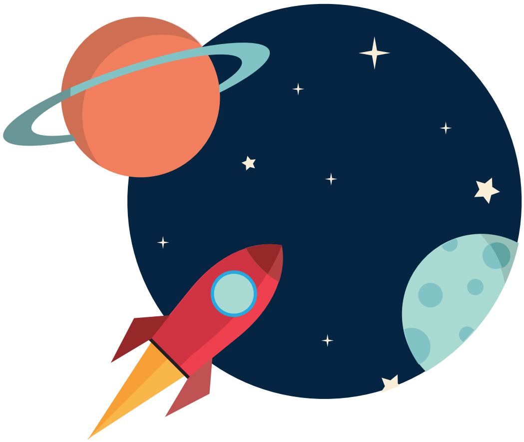
The Type Astronaut's Guide to Shapeless



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underscore

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[1] http://underscore.io

Contents

Chapter 1

Introduction

This book is a guide to using shapeless[1], a library for *generic programming* in Scala. We assume Shapeless 2.3.2 and either Lightbend Scala 2.11.9 or Typelevel Scala 2.11.8.

Shapeless is large library, so rather than cover everything it has to offer, we will concentrate on a few compelling use cases and use them to build a picture of the tools and patterns available.

Before we start, let's talk about what generic programming is and why shapeless is so exciting to Scala developers.

> *Source code for examples*
>
> We've placed source code for many of the examples in this guide in an accompanying Github repo:
>
> `https://github.com/davegurnell/shapeless-guide-code`
>
> The `exercises` branch contains skeleton Scala files with `TODO`s to fill in, and the `solutions` branch contains completed implementations.

[1] https://github.com/milessabin/shapeless

1.1 What is generic programming?

As Scala developers we are used to types. Types are helpful because they are specific: they show us how different pieces of code fit together, help us prevent bugs, and guide us toward solutions when we code.

Sometimes, however, types are *too* specific. There are situations where we want to exploit similarities between types to avoid repetition and boilerplate. For example, consider the following definitions:

```scala
case class Employee(name: String, number: Int, manager: Boolean)

case class IceCream(name: String, numCherries: Int, inCone: Boolean)
```

These two case classes represent different kinds of data but they have clear similarities: they both contain three fields of the same types. Suppose we want to implement a generic operation such as serializing to a CSV file. Despite the similarity between the two types, we have to write two separate serialization methods:

```scala
def employeeCsv(e: Employee): List[String] =
  List(e.name, e.number.toString, e.manager.toString)

def iceCreamCsv(c: IceCream): List[String] =
  List(c.name, c.numCherries.toString, c.inCone.toString)
```

Generic programming is about overcoming differences like these. Shapeless makes it convenient to convert specific types into generic ones that we can manipulate with common code.

For example, we can use the code below to convert employees and ice creams to values of the same type. Don't worry if you don't follow this example yet: we'll get to grips with the various concepts later on:

```scala
import shapeless._

val genericEmployee = Generic[Employee].to(Employee("Dave", 123, false))
// genericEmployee: shapeless.::[String,shapeless.::[Int,shapeless.::[
```

```
    Boolean,shapeless.HNil]]] = Dave :: 123 :: false :: HNil

val genericIceCream = Generic[IceCream].to(IceCream("Sundae", 1, false))
// genericIceCream: shapeless.::[String,shapeless.::[Int,shapeless.::[
    Boolean,shapeless.HNil]]] = Sundae :: 1 :: false :: HNil
```

Now that both sets of data are the same type, we can serialize them with the same function:

```
def genericCsv(gen: String :: Int :: Boolean :: HNil): List[String] =
  List(gen(0), gen(1).toString, gen(2).toString)
// genericCsv: (gen: shapeless.::[String,shapeless.::[Int,shapeless.::[
    Boolean,shapeless.HNil]]])List[String]

genericCsv(genericEmployee)
// res2: List[String] = List(Dave, 123, false)

genericCsv(genericIceCream)
// res3: List[String] = List(Sundae, 1, false)
```

This example is basic but it hints at the essence of generic programming. We reformulate problems so we can solve them use generic building blocks, and write small kernels of code that work with a wide variety of types. Generic programming with shapeless allows us to eliminate huge amounts of boilerplate, making Scala applications easier to read, write, and maintain.

