9 Implementing Subtyping

Last time, we saw the kind of code reuse we can obtain when we have a subtyping relation between two types. But we didn’t say that much about how to get subtyping. In fact, the only subtyping we’ve seen is in the Specification Design Pattern, here we defined the concrete classes describing the representation of data corresponding to each of the creators as subtypes of an abstract class defining the signature. How about other kind of subtypings between ADTs? Note that for the time being we will look at subtyping between abstract classes only. It makes a lot of things much simpler.

There are three main reasons for introducing subtyping between types \( D \) and \( C \):

(1) \( D \) may be a generalization of \( C \) with extra operations defined. For instance, a \( \text{CPoint} \) is a \( \text{Point} \) with extra operations to deal with the fact that \( \text{CPoints} \) have a color.

(2) \( D \) may be a restricted form of \( C \) with additional properties coming from the restriction, but no additional operations. For instance, a nonempty list \( \text{NEList} \) is a \( \text{List} \) with the additional property that it is never empty.

(3) \( D \) may bear some relationship to \( C \) that makes it a suitable candidate for subtyping in the context of the application at hand. This is much more \textit{ad hoc}, in the sense that it really depends on the application. For example, lists could be declared to be a subtype of trees, since a list can be seen as a degenerate tree in which every node only has a right subtree (which is the rest of the list, recursively). It rarely is useful to think of lists as trees, but the point is we could, and some applications may benefit from it.

We won’t have much to say about (3), but (1) and (2) are common enough that it pays to see how to set-up those kind of subtyping relations.

9.1 Subtyping by Generalization

Consider our standard ADTs \( \text{POINT} \), simplified somewhat so that it only has one creator to simplify our examples

\[
\text{CREATORS}
\begin{align*}
\text{cartesian} & : (\text{Double, Double}) \rightarrow \text{Point}
\end{align*}
\]
OPERATIONS

\[
\begin{align*}
\text{xCoord} & : () \to \text{Double} \\
\text{yCoord} & : () \to \text{Double} \\
\text{move} & : (\text{Double, Double}) \to \text{Point} \\
\text{rotate} & : (\text{Double}) \to \text{Point} \\
\text{add} & : (\text{Point}) \to \text{Point} \\
\text{isEqual} & : (\text{Point}) \to \text{Boolean}
\end{align*}
\]

and CPOINT:

CREATORS

\[
\text{cartesian} : (\text{Double, Double, Color}) \to \text{CPoint}
\]

OPERATIONS

\[
\begin{align*}
\text{xCoord} & : () \to \text{Double} \\
\text{yCoord} & : () \to \text{Double} \\
\text{color} & : () \to \text{Color} \\
\text{updateColor} & : (\text{Color}) \to \text{CPoint} \\
\text{move} & : (\text{Double, Double}) \to \text{CPoint} \\
\text{rotate} & : (\text{Double}) \to \text{CPoint} \\
\text{add} & : (\text{CPoint}) \to \text{CPoint} \\
\text{isEqual} & : (\text{CPoint}) \to \text{Boolean}
\end{align*}
\]

with the usual specification.\(^1\)

We want to set things up so that CPoint is a subtype of Point. Let’s get a version going for the ADT without methods add() and isEqual() first. We’ll see that they cause a few problems.

Ideally, we would like it to be the case that we could call the following code with either Points or CPoints. That will be our test to make sure that our subtyping enables us to get reuse.

\[
\begin{align*}
\text{def negatePoint} \ (p: \text{Point}): \text{Point} & = \\
& \quad p.\text{move}(-2*p.\text{xCoord()},-2*p.\text{yCoord()})
\end{align*}
\]

\[
\begin{align*}
\text{def addPoint} \ (p: \text{Point}, q: \text{Point}): \text{Point} & = \\
& \quad p.\text{move}(q.\text{xCoord()},q.\text{yCoord()})
\end{align*}
\]

---

\(^1\)For add() in CPoint, assume that the color of the result of p.add(q) is the color of q.
def rotateAroundPoint (p:Point, angle:Double, center:Point):Point =
    addPoint(center,addPoint(p,negatePoint(center)).rotate(angle))

Let's first define an implementation for ADT Point using the Specification Design Pattern,
as usual — remember, we do not have add() and isEqual() in the abstract class, so while
we do have those methods implemented in the implementation class for cartesian points,
those methods are not accessible. (Why?)

