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Advanced Programming

Type Classes and Implicits (on the example of a PBT library)

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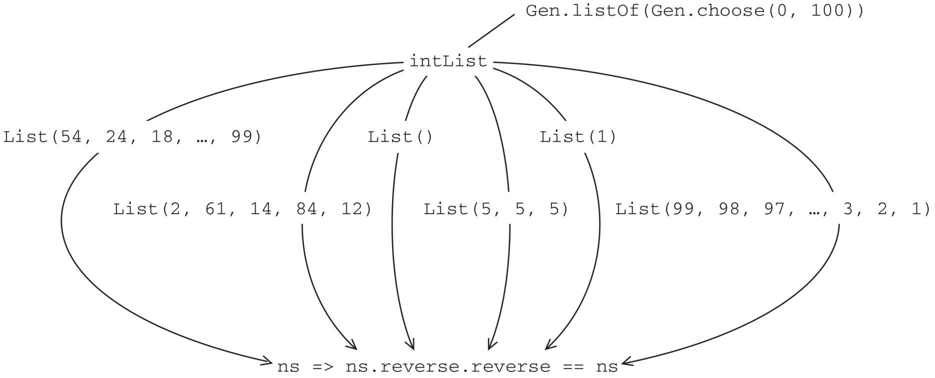
SOFTWARE QUALITY RESEARCH

Generators and properties

`forAll(intList)(ns => ns.reverse.reverse == ns)`



A `Gen` object generates a variety of different objects to pass to a Boolean expression, searching for one that will make it false.

Figure from [Chiusano, Bjarnason 2014]

The Prop Type

Represents a property to test

```scala
case class Prop (run: (MaxSize, TestCases, RNG) => Result) {
  def && (p: Prop): Prop = ???
  def || (p: Prop): Prop = ???
}

object Prop {
  type SuccessCount = Int
  type TestCases = Int
  type MaxSize = Int
  type FailedCase = String

  sealed trait Result { def isFalsified: Boolean }

  case object Passed extends Result { def isFalsified = false }
  case class Falsified (failure: FailedCase, successes: SuccessCount)
    extends Result { def isFalsified = true }

  case object Proved extends Result { def isFalsified = false }
  ...
```


The Prop Type

A simple implementation of `forAll`

A stream of pairs `(a, i)` where `a` is a random value and `i` is its index in the stream.

```
def forAll[A](as: Gen[A])(f: A => Boolean): Prop = Prop {
  (n,rng) => randomStream(as)(rng).zip(Stream.from(0)).take(n).map {
    case (a, i) => try {
      if (f(a)) Passed else Falsified(a.toString, i)
    } catch { case e: Exception => Falsified(buildMsg(a, e), i) }
  }.find(_.isFalsified).getOrElse(Passed)
}

def randomStream[A](g: Gen[A])(rng: RNG): Stream[A] =
  Stream.unfold(rng)(rng => Some(g.sample.run(rng)))
def buildMsg[A](s: A, e: Exception): String =
  s"test case: $s\n" +
  s"generated an exception: ${e.getMessage}\n" +
  s"stack trace:\n ${e.getStackTrace.mkString("\n")}"
```

If a test case generates an exception, record it in the result.

When a test fails, record the failed case and its index so we know how many tests succeeded before it.

Generates an infinite stream of `A` values by repeatedly sampling a generator.

String interpolation syntax. A string starting with `s"` can refer to a Scala value `v` as `$v` or `${v}` in the string. The Scala compiler will expand this to `v.toString`.