Does that sound compelling? Thought so. Let's jump in!

1.2 About this book

This book is divided into chapters that introduce parts of the shapeless machinery.

In Chapter **??** we introduce *generic representations* and shapeless' `Generic` type class, which can produce a generic encoding for any case class or sealed trait. The main use case will be something basic: converting one type of data to another.

In Chapter 3 we use `Generic` to derive instances of a custom type class. We use CSV encoding as an example, but these techniques can be extended to many situations. We will introduce shapeless' `Lazy` type, which lets us handle recursive data like lists and trees.

In Chapter 4 we cover some more theory: dependent types, dependently typed functions, and type level programming. We will introduce the programming patterns we need to generalise from deriving type class instances to doing more advanced things in shapeless.

In Chapter 5 we introduce `LabelledGeneric`, a variant of `Generic` that exposes field and type names as part of its generic representations. We also introduce some new theory: literal types, singleton types, phantom types, and type tagging. In our examples we upgrade from CSV encoding to writing JSON encoders that preserve field and type names in their output.

In Chapter **??** we open the shapeless toolbox, introducing a variety of operations on generic representations including mapping and filtering. We also introduce *polymorphic functions* that can have different output types depending on their parameter types.

TODO: Function and tuple interop

TODO: Counting with types

TODO: Polymorphic functions

Chapter 2

Algebraic data types and generic representations

The main idea behind generic programming is to solve problems for a wide variety of types by writing a small amount of generic code. Shapeless provides two sets of tools to this end:

1. a set of generic data types that can be inspected, traversed, and manipulated at the type level;

2. automatic mapping between *algebraic data types (ADTs)* (encoded in Scala as case classes and sealed traits) and these generic representations.

In this chapter we will start by recapping on what algebraic data types are and why they might be familiar to Scala developers. Then we will look at the data types shapeless uses as generic representations and discuss how they map on to concrete ADTs. Finally, we will introduce a type class called `Generic` that provides automatic mapping back and forth between ADTs and generic representations. We will finish with some simple examples using `Generic` to convert values from one type to another.

2.1 Recap: algebraic data types

Algebraic data types (*ADTs*[1]) are a functional programming concept with a fancy name but a very simple meaning. They are simply an idiomatic way of representing data using "ands" and "ors". For example:

- a shape is a rectangle **or** a circle
- a rectangle has a width **and** a height
- a circle has a radius

In ADT terminology, "and" types such as rectangle and circle are called *products*, and "or" types such as shape are called *coproducts*. In Scala we typically represent products using case classes and coproducts using sealed traits:

```
sealed trait Shape
final case class Rectangle(width: Double, height: Double) extends Shape
final case class Circle(radius: Double) extends Shape

val rect: Shape = Rectangle(3.0, 4.0)
val circ: Shape = Circle(1.0)
```

The beauty of ADTs is that they are completely type safe. The compiler has complete knowledge of the algebras we define, so it can support us in writing complete, correctly typed methods involving our types:

```
def area(shape: Shape): Double =
  shape match {
    case Rectangle(w, h) => w * h
    case Circle(r)       => math.Pi * r * r
  }

area(rect)
// res1: Double = 12.0
```

[1]Be careful not to confuse algebraic data types with "abstract data types", which are a different modelling tool with little bearing on the discussion here.

```
area(circ)
// res2: Double = 3.141592653589793
```

2.1.1 Alternative encodings

Sealed traits and case classes are undoubtedly the most convenient encoding of ADTs in Scala. However, they aren't the *only* encoding. For example, the Scala standard library provides generic products in the form of `Tuples` and a generic coproduct in the form of `Either`. We could have chosen these to encode our `Shape`:

```
type Rectangle2 = (Double, Double)
type Circle2    = Double
type Shape2     = Either[Rectangle2, Circle2]

val rect2: Shape2 = Left((3.0, 4.0))
val circ2: Shape2 = Right(1.0)
```

While this encoding is less readable than the case class encoding above, it does have some of the same desirable properties. We can still write completely type safe operations involving `Shape2`:

```
def area2(shape: Shape2): Double =
  shape match {
    case Left((w, h)) => w * h
    case Right(r)     => math.Pi * r * r
  }

area2(rect2)
// res4: Double = 12.0

area2(circ2)
// res5: Double = 3.141592653589793
```