object Point {

    def cartesian (x:Double,y:Double):Point =
        new CarPoint(x,y)

    private class CarPoint (first:Double, second:Double) extends Point {
        def xCoord ():Double =
            first

        def yCoord ():Double =
            second

        def move (dx:Double,dy:Double):Point =
            cartesian(first+dx,second+dy)

        def rotate (theta:Double):Point =
            new CarPoint(first * math.cos(theta) - second * math.sin(theta),
                        first * math.sin(theta) + second * math.cos(theta))

        def add (p:Point):Point =
            move(p.xCoord(),p.yCoord())

        def isEqual (q:Point):Boolean =
            (first==q.xCoord() && second==q.yCoord())

        // CANONICAL

        override def toString ():String =
            "cart(" + first + "," + second + ")"

        override def equals (other : Any):Boolean =
            other match {
                case that : Point => this.isEqual(that)
                case _ => false
            }

    }

    // ...

}
override def hashCode ():Int =
  41 * (41 + first.hashCode()) + second.hashCode()
}

abstract class Point {
  def xCoord ():Double
  def yCoord ():Double

  def move (dx:Double,dy:Double):Point
  def rotate (t:Double):Point
}

Now, onto an implementation for ADT CPoint. Again, we implement it using the Specification Design Pattern. The implementation is completely straightforward. And it turns out that we can specify that a CPoint is a subtype of Point by simply stating that the abstract class CPoint extends Point. Note that subtyping relationship is between the abstract class representing the signatures here. There is no relationship between the implementation of those signatures. (Draw a diagram of the subtyping relationship, if it helps you.)

object CPoint {
  def cartesian (x:Double,y:Double,c:Color):CPoint =
    new CarCPoint(x,y,c)

  private class CarCPoint (first:Double, second:Double,
    col: Color) extends CPoint {
    def color ():Color = col

    def updateColor (c:Color):CPoint =
      new CarCPoint(first,second,c)

    def xCoord ():Double =
      first

    def yCoord ():Double =
      second

def move (dx: Double, dy: Double): CPoint =
    new CarCPoint(first + dx, second + dy, col)

def add (cp: CPoint): CPoint =
    new CarCPoint(first + cp.xCoord(), second + cp.yCoord(), cp.color())

def rotate (theta: Double): CPoint =
    new CarCPoint(first * math.cos(theta) - second * math.sin(theta),
                   first * math.sin(theta) + second * math.cos(theta),
                   col)

def isEqual (q: CPoint): Boolean =
    (first == q.xCoord() && second == q.yCoord() && col == q.color())

// CANONICAL

override def toString (): String =
    "cart(" + first + "," + second + "," + col + ")"

override def equals (other : Any): Boolean =
    other match {
        case that : CPoint => this.isEqual(that)
        case _ => false
    }

override def hashCode (): Int =
    41 * (
        41 * (
            41 + first.hashCode()
        ) + second.hashCode()
    ) + col.hashCode()
}

abstract class CPoint extends Point {

def color (): Color

def updateColor (c: Color): CPoint

def xCoord (): Double
```java
def yCoord ():Double

def move (dx:Double,dy:Double):CPoint

def rotate (t:Double):CPoint

And it's that simple. Let's make sure we can call our rotateAroundPoint() function with Points:

```java
val p : Point = Point.cartesian(1,1)
val q : Point = Point.cartesian(1,2)
val r : Point = rotateAroundPoint(q,math.Pi/2,p)
println("Result = " + r)
```

Running this yields:

Result = cart(0.0,1.0)

And we can reuse the same rotateAroundPoint() function to work with CPoints as well:

```java
val p : Point = CPoint.cartesian(1,1,Color.blue())
val q : Point = CPoint.cartesian(1,2,Color.red())
val r : Point = TestCore.rotateAroundPoint(q,math.Pi/2,p)
println("Result = " + r)
```

yielding

Result = cart(0.0,1.0,blue)

What about those two operations we haven't dealt with yet, add() and isEqual()? They're already implemented in both implementation classes CarPoint and CarCPoint. It's just a matter of revealing them through the abstract classes. It's no problem to add them to the Point abstract class:

```java
object Point {

  def cartesian (x:Double,y:Double):Point =
    new CarPoint(x,y)

  private class CarPoint (first:Double, second:Double) extends Point {
    def xCoord ():Double =
      first
```
def yCoord():Double =
  second

def move(dx:Double,dy:Double):Point =
  cartesian(first+dx,second+dy)

def rotate(theta:Double):Point =
  new CarPoint(first * math.cos(theta) - second * math.sin(theta),
               first * math.sin(theta) + second * math.cos(theta))

def add(p:Point):Point =
  move(p.xCoord(),p.yCoord())

def isEqual(q:Point):Boolean =
  (first==q.xCoord() && second==q.yCoord())

// CANONICAL

override def toString():String =
  "cart(" + first + "," + second + ")"

override def equals(other: Any):Boolean =
  other match {
    case that : Point => this.isEqual(that)
    case _ => false
  }

override def hashCode():Int =
  41 * (41 + first.hashCode()) + second.hashCode()
The problems occur when we try to do the same thing with the `CPoint` abstract class. If we simply update it to be:

```scala
abstract class CPoint extends Point {

  def color ():Color
  def updateColor (c:Color):CPoint

  def xCoord ():Double
  def yCoord ():Double

  def move (dx:Double,dy:Double):CPoint
  def rotate (t:Double):CPoint

  def add (p:CPoint):CPoint
  def isEqual (p:CPoint):Boolean
}
```

then the Scala type checker complains horribly:

```
CPoint.scala:8: error: class CarCPoint needs to be abstract, since:
  method isEqual in class CPoint of type (p: Point)Boolean is not defined
  method add in class CPoint of type (p: Point)Point is not defined
private class CarCPoint (first:Double, second:Double,
^  one error found
```

Basically, the type checker is complaining that we’re missing methods `add()` and `isEqual()` that can work on `Point`s in our `CPoint` class. The type checker complaining means that there’s a possibility of our code being unsafe. So what’s the problem?

The problem is subtle. Can we come up with code that, were the code above to be accepted by the type checker, would be unsafe — that is, cause a method-not-found error?

Here’s the offending code:

```scala
val p:Point = CPoint.cartesian(2,4,Color.yellow())
val q:Point = Point.cartesian(0,100)
val r:Point = p.add(q)
```
What’s going on here? Note that if we assume that the type checker accepted our CPoint implementation and made CPoint a subtype of Point, then the static types all agree (after the type checker adds the upcast in the first binding to treat the CPoint as a Point). But what happens during execution? p is bound to a CPoint (so that the dynamic type of p is CPoint) and q is bound to a Point. The call p.add(q) requires the system to look at the appropriate add() method in the dynamic type of p, so in CPoint. The add() method in CPoint expects a value of static type CPoint, and we’re giving it q, a value of static type Point. We would need a downcast for this to work, and the type checker never introduces downcasts for us, so this fails to type check. And indeed, were we to execute this, the add() method in CPoint would try to access the color() method on q, and since q is a Point, the method color() would not be found. So the type checker prevented this error from happening.

Great. But then how do we get CPoint to be a subtype of Point, since we still intuitively believe that they should be subtypes? The solution is in the example above. We need to provide methods add() (and isEqual()) in CPoint that can work with Points, on top of those we already have that can work with CPoints.

The easiest way to do this is simply to add a new method declaration to the CPoint abstract class, telling Scala that there is an additional add() method (and isEqual() method) of the appropriate type, and implement those two new methods in CarCPoint:

```scala
object CPoint {

  def cartesian (x:Double,y:Double,c:Color):CPoint =
    new CarCPoint(x,y,c)

  private class CarCPoint (first:Double, second:Double,
                           col: Color) extends CPoint {

    def color ():Color = col

    def updateColor (c:Color):CPoint =
      new CarCPoint(first,second,c)

    def xCoord ():Double =
      first

    def yCoord ():Double =
      second

    def move (dx:Double,dy:Double):CPoint =
      new CarCPoint(first+dx, second+dy,col)

