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# Advanced Programming

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

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# API for Property Based Testing

What problem we are solving today?

## The Problem:

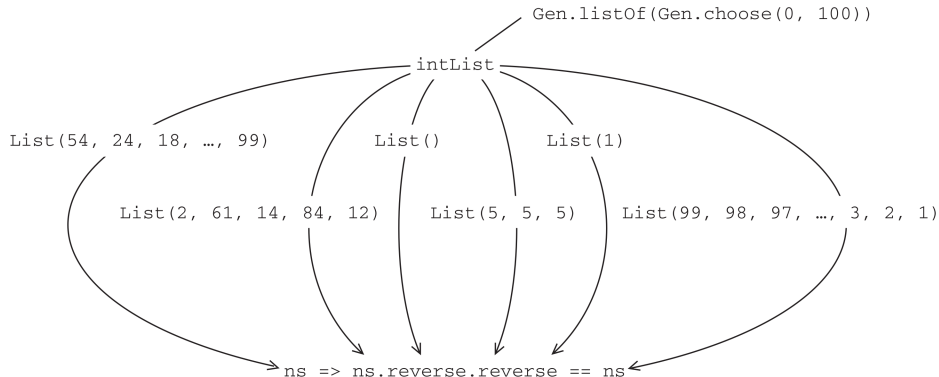
- Design a general property-based testing library like scalacheck
- With generation, property checking, test-case size control

## The Solution:

- Implement a type to represent properties
- Implement composable generators (essentially like Rand)
- Minimize user effort to program generators by using type classes

## 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.

# The Prop Type

Represents a property to test

```
1 opaque type Prop = (MaxSize, TestCases, RNG) => Result

3 extension (self: Prop)
4   def && (that: Prop): Prop = ???
5   def || (that: Prop): Prop = ???

7 opaque type TestCases = Int
8 opaque type FailedCase = String
9 opaque type SuccessCount = Int
10 opaque type MaxSize = Int

12 enum Result:
13   case Passed
14   case Falsified(failure: FailedCase, successes: SuccessCount)

16 def isFalsified: Boolean = this match
17   case Passed => false
18   case Falsified(_, _) => true
```

- Making Prop opaque allows to limit the extension just to this type
- Could have used a class, but this has a cost of Boxing
- For the types in lines 7–10 is annoying, as one cannot give these params as simply integers, but it increases safety
- Confusing parameters in a tuple is less likely

# The Prop Type

## A simple implementation of `forAll`

```
1 def randomLazyList[A](g: Gen[A])(rng: RNG): LazyList[A] =
2   LazyList.unfold(rng)(rng => Some(g.run(rng)))

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

9 def forAll[A](as: Gen[A])(f: A => Boolean): Prop = (max, n, rng) =>
10  randomLazyList(as)(rng)
11    .zip(LazyList.from(0)).take(n)
12    .map { (a, i) =>
13      try if f(a) then Passed else Falsified(a.toString, i)
14      catch case e: Exception => Falsified(buildMsg(a, e), i) }
15    .find { _.isFalsified }
16    .getOrElse(Passed)
```

The `max` parameter is not used in this variant (it is in the sized version)

# QuickCheck and ScalaCheck Use Shrinking

We implement sized generation instead

```
1 opaque type TestCases = Int
2 opaque type FailedCase = String
3 opaque type SuccessCount = Int
4 opaque type MaxSize = Int
5 opaque type Prop = (MaxSize, TestCases, RNG) => Result

7 // The type of generators bounded by size
8 opaque type SGen[+A] = Int => Gen[A]

10 def forAll[A](g: SGen[A])(f: A => Boolean): Prop = (max, n, rng) =>
11   val casesPerSize = (n.toInt - 1) / max.toInt + 1
12   val props: LazyList[Prop] = LazyList.from(0)
13     .take((n.toInt min max.toInt) + 1)
14     .map { i => forAllNotSized(g(i))(f) } // call the other forAll
15   val prop: Prop = props
16     .map[Prop] { p => (max, n, rng) => p(max, casesPerSize, rng) }
17     .toList
18     .reduce { _ && _ }
19   prop(max, n, rng)
```