Importantly, `Shape2` is a more *generic* encoding than `Shape`[2]. Any code that operates on a pair of `Doubles` will be able to operate on a `Rectangle2` and

[2]We're using "generic" with an informal way here, not the formal meaning of "a type with a type parameter".

vice versa. As Scala developers we tend to see interoperability as a bad thing: what havoc will we accidentally wreak across our codebase with such freedom?! However, in some cases it is a desirable feature. For example, if we're serializing data to disk, we don't care about the difference between a pair of `Doubles` and a `Rectangle2`. Just write or read two numbers and we're done.

shapeless gives us the best of both worlds: we can use friendly sealed traits and case classes by default, and switch to generic representations when we want interoperability (more on this later). However, instead of using `Tuples` and `Either`, shapeless uses its own data types to represent generic products and coproducts. We'll introduce to these types in the next sections.

2.2 Generic product encodings

In the previous section we introduced tuples as a generic representation of products. Unfortunately, Scala's built-in tuples have a couple of disadvantages that make them unsuitable for shapeless' purposes:

1. each size of tuple has a different, unrelated type, making it difficult to write code that abstracts over sizes;
2. there are no types for 0- and 1-length tuples, which are important for representing products with 0 and 1 fields.

For these reasons, shapeless uses a different generic encoding for product types called *heterogeneous lists* or `HLists`[3].

An `HList` is either the empty list `HNil`, or a pair `::[H, T]` where `H` is an arbitrary type and `T` is another `HList`. Because every `::` has its own `H` and `T`, the type each element is encoded separately in the type of the overall list:

[3] `Product` is perhaps a better name for `HList`, but the standard library unfortunately already has a type `scala.Product`.

```scala
import shapeless.{HList, ::, HNil}

val product: String :: Int :: Boolean :: HNil =
  "Sunday" :: 1 :: false :: HNil
```

The types and values of the HLists above mirror one another. Both represent three members: a String, an Int, and a Boolean. We can retrieve the head and tail and the types of the elements are preserved:

```scala
val first: String =
  product.head
// first: String = Sunday

val second: Int =
  product.tail.head
// second: Int = 1

val rest: Boolean :: HNil =
  product.tail.tail
// rest: shapeless.::[Boolean,shapeless.HNil] = false :: HNil
```

The compiler knows the exact length of each HList, so it becomes a compilation error to take the head or tail of an empty list:

```scala
product.tail.tail.tail.head
// <console>:15: error: could not find implicit value for parameter c:
     shapeless.ops.hlist.IsHCons[shapeless.HNil]
//        product.tail.tail.tail.head
//                               ^
```

We can manipulate and transform HLists in addition to being able to inspect and traverse them. For example, we can prepend an element with the :: method. Again, notice how the type of the result reflects the number and types of its elements:

```scala
val newProduct: Long :: String :: Int :: Boolean :: HNil =
  42L :: product
// newProduct: shapeless.::[Long,shapeless.::[String,shapeless.::[Int,
     shapeless.::[Boolean,shapeless.HNil]]]] = 42 :: Sunday :: 1 ::
```

```
    false :: HNil
```

Shapeless also provides tools for performing more complex operations such as mapping, filtering, and concatenating lists. We'll discuss these in more detail in later chapters.

DJG: INSERT CHAPTER NUMBER ABOVE

2.2.1 Switching representations using *Generic*

Shapeless provides a type class called `Generic` that allows us to switch back and forth between a concrete ADT and its generic representation. There's some macro magic going on behind the scenes that allows us to summon instances of `Generic` without boilerplate:

```
import shapeless.Generic

case class IceCream(name: String, numCherries: Int, inCone: Boolean)

val iceCreamGen = Generic[IceCream]
// iceCreamGen: shapeless.Generic[IceCream]{type Repr = shapeless.::[
    String,shapeless.::[Int,shapeless.::[Boolean,shapeless.HNil]]]} =
    anon$macro$4$1@1bc72463
```