  }

}
```
def add (cp:CPoint):CPoint =
    new CarCPoint(first+cp.xCoord(),second+cp.yCoord(),cp.color())

def add (p:Point):Point =
    p match {
        case cp:CPoint => add(cp)
        case _ => Point.cartesian(first+p.xCoord(),second+p.yCoord())
    }

def rotate (theta:Double):CPoint =
    new CarCPoint(first * math.cos(theta) - second * math.sin(theta),
                  first * math.sin(theta) + second * math.cos(theta),
                  col)

def isEqual (q:CPoint):Boolean =
    (first==q.xCoord() && second==q.yCoord() && col==q.color())

def isEqual (q:Point):Boolean =
    q match {
        case cq:CPoint => isEqual(cq)
        case _ => false
    }

// CANONICAL

override def toString ():String =
    "cart(" + first + "," + second + "," + col + ")"

override def equals (other : Any):Boolean =
    other match {
        case that : CPoint => this.isEqual(that)
        case _ => false
    }

override def hashCode ():Int =
    41 * (
        41 * (41 + first.hashCode() + second.hashCode())
        + col.hashCode()
    )
abstract class CPoint extends Point {

    def color ():Color
    def updateColor (c:Color):CPoint

    def xCoord ():Double
    def yCoord ():Double

    def move (dx:Double,dy:Double):CPoint
    def rotate (t:Double):CPoint

    def add (p:CPoint):CPoint
    def isEqual (p:CPoint):Boolean

    // needed for subtyping
    def add (p:Point):Point
    def isEqual (p:Point):Boolean
}

A couple of things to notice: first, there are now multiple add() and isEqual() methods available in CPoint (and in CarCPoint). This is called overloading, and it is allowed, as long as the methods take arguments of different types.

How does Scala resolve the overloading? That is, given something like cp.add(q), where cp is a value with dynamic type CPoint, how does it decide which of the two add() methods available in CPoint to call? It decides based on the static type of the argument. So if q is of static type Point, then Scala will call the add(p:Point) method in CPoint. If q is of static type CPoint, then it will call the add(cp:CPoint) method in CPoint. This may be counterintuitive (I certainly find it counterintuitive myself) but that’s the way it is.

The second thing to notice is that in the implementation of add() that takes a Point as an argument, we do a dynamic check to see if the value we took as an argument really has dynamic type CPoint — if so, we may as well call the add() method that can deal with CPoints. If not, then we add the points as though they were Points. A similar deal occurs with isEqual() — if the argument really has dynamic type CPoint, we call the isEqual() method that can deal with CPoints, and if not, then we return false, because points and colored points should not be equal.

This kind of problem will occur every time you try to define a subtype D for a type C whose signature contains methods that expect arguments of type C. In D, those methods will generally take values of type D, and you will need to define “bridge methods” in D for those methods that can also take values of type C. Unfortunately, there is in general
no principled way to devise those bridge methods. You’ll need to think them through from scratch, depending on the ADT and what it might mean to perform the operation at hand on values of different types.

With the (corrected) code above, we can try a different version of our test, since now we have an `add()` we can call:

```scala
def negatePoint (p:Point):Point =  
  p.move(-2*p.xCoord(),-2*p.yCoord())

def rotateAroundPoint (p:Point, angle:Double, center:Point):Point =  
  p.add(negatePoint(center)).rotate(angle).add(center)
```

Running the examples above with this version of `rotateAroundPoint()` gives exactly the same results, as expected.

### 9.2 Subtyping by Restriction

Subtyping by restricting an ADT is less frequent, but still sometimes useful. Let’s illustrate it with non-empty lists as a subtype of lists.

First, recall the `List` ADT:

**CREATORS**

- `empty : () -> List`
- `cons : (Int, List) -> List`

**OPERATIONS**

- `isEmpty : () -> Boolean`
- `first : () -> Int`
- `rest : () -> List`
- `length : () -> Int`
- `append : (List) -> List`
- `find : (Int) -> Boolean`
- `isEqual : (List) -> Boolean`

with the usual specification:

- `empty().isEmpty() = true`
- `cons(n,L).isEmpty() = false`
- `cons(n,L).first() = n`
- `cons(n,L).rest() = L`
- `empty().length() = 0`
cons(n, L).length() = 1 + L.length()
empty().append(M) = M
cons(n, L).append(M) = cons(n, L.append(M))
empty().find(f) = false
cons(n, L).find(f) = \begin{cases} 
    true & \text{if } n = f \\
    true & \text{if } L.find(f) = true \\
    false & \text{otherwise} 
\end{cases}
empty().isEqual(M) = \begin{cases} 
    true & \text{if } M.isEmpty() = true \\
    false & \text{otherwise} 
\end{cases}
cons(n, L).isEqual(M) = \begin{cases} 
    false & \text{if } M.isEmpty() = true \\
    true & \text{if } n = M.first() \\
    \text{and } L.isEqual(M.rest()) = true 
\end{cases}

The implementation, you’ll recall, is completely straightforward using the Specification Design Pattern:

```scala
object List {

    def empty ():List = new ListEmpty()

    def cons (n:Int, L:List):List = new ListCons(n,L)

    // EMPTY LIST REPRESENTATION
    //
    private class ListEmpty () extends List {

        def isEmpty ():Boolean = true

        def first ():Int =
            throw new RuntimeException("empty().first()")

        def rest ():List =
            throw new RuntimeException("empty().rest()")

        def length ():Int = 0

        def append (M:List):List = M

        def find (f:Int):Boolean = false

```
def isEqual (M:List):Boolean = M.isEmpty()

override def equals (other:Any):Boolean = 
  other match {
    case that:List => this.isEqual(that)
    case _ => false
  }

override def hashCode ():Int = 41

override def toString ():String = ""

// CONS LIST REPRESENTATION
//
private class ListCons (n:Int, L:List) extends List {

  def isEmpty ():Boolean = false

  def first ():Int = n

  def rest ():List = L

  def length ():Int = 1 + L.length()

  def append (M:List):List = List.cons(n,L.append(M))

  def find (f:Int):Boolean = { (f == n) || L.find(f) }

  def isEqual (M:List):Boolean = 
    !(M.isEmpty()) && n==M.first() && L.isEqual(M.rest())

  override def equals (other : Any) : Boolean = 
    other match {
      case that:List => this.isEqual(that)
      case _ => false
    }

  override def hashCode ():Int = 41 * (41 + n.hashCode())
abstract class List {

  def isEmpty ():Boolean
  def first ():Int
  def rest ():List
  def length ():Int
  def append (M:List):List
  def find (f:Int):Boolean
  def isEqual (M:List):Boolean

}

Here are a few test functions to compute the average of the elements of a list:

    def sum (x:List):Int =
      if (x.isEmpty())
        0
      else
        x.first() + sum(x.rest())

    def average (x:List):Int = {
      if (x.isEmpty())
        throw new IllegalArgumentException("Average of empty list")
      else
        (sum(x) / x.length())
    }

We can try this out on a sample list:

    val L1:List = List.cons(33,List.cons(66,List.cons(99,List.empty())))
    println("Sum = " + sum(L1))
    println("Average = " + average(L1))

which yields:

    Sum = 198
    Average = 66
Now, consider the following variant defining non-empty lists, the NEList ADT:

**CREATORS**
- `singleton : (Int) -> NEList`
- `cons : (Int, List) -> NEList`

**OPERATIONS**
- `isEmpty : () -> Boolean`
- `isSingleton : () -> Boolean`
- `first : () -> Int`
- `rest : () -> List`
- `length : () -> Int`
- `append : (List) -> NEList`
- `find : (Int) -> Boolean`
- `isEqual : (List) -> Boolean`

with the expected specification:

\[
\begin{align*}
\text{singleton}(n).\text{isEmpty()} &= false \\
\text{cons}(n,L).\text{isEmpty()} &= false \\
\text{singleton}(n).\text{isSingleton()} &= true \\
\text{cons}(n,L).\text{isSingleton()} &= \begin{cases} 
  true & \text{if } L.\text{isEmpty()} = true \\
  false & \text{otherwise}
\end{cases} \\
\text{singleton}(n).\text{first()} &= n \\
\text{cons}(n,L).\text{first()} &= n \\
\text{singleton}(n).\text{rest()} &= L \\
\text{cons}(n,L).\text{rest()} &= L \\
\text{singleton}(n).\text{length()} &= 1 \\
\text{cons}(n,L).\text{length()} &= 1 + L.\text{length()} \\
\text{singleton}(n).\text{append}(M) &= \text{cons}(n,M) \\
\text{cons}(n,L).\text{append}(M) &= \text{cons}(n,L.\text{append}(M)) \\
\text{singleton}(n).\text{find}(f) &= \begin{cases} 
  true & \text{if } n = f \\
  false & \text{otherwise}
\end{cases} \\
\text{cons}(n,L).\text{find}(f) &= \begin{cases} 
  true & \text{if } n = f \\
  true & \text{if } L.\text{find}(f) = true \\
  false & \text{otherwise}
\end{cases}
\end{align*}
\]
Singleton(n).isEqual(M) = \[
\begin{cases}
  false & \text{if } M\text{.isEmpty()} = true \\
