implement interfaces
  - Interface is like a class with declarations but no code
- Classes may extend one other class, but can implement many interfaces
  - Multiple inheritance is tricky to understand/implement

Subtyping

- Both inheritance and interfaces allow one class to be used where another is specified
  – This is really the same idea: subtyping

- We say that A is a *subtype* of B if
  – A extends B or a subtype of B, or
  – A implements B or a subtype of B

Liskov Substitution Principle

If for each object *o1 of type S there is an object o2 of type T such that for all programs P defined in terms of T, the behavior of P is unchanged when o1 is substituted for o2 then S is a subtype of T.*

– I.e, if anyone expecting a T can be given an S, then S is a subtype of T.
– Does our definition of subtyping in terms of extends and implements obey this principle?

Polymorphism in Java

- Subtyping is a kind of polymorphism
  – Sometimes called *subtype polymorphism*
  – Allows method to accept objects of *many* types
- Another kind: *parametric polymorphism*
  – Implemented as generic methods in Java
- *Ad-hoc polymorphism* is overloading
  – Method overloading

A Stack of Integers

```
class IntegerStack {
  class Entry {
    Integer elt; Entry next;
    Entry(Integer i, Entry n) { elt = i; next = n; }
  }
  Entry theStack;
  void push(Integer i) {
    theStack = new Entry(i, theStack);
  }
  Integer pop() throws EmptyStackException {
    if (theStack == null)
      throw new EmptyStackException();
    else {
      Integer i = theStack.elt;
      theStack = theStack.next;
      return i;
  }}}
```

Inner Classes

- Classes can be nested inside other classes
  - These are called *inner classes*

- Within a class that contains an inner class, you can use the inner class just like any other class

Referring to Outer Class

```
class Stack {
 ...
 private int numEntries;
 class Entry {
    Integer elt; Entry next;
    Entry(Integer i) { elt = i; next = null;
                       numEntries++; }
 }
}
```

- Each inner "object" has an implicit reference to the outer "object" whose method created it
  - Can refer to fields directly, or use outer class name

Other Features of Inner Classes

- Outside of the outer class, use outer.inner notation to refer to type of inner class
  – E.g., Stack.Entry
- An inner class marked *static* does not have a reference to outer class
  – Can't refer to instance variables of outer class
  – Must also use outer.inner notation to refer to inner class
- Question: Can Stack.Entry be made static?

Compiling Inner Classes

- The JVM doesn't know about inner classes
  - Compiled away, similar to generics
  - Inner class Foo of outer class A produces A$Foo.class
  - Anonymous inner class of outer class A produces A$1.class
    - We'll see these later

- Why are inner classes useful?

IntegerStack Client

```
IntegerStack is = new IntegerStack();
Integer i;
is.push(new Integer(3));
is.push(new Integer(4));
i = is.pop();
```

- This is OK, but what if we want other kinds of stacks?
  - Need to make one XStack for each kind of X
  - Problems: Code bloat, maintainability nightmare

Polymorphism Using Object

```
class Stack {
  class Entry {
    Object elt; Entry next;
    Entry(Object i, Entry n) { elt = i; next = n; }
  }
  Entry theStack;
  void push(Object i) {
    theStack = new Entry(i, theStack);
  }
  Object pop() throws EmptyStackException {
    if (theStack == null)
      throw new EmptyStackException();
    else {
      Object i = theStack.elt;
      theStack = theStack.next;
      return i;
  }}}
```

Stack Client

```
Stack is = new Stack();
Integer i;
is.push(new Integer(3));
is.push(new Integer(4));
i = (Integer) is.pop();
```

- Now Stacks are reusable
  - push() works the same
  - But now pop() returns an Object
    - Have to downcast back to Integer
    - Not checked until run-time

General Problem

- When we move from an X container to an Object container
  – Methods that take X's as input parameters are OK
    - If you're allowed to pass Object in, you can pass any X in
  – Methods that return X's as results require downcasts
    - You only get Objects out, which you need to cast down to X

- This is a general feature of *subtype* polymorphism

Parametric Polymorphism (for Classes)

- In Java 1.5 we can *parameterize* the Stack class by its element type
- Syntax:
  - Class declaration: class A<T> { ... }
    - A is the class name, as before
    - T is a *type variable*, can be used in body of class (...)
  - Client usage declaration: A<Integer> x;
    - We *instantiate* A with the Integer type

Parametric Polymorphism for Stack

```
class Stack<ElementType> {
  class Entry {
    ElementType elt; Entry next;
    Entry(ElementType i, Entry n) { elt = i; next = n;
   }
  }
  Entry theStack;
  void push(ElementType i) {
    theStack = new Entry(i, theStack);
  }
  ElementType pop() throws EmptyStackException {
    if (theStack == null)
      throw new EmptyStackException();
    else {
      ElementType i = theStack.elt;
      theStack = theStack.next;
      return i;
  }}}
```

