Elements of Programming Languages
Tutorial 6: Classes, subtyping, and comprehensions
Week 8 (November 6–10, 2017)

Starred exercises are more challenging. Please try all unstarred exercises before the tutorial meeting.

1. **Covariant and contravariant type parameters**
   In Scala, a type parameter in a definition can be marked *covariant* by prefixing it with `+` and *contravariant* by prefixing it with `−`.

   Consider the following Scala code:

   ```scala
   abstract class Super
   class Sub1(n: Int) extends Super
   class Sub2(b: Boolean) extends Super
   class Box1[+A] // covariant
   class Box2[−A] // contravariant

   def g1(x: Box1[Super]) = x
   def g2(x: Box1[Sub1]) = x
   def h1(x: Box2[Super]) = x
   def h2(x: Box2[Sub1]) = x
   ```

   Suppose that `A` is replaced with one of the types `Any`, `Nothing`, `Super`, `Sub1`, or `Sub2`. For which values of `A` do the following calls typecheck:

   - `g1(new Box1[A])`
   - `g2(new Box1[A])`
   - `h1(new Box2[A])`
   - `h2(new Box2[A])`

   (It may help to draw a matrix with rows labeled by the function names and columns by the five possible types for `A`). You can type all of these expressions into Scala to find this out. What is the pattern?

2. **Parameterized traits**
   Traits can also be parameterized by types. The built-in trait `Ordered[T]` is an example:

   ```scala
   trait Ordered[T] {
     def compare(that: T): Int
     def < (that: T): Boolean = ???
     def <= (that: T): Boolean = ???
   }
   ```
Here, the type parameter $T$ is needed to name the type of other elements to which this will be compared. The this.compare(that) operation returns a negative integer if this is less than that, zero if they are equal and a positive integer if this is greater than that.

Based on this specification, fill in the ??? regions in the above code snippet with code that defines standard comparison operators such as $<$ in terms of compare. Define the remaining operations $>$, $\geq$ and $\neq$ equalTo, nequalTo. (The operator names $==$ and $!=$ are already defined in Scala and can’t be overridden at a different type in this trait.)

3. List comprehensions

Using the desugaring rules for list comprehensions described in Lecture 11, give the resulting list and convert the following list comprehension expressions to plain Scala code.

(a) for (x <- List(1,2,3)) yield (x + 1)
(b) for (x <- List(1,2,3); if (x % 2 == 0)) yield (x / 2)
(c) (*) for (x <- List(1,2,3); y <- List(1,2,3); if (x < y)) yield (x, y)

4. Covariant lists

Covariance and subtyping allows us to define lists more cleanly:

```scala
abstract class List[+A]
case object Nil extends List[Nothing]
case class Cons[+A](head: A, tail: List[A]) extends List[A]
```

Now Nil is a case object, so it doesn’t need a parameter list, and it extends List[Nothing], so it doesn’t need a type parameter. (Case objects with only a type parameter and no value parameters are not allowed in Scala.) This is much closer to the way lists are actually defined in Scala.

(a) Define a list expression that has type List[Any] and would not type-check in the absence of subtyping.

(b) Define a List[A] member append that allows lists of different types as arguments, provided the two element types have a common supertype. (Hint: Scala type parameters can be given both lower and upper type bounds, e.g. def foo[A, B : A, C <: A] says that foo has three type parameters, A, B which must be a supertype of A, and C which must be a subtype of A.)