  true & \text{if } M\text{.first()} = n \\
  & \text{and } M\text{.rest()}\text{.isEmpty()} = true \\
  false & \text{otherwise}
\end{cases}
\]

Cons(n,L).isEqual(M) = \[
\begin{cases}
  false & \text{if } M\text{.isEmpty()} = true \\
  true & \text{if } n = M\text{.first()} \\
  & \text{and } L\text{.isEqual}(M\text{.rest()}) = true \\
  false & \text{otherwise}
\end{cases}
\]

Again, this is straightforward to implement using the Specification Design Pattern, without knowing anything about the implementation of lists. Note that we do not need “bridge methods” because we cleverly (!) defined the isEqual() and append() methods in NEList to expect a List as argument, and not an NEList – in both cases because the operation makes perfect sense when given a non-empty list.

object NEList {
  def singleton (n:Int):NEList = new Singleton(n)
  def cons (n:Int, L:List):NEList = new Cons(n,L)

  // SINGLETON LIST REPRESENTATION
  //
  private class Singleton (n:Int) extends NEList {
    def isEmpty ():Boolean = false
    def isSingleton ():Boolean = true
    def first ():Int = n
    def rest ():List = List.empty()
    def length ():Int = 1
    def append (M:List):NEList = cons(n,M)
    def find (f:Int):Boolean = (f==n)
    def isEqual (M:List):Boolean = {
      M.length()==1 && M.first()==n
    }
  }
}
override def equals (other:Any):Boolean =
  other match {
    case that:List => this.isEqual(that)
    case _ => false
  }

override def hashCode ():Int = 41

override def toString ():String = n.toString()
}

// CONS LIST REPRESENTATION

private class Cons (n:Int, L:List) extends NEList {

def isEmpty ():Boolean = false

def isSingleton ():Boolean = L.isEmpty()

def first ():Int = n

def rest ():List = L

def length ():Int = 1 + L.length()

def append (M:List):NEList = cons(n,L.append(M))

def find (f:Int):Boolean = { (f == n) || L.find(f) }

def isEqual (M:List):Boolean =
  { !(M.isEmpty()) && n==M.first() && L.isEqual(M.rest()) }

override def equals (other:Any):Boolean =
  other match {
    case that:List => this.isEqual(that)
    case _ => false
  }

override def hashCode ():Int =
  41 * (
abstract class NEList extends List {

  def isEmpty ():Boolean
  def isSingleton ():Boolean
  def first ():Int
  def rest ():List
  def length ():Int
  def find (f:Int):Boolean
  def append (M:List):NEList
  def isEqual (M:List):Boolean
}

We can certainly check that the previously defined sum() and average() functions work with NEList, but we can do a bit better here. The average() function above needed to check that the list was non-empty before computing the average. With an NEList, we do not need to do this check. So we can define a variant of average() that works on NELists and that does not perform that check. (We’re using overloading to define a method with the same name as before, but working on different types — recall that Scala will disambiguate based on the static type of the argument.)

    def average (x:NEList):Int = {
      (sum(x) / x.length())
    }

Trying it out on the previous list, but now reconstructed as a NEList:

    val L2:NEList = NEList.cons(33,NEList.cons(66,NEList.singleton(99)))
    println("Sum = " + sum(L2))
    println("Average (no check) = " + average(L2))

which yields, as before

    Sum = 198
    Average (no check) = 66
The result is of course the same, but the average function now does not need to do the emptiness check.

This may not look like a big win, but that’s because the example is rather simple. More involved examples can be devised, for instance, a subtype of Atlas from your last homework that guarantees that all the exits lead to room that actually occur in the atlas. I’ll leave that as an exercise.