Figure from [Chiusano, Bjarnason 2014]

Shrinking

(More precisely: sized generation)

A generator of objects of bounded size: `case class SGen[+A] (forSize: Int =>Gen[A])`

```
type MaxSize = Int
case class Prop(run: (MaxSize,TestCases,RNG) => Result)

def forAll[A](g: SGen[A])(f: A => Boolean): Prop =
  forAll(g(_))(f)

def forAll[A](g: Int => Gen[A])(f: A => Boolean): Prop = Prop {
  (max,n,rng) =>
    val casesPerSize = (n + (max - 1)) / max
    val props: Stream[Prop] =
      Stream.from(0).take((n min max) + 1).map(i => forAll(g(i))(f))
    val prop: Prop =
      props.map(p => Prop { (max, _, rng) =>
        p.run(max, casesPerSize, rng)
      }).toList.reduce(_ && _)
    prop.run(max,n,rng)
}
```

For each size, generate this many random cases.

Make one property per size, but no more than n properties.

Combine them all into one property.

Figure from [Chiusano, Bjarnason 2014]

Executing Tests

```scala
def run(p: Prop,
        maxSize: Int = 100,
        testCases: Int = 100,
        rng: RNG = RNG.Simple(System.currentTimeMillis)): Unit =
  p.run(maxSize, testCases, rng) match {
    case Falsified(msg, n) =>
      println(s"! Falsified after $n passed tests:\n $msg")
    case Passed =>
      println(s"+ OK, passed $testCases tests.")
  }
```

A default argument of `100`

Figure from [Chiusano, Bjarnason 2014]

Generation for PBT as an Instance of State

- For property-based testing (PBT) we need to **implement generators**
- First, need random **number generators**, to generate arbitrary random data
- Random number generators can be `mapped`, `flatMapped`, and `map2ed` to generate other values
- Recall class `State`, implementing the **automaton abstraction** with state space `S` and outputs `A`:

```
case class State[S,+A] (run: S =>(A,S))
```

- We define generators of `A`'s as an automaton producing `A`'s with `RNG` as a state space:

```
case class Gen[+A] (sample: State[RNG,A])
```

- **Question**: Why are generators covariant? What this will allow?
- Examples:

  Recall: `_.nextInt: RNG =>(Int,RNG)`

  then `def anyInteger: Gen[Int] =Gen (State (_.nextInt))`
- **Mentimeter:** How do I get an integer number out of `anyInteger`? (the first one)

How do we create more complex generators?

- Let's begin with a generator of **pairs of integers**, so `Gen[(Int,Int)]`
- Recall the **sequential chaining of automata** with `map2` for `State[S,A]`:

```
def map2[B,C] (that: State[S,B]) (f: (A,B) =>C): State[S,C] =...
```

- `Gen[A]` is a `State[RNG,A]`, so it has `map2` like above

- We use `map2` to create the **generator of pairs of integers** `def intPair: Gen[(Int,Int)]`:

```
= Gen (anyInteger.sample.map2 (anyInteger.sample) (xy=>xy))
```

- Note how nicely composable are the libraries we build!
  (We use the code from chapter 6)
- **Question**: What is the following generator creating ?

```
Gen (anyInteger.sample.map (x =>x % 100 + 200)): Gen[Int]
```

Generating random lists of integers

- Assume that we have a generator of lists of random integers of length `n`

```
def listOfN (n: Int): Gen[List[Int]]
```

- **Question:** What is the type of `G` in

```
val G =Gen (anyInteger.sample.flatMap (n =>listOfN (n).sample))
```

- **Answer**: `Gen[List[Int]]`
- Once we implement `flatMap` for `Gen` (delegating to `State`), we can simplify:

```
val G: Gen[List[Int]] =anyInteger.flatMap (n =>listOfN (n))
```

- This is the first complex data structure we generated!!!
- **Question**: Well, what exactly is the generator G generating?