Stack<Element> Client

```
Stack<Integer> is = new Stack<Integer>();
Integer i;
is.push(new Integer(3));
is.push(new Integer(4));
i = is.pop();
```

- No downcasts
- Type-checked at compile time
- No need to duplicate Stack code for every usage

Parametric Polymorphism for Methods

- String is a subtype of Object
  1. static Object id(Object x) { return x; }
  2. static Object id(String x) { return x; }
  3. static String id(Object x) { return x; }
  4. static String id(String x) { return x; }

- Can't pass an Object to 2 or 4
- 3 doesn't type check
- Can pass a String to 1 but the compiler only knows that the value returned is an Object

Parametric Polymorphism, Again

- But id() doesn't care about the type of x
  - It works *for any* type

- So parameterize *the static method*:

```
static <T> T id(T x) { return x; }
Integer j = id(new Integer(3));
```

  - There's no need to explicitly instantiate id; compiler figures out the correct type.
    - In contrast, consider

```
List<Integer> list = new ArrayList<Integer>();
```

Standard Library, and Java 1.5

- Part of Java 1.5 (called “generics”)
  - Comes with replacement for java.util.*
    - class LinkedList<A> { ...}
    - class HashMap<A, B> { ... }
    - interface Collection<A> { ... }

- But they didn’t change the JVM to add generics
  - So how does that work?
  - Will answer this question shortly.

Subtyping for Generics

- Is Stack<Integer> a subtype of Stack<Object>?
  - The following code seems OK:

```
int count(Collection<Object> c) {
  int j = 0;
  for (Iterator<Object> i = c.iterator(); i.hasNext(); ) {
    Object e = i.next(); j++;
  }
  return j;}
```

- But I'm not allowed to call count(x) where x has type Stack<Integer>
- Let's a take a step back and consider arrays …

Subtyping and Arrays

- Java has a subtyping “feature”:
  - If S is a subtype of T, then
  - S[] is a subtype of T[]

- Lets us write methods that take arbitrary arrays

```
public static void reverseArray(Object [] A) {
     for(int i=0, j=A.length-1; i<j; i++,j--) {
       Object tmp = A[i];
       A[i] = A[j];
       A[j] = tmp;
     }
}
```

Problem with Subtyping Arrays

```
public class A { ... }
public class B extends A { void newMethod(); }
...
  void foo(void) {
     B[] bs = new B[3];
     A[] as;

     as = bs;              // Since B[] subtype of A[]
     as[0] = new A();      // (1)
     bs[0].newMethod();    // (2)
  }
```

- Program compiles without warning
- Java must generate run-time check at (1) to prevent (2) from blowing up
  - Type written to array must be subtype of array contents

Trouble with Subtyping for Generics

- What if List<Integer> is subtype of List<Object>?
  - The following code compiles OK:

```
void deepThought(List<Object> s) {
  s.add("The answer is");
  s.add(new Integer(42));
```

- Calling deepThought on a List<Object> would be OK
- But calling deepThought on a List<Integer> would be bad
  - don't have the information needed to do a runtime check
  - prefer to avoid runtime checks anyway
  - prefer to get errors at compile time

Solution I: Use Polymorphic Methods

```
<T> int count(Collection<T> c) {
  int j = 0;
  for (Iterator<T> i = c.iterator(); i.hasNext(); ) {
    T e = i.next(); j++;
  }
  return j;}
```

- But requires a “dummy” type variable that isn’t really used for anything
- Only works for methods, which can instantiate the type differently at each call site.
  – Can’t use for fields

Solution II: Wildcards

```
int count(Collection<?> c) {
  int j = 0;
  for (Iterator<?> i = c.iterator(); i.hasNext(); ) {
    Object e = i.next(); j++;
  }
  return j; }
```

- Use ? as the type variable
  - Collection<?> is "Collection of unknown"
- Generally, any time a type variable is used in only one place, can replace it with ?
  - and not have to declare the type variable
- Can use this for fields

Legal Wildcard Usage

- Reasonable question:
  - Why is Stack<Integer> not a subtype of Stack<Object>, but Stack<Integer> is a subtype of Stack<?>? In both cases, I have to cast the Stack's elements to type Object.
- Answer:
  - Loosely speaking: wildcards permit reading but not writing.
  - In general, if a generic class C is declared as

    ```
    class C<T> { … }
    ```

  - When called on a C<?>, methods that return T can have these values cast to Object, but a method that takes T as an argument can only be given null.