# Executing Tests

```
1 opaque type Prop = (MaxSize, TestCases, RNG) => Result

3 extension (self: Prop)
4   def run(
5     maxSize: MaxSize = 100,           // by default objects up to 100 size
6     testCases: TestCases = 100,       // by default try 100 test cases
7     rng: RNG = RNG.Simple(System.currentTimeMillis) // by default use a different seed each time
8   ): Boolean =

10    self(maxSize, testCases, rng) match
11      case Result.Falsified(msg, n) =>
12        println(s"Falsified after $n passed tests:\n $msg [message from our Prop framework]")
13        false

15      case Result.Passed =>
16        println(s"+ OK, passed $testCases tests. [message from our Prop framework]")
17        true
```

# 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 the type State, implementing the **automaton abstraction** with state space S and outputs A:

```
opaque type State[S, +A] = S => (A, S)
```

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

```
opaque type Gen[+A] = State[RNG, A]
```

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

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

```
then def anyInteger: Gen[Int] = _.nextInt
```

- **Mentimeter:** How do I get an integer number out of anyInteger?



# 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)] = anyInteger.map2(anyInteger) (xy=>xy)
```

(because `Gen` is opaque we need to provide a delegation to `State.map2`)

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

```
anyInteger.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 = anyInteger.flatMap (n => listOfN (n))
```

- **Answer:** Gen[List[Int]]
- This needs a delegate for flatMap from Gen to State as well
- **Question:** Well, what exactly is the generator G generating? (menti)

# 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)
```

I assume that `map2` on `Gen` delegates to `State` again.

- 
- 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 ...

# Using arguments as type class constraints /1

- A **type class** is mechanism to add constraints on type variables in generic types
- **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 with **using constraints** and **given** values

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

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

When you use it, in the context a given value of type Gen[A] must exist

```
given val anyStudent: Gen[Student] =... //the user provides this
```

Then: `... listOfN[Student] (5) ...` will work without the last argument

- The compiler will find genA by searching for available given 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 given Gen[A] instance is found
- So `using genA: Gen[A]` **constrains** possible types A
- If you want to override the **using** 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 Given Values: Odds and Ends

- So `(using 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 `'summon[Gen[A]]'` to **access the unnamed using argument**:

```
... =sequence (List.fill (n, summon[Gen[A]]))
```

- Fun fact from `Predef.scala`, `summon` is just **identity with a constraint**

```
def summon[T](using e: T): T = e
```

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

```
given 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 givens in most cases, for standard types
- Note that in **scalacheck** the type is not `Gen[A]` but `Arbitrary[A]`, but the idea is the same

# Using Arguments vs Default Argument Values

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

- Using arguments 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 given objects)

# Type classes: History and Context

This is not only about Scala ...

- **Implicits** / **givens-using** (under this name) are a Scala-specific invention but other languages picked them up (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
- When reading blogs and Stack Overflow, it is useful to know **Scala 2** terminology
  - given was an `implicit` value
  - using was an `implicit` argument
  - summon was `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 the '**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/givens the extension is bound when **the caller (client) of our code is compiled** (the latest binding of all the discussed mechanism)

# The Prop Type, forAll revisited [Menti]

This time with givens

```
1 def randomLazyList[A](rng: RNG)(using g: Gen[A]): LazyList[A] =
2   LazyList.unfold(rng)(rng => Some(g.run(rng)))

4 def buildMsg[A](s: A, e: Exception): String =
5   s"test case: $s\n" +
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10  randomLazyList(as)(rng)
11    .zip(LazyList.from(0)).take(n)
12    .map { (a, i) =>
13      try if f(a) then Passed else Falsified(a.toString, i)
14      catch case e: Exception => Falsified(buildMsg(a, e), i) }
15    .find { _.isFalsified }
16    .getOrElse(Passed)
```

Adapted to better resemble scalacheck

# The Prop Type, forAll revisited

with more concise syntax

```
1 def randomLazyList[A: Gen](rng: RNG): LazyList[A] =
2   LazyList.unfold(rng)(rng => Some(summon[Gen[A]].run(rng)))

4 def buildMsg[A](s: A, e: Exception): String =
5   s"test case: $s\n" +
6   s"generated an exception: ${e.getMessage}\n" +
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10  randomLazyList(as)(rng)
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12    .map { (a, i) =>
13      try if f(a) then Passed else Falsified(a.toString, i)
14      catch case e: Exception => Falsified(buildMsg(a, e), i) }
15    .find { _.isFalsified }
16    .getOrElse(Passed)
```

where is Waldo?