Generating instances of polymorphic types /1

- Let's return to generating random pairs. Can you do a `Gen[(A,B)]`?

```
def anyPair[A,B]: Gen[(A,B)] =???
```

Below `intPair` as a hint:

```
def intPair: Gen[(Int,Int)] =anyInteger.map2 (anyInteger) (xy =>xy)
```

- We seem to lack a way to generate A's and B's! So let's add them as arguments:

```
def anyPair[A,B] (genA: Gen[A], genB: Gen[B]): Gen[(A,B)] =genA.map2 (genB) (ab =>ab)
```

For simplicity, I am assuming that we have `map2` on Gen. Otherwise:

```
def anyPair[A,B] (genA: Gen[A], genB: Gen[B]) =Gen (genA.sample.map2 (genB.sample) (ab =>ab))
```

- Similarly, if we wanted a polymorphic generator of lists:

```
def listOfN[A] (n: Int, anyA: Gen[A])=???
```

- Or if the list is to be of the random size:

```
def listOf[A] (anyInt: Gen[Int], anyA: Gen[A])=...
```

- Alternatively toss a coin to see whether the list is long enough:

```
def listOf[A] (anyBool: Gen[Bool], anyA: Gen[A])=...
```

Generating instances of polymorphic types /2

Actual test code from exercises in the prior weeks

- Now when we use `listOf[A]` we have to do something like:

  ```
  listOf[Student] (anyInt, anyStudent)
  ```

  We already have `anyInt`, we just need to implement `anyStudent` (not shown)
- A bit annoying to have to always parameterize all these calls
- We might be able to eliminate `anyInt` but `anyStudent` seems difficult. **Why?**

- Now think about the `forAll` function from ScalaTest; It could have type like

  ```
  def forAll[A] (p: A =>Boolean) (genA: Gen[A]): Prop
  ```

- In many cases, providing generators would feel **redundant** for the user, as the `forAll` **type parameter already specifies** that we are quantifying over `A`'s
- Particularly annoying if `A` is just a complex library type, like: `List[Stream[Option[(Double,Double)]]]` **Scalatest should know how to generate standard types!**
- Should we now write generators **for any combinations of types that programmers imagine**???
- It would be nice for the **compiler to find a generator** for `A` in the library and just use it ...

Implicit arguments as type class constraints /1

- **Formally:** `Gen` is a **type class** and in order to generate instances of `A` we need **an instance of this type class** for `A` so a **value of type `Gen[A]`**
- In Scala type classes are implemented using **implicit arguments and values**

  ```
  def listOfN[A] (n: Int) (implicit genA: Gen[A]): Gen[List[A]] =... //use genA to generate A's
  ```

  For instance: `... =Gen (State.sequence (List.fill (n, genA.sample)))`

  When you use it, in the context something like this must exist

  ```
  implicit val anyStudent: Gen[Student] =...
  ```

  Then: `... listOfN[Student] (5) ...` will work without the last argument
- The compiler will find `genA` by searching visible implicit values of type `Gen[A]`.
- If there is a single such, it will be bound to `genA`, and you can use `genA` in the body
- The compiler **fails** if you call `listOfN[A]` for a type A for each no implicit `Gen[A]` instance is found
- `implicit genA: Gen[A]` **constrains** possible types `A`
- If you want to override the implicitly used argument, you can always **add it explicitly**, as if it was a normal argument: `listOfN[Int] (5) (anyInt): Gen[List[Int]]`

Type Classes and Implicit Values: Odds and Ends

- So `(implicit genA: Gen[A])` is a **type constraint** on `A` (it must be a type with `Gen`)
- This is why Scala provides an alternative syntax for this pattern, called **type bounds**:

  ```
  def listOfN[A: Gen] (n: Int): Gen[List[A]] =...
  ```

  Use `'implicitly[Gen[A]]'` to **access the unnamed implicit argument**:

  ```
  ... =Gen (State.sequence (List.fill (n, implicitly[Gen[A]].sample)))
  ```

- Fun fact from Predef.scala, `implicitly` is just **identity with an implicit argument**

  ```
  def implicitly[T](implicit e: T): T =e
  ```

- Finally, type classes as functions (or type class instance generators) are very useful:

  ```
  implicit def listOf[A: Gen]: Gen[List[A]] =...
  ```

  The compiler **will automatically construct** a generator for list of anything that has a generator