Example: Can read but cannot write

```
int count(Collection<?> c) {
  int j = 0;
  for (Iterator<?> i = c.iterator(); i.hasNext(); ) {
    Object e = i.next();
    c.add(e); // fails: Object is not ?
    j++;
  }
  return j; }
```

More on Generic Classes

- Suppose we have classes Circle, Square, and Rectangle, all subtypes of Shape

```
void drawAll(Collection<Shape> c) {
  for (Shape s : c)
    s.draw();
}
```

  – Can we pass this method a Collection<Square>?
    - No, not a subtype of Collection<Shape>
  – How about the following?

```
void drawAll(Collection<?> c) {
  for (Shape s : c)   // not allowed
    s.draw();
}
```

Bounded Wildcards

- We want drawAll to take a Collection of anything that is a *subtype* of shape

```
void drawAll(Collection<? extends Shape> c) {
  for (Shape s : c)
    s.draw();
}
```

  - This is a *bounded wildcard*
  - We can pass Collection<Circle>
  - We can safely treat e as a Shape

Bounded Wildcards (cont'd)

- Should the following be allowed?

```
void foo(Collection<? extends Shape> c) {
  c.add(new Circle());
}
```

  – No, because c might be a Collection of something that is not compatible with Circle
  – This code is forbidden at compile time

Lower Bounded Wildcards (cont'd)

- But the following is allowed?

```
void foo(Collection<? super Circle> c) {
  c.add(new Circle());
  c.add(new Shape()); // fails
}
```

  – Because c is a Collection of something that always compatible with Circle

A more realistic example

```
public interface Comparable<T> {
  int compareTo(T o);
}
// e.g., Boolean implements Comparable<Boolean>

public static <T extends Comparable<? super T>>
  void sort(List<T> list) {
    Object a[] = list.toArray();
    Arrays.sort(a);
    ListIterator<T> i = list.listIterator();
    for(int j=0; j<a.length; j++) {
       i.nextIndex();
       i.set((T)a[j]);
    }
  }
```

- I’m modifying the list via the Iterator. Why is this OK?

Bounded Type Variables

- You can also add bounds to regular type vars

```
<T extends Shape> T getAndDrawShape(List<T> c) {
  c.get(1).draw();
  return c.get(2);
}
```

  – This method can take a List of any subclass of Shape
    - This addresses some of the reason that we decided to introduce wild cards. Once again, this only works for methods; you could not declare a variable with this bound without wildcards.

Bounding and Wildcards

- Our legal wildcard rule from earlier can be refined to include bounds:
  - In general, if a generic class C is declared as

    ```
    class C<T extends B> { … }
    ```

  - When called on a C<?>, methods that return T can have these values cast to B, but a method that takes T as an argument can only be given values known to be of type T (including null)

Exercise: Annotate Java Libraries

- Look at the Java 1.4 API, and figure out how you would best annotate the following classes
  - Collection
  - Comparator
  - Collections
  - Class

  - Look at others too!

Collection<E>

boolean add(E e)

boolean addAll(Collection <? extends E> c)

boolean contains(Object o)

boolean containsAll(Collection<?> c)

boolean remove(Object o)

boolean removeAll(Collection<?> c)

boolean retainAll(Collection<?> c)

Object[] toArray()

<T> T[] toArray(T[] a)

Translation via Erasure

- Replace uses of type variables with Object
  - class A<T> { ...T x;... } becomes
  - class A { ...Object x;... }
- Add downcasts wherever necessary
  - Integer x = A<Integer>.get(); becomes
  - Integer x = (Integer) (A.get());
- Uh...so why did we bother with generics if they're just going to be removed?
  - Because the compiler still did type checking for us
  - We know that those casts will not fail at run time

Limitations of Translation

- Some type information not available at run-time
  - Recall type variables T are rewritten to Object

- Thus, assuming T is type variable
  - new T() would translate to new Object() (error)
  - new T[n] would translate to new Object[n] (warning)
  - Some casts/instanceofs that use T
    - (Only ones the compiler can figure out are allowed)

- Also produces some oddities
  - LinkedList<Integer> and LinkedList<String> share the same static variables (can't use T in static methods/fields)
  - LinkedList<Integer>.class == LinkedList<String>.class
    - (These are uses of reflection to get the class object)

Using with Legacy Code

- Translation via type erasure
  - class A <T> becomes class A
- Thus class A is available as a "raw type"
  - class A<T> { ... }
  - class B { A x; }   // use A as raw type
- Sometimes useful with legacy code, but...
  - Dangerous feature to use, plus unsafe
  - Relies on implementation of generics, not semantics