  E.g., `listOf[List[List[Int]]` works automatically using the above generator and `anyInteger`

- For `listOfN (5)` type inference will often fail, better **add the annotation**: `listOfN[Student] (5)`
- Not only to help the type checker, but to make the code **more self-explanatory**
- In practice you **import or inherit** the implicits in most cases, for standard types
- Note that **in scalatest** the type is not `Gen[A]` but `Arbitrary[A]`, but the idea is the same

Implicit Arguments vs Default Argument Values

```
def listOfN[A: Gen] (n: Int) (implicit genA: Gen[A]) =???
def listOfN[A: Gen] (n: Int) (genA: Gen[A] =null) =???
```

- Implicit parameters are **more general than default parameter** values
- Unlike for default parameter values, the actual values of implicit parameters are **not known at the implementation and compilation time** of the function
- **For generic parameter types default values do not work**
- What default value should I give for genA, if we do not know what A is?
- Like with default parameters you can **override the value at call site**
- Unlike default parameter values you can also override them at call site **implicitly** (for instance by importing a different set of implicit objects)

Type classes: History and Context

This is not only about Scala ...

- **Implicits** (under this name) are a Scala-specific invention, but some other languages picked them up too (Idris, Agda, Coq, some logic programming languages)
- **Type classes** originally invented by Phil Wadler for Standard ML to allow adding implementation of equality test to new types,
- Type classes are the main extension mechanism in **Haskell**
- **Rust's traits** are a limited form of type class;
- In **F#** there is a neverending debate whether to add or not to add type classes.
- **C++** has recently introduced **Concepts,** which can be used to implement a form of type classes
- In **Scala 3** the type-class pattern is reinforced by specific keywords
  - `given` (an implicit instance)
  - `using` (an implicit constraint).
  - Also `summon` means the same as `implicitly`.

Type Classes and Implicits: Key Points

- Type classes are a bit like traits and extension methods:
  - You define a type class as a generic class, an interface, a new **’skill’** for a type
  - You can add this new ’skill’, say generation,
  - to any type, like with extension methods,
  - after it has been implemented,
  - without recompiling or otherwise changing the type, and
  - any library that needs generation ’skill’ will recognize it
- Important: whatever code we write, we can constrain its users to provide an instance of the skill (an instance of the type class)
- The library using generation (or any other ’skill’) does not have to know about the type it operates on, it just gets the instance of the ’skill’, the instance is often called **evidence**
- Traits can only be mixed into objects at **creation time**, so they are **not good for extending objects created by legacy code** (for instance a factory method in a legacy library)
- An **extension method implementation must exist** when compiling the code that uses the extension
- For type classes/implicits the extension is bound when **the caller (client) of our code is compiled** (the latest binding of all the discussed mechanism)

A simple example of forAll [back to PBT]

```scala
def forAll[A] (f: A => Boolean) (implicit genA: Gen[A]): Prop = Prop (

  (n,rng) =>                                  // number of trials, random seed
    randomStream (rng)                        // the implicit argument is propagated
      .zip (Stream.from (0))                  // stream of random A's and indexes
      .take (n)                               // we only want to try n times
      .map { case (a, i) =>                   // run the test and produce the result
               try { if (f (a)) Passed
                     else Falsified (a.toString, i)
               } catch { case e: Exception => Falsified (buildMsg (a, e), i) } }
      .find (_.isFalsified)
      .getOrElse (Passed)                     // report the first failure or pass
)

def randomStream[A] (rng: RNG) (implicit g: Gen[A]): Stream[A] =
  Stream.unfold (rng) (rng => Some (g.sample.run (rng)))

def buildMsg[A] (s: A, e: Exception): String =                   // uninteresting
  s"test case: $s\n" +
  s"generated an exception: ${e.getMessage}\n" +
  s"stack trace:\n ${e.getStackTrace.mkString("\n")}"
```

Adapted from the textbook, Listing 8.3, to resemble scalatest/scalacheck more