Note that the instance of `Generic` has a type member `Repr` containing the type of its generic representation. In this case `iceCreamGen.Repr` is `String :: Int :: Boolean :: HNil`. Instances of `Generic` have two methods: one for converting `to` `Repr` and one for converting `from` it:

```
val iceCream: IceCream =
  IceCream("Sundae", 1, false)
// iceCream: IceCream = IceCream(Sundae,1,false)

val repr: iceCreamGen.Repr =
  iceCreamGen.to(iceCream)
// repr: iceCreamGen.Repr = Sundae :: 1 :: false :: HNil

val iceCream2: IceCream =
```

```
  iceCreamGen.from(repr)
// iceCream2: IceCream = IceCream(Sundae,1,false)
```

If two ADTs have the same `Repr`, we can convert back and forth between them using their `Generic`s:

```
case class Employee(name: String, number: Int, manager: Boolean)

// Create an employee from an ice cream:
val strangeEmployee: Employee =
  Generic[Employee].from(Generic[IceCream].to(iceCream))
// strangeEmployee: Employee = Employee(Sundae,1,false)
```

2.3 Generic coproducts

Now we know how shapeless encodes product types. What about coproducts? We looked at `Either` earlier, but that suffers from a similar drawback to tuples: we have no way of representing a disjunction of fewer than two types. For this reason, shapeless provides a different encoding that is similar to `HList`.

The type of a `Coproduct` encodes all the possible types in the disjunction, but each concrete instantiation contains a value for just one of the possibilities.

```
import shapeless.{Coproduct, :+:, CNil}

case class Red()
case class Amber()
case class Green()

type Light = Red :+: Amber :+: Green :+: CNil
```

In general, coproducts take the form `A :+: B :+: C :+: CNil` meaning "A or B or C". `:+:` can be loosely interpreted as an `Either`, with subtypes `Inl` and `Inr` corresponding loosely to `Left` and `Right`. `CNil` is an empty type with no values, similar to `Nothing`, so we can never instantiate an empty `Coproduct`. Similarly, we can never create a `Coproduct` purely from instances of `Inr`. We always have to have exactly one `Inl` in a value:

```scala
import shapeless.{Inl, Inr}

val red: Light = Inl(Red())
val green: Light = Inr(Inr(Inl(Green())))
```

2.3.1 Switching encodings using *Generic*

`Coproduct` types are difficult to parse on first glance. However, it is relatively easy to see how they fit into the larger picture of generic encodings. In addition to understanding case classes and case objects, shapeless' `Generic` type class also understands sealed traits and abstract classes:

```scala
import shapeless.Generic

sealed trait Shape
final case class Rectangle(width: Double, height: Double) extends Shape
final case class Circle(radius: Double) extends Shape

val gen = Generic[Shape]
// gen: shapeless.Generic[Shape]{type Repr = shapeless.:+:[Rectangle,
     shapeless.:+:[Circle,shapeless.CNil]]} = anon$macro$1$1@3492f8af
```

Note that the `Repr` of the `Generic` is a `Coproduct` of the subtypes of the sealed trait: `Rectangle :+: Circle :+: CNil`. We can use the `to` and `from` methods of the generic to map back and forth between `Shape` and `gen.Repr`:

```scala
gen.to(Rectangle(3.0, 4.0))
// res4: gen.Repr = Inl(Rectangle(3.0,4.0))

gen.to(Circle(1.0))
// res5: gen.Repr = Inr(Inl(Circle(1.0)))
```

2.4 Summary

In this chapter we discussed the generic representations shapeless provides for algebraic data types in Scala: `HLists` for product types and `Coproducts` for coproduct types. We also introduced the `Generic` type class to map back and forth between concrete ADTs and their generic representations. We haven't yet discussed why generic encodings are so attractive. The one use case we did cover—converting between ADTs—is fun but not tremendously useful.

The real power of `HLists` and `Coproducts` comes from their recursive structure. We can write code to traverse the structures and calculate values from their constituents. In the next chapter we will look at our first real use case: automatically deriving type class instances.

Chapter 3

Automatically deriving type class instances

In the last chapter we saw how the `Generic` type class allowed us to convert any instance of an ADT to a generic encoding made of `HLists` and `Coproducts`. In this chapter we will look at our first serious use case: automatic derivation of type class instances.

3.1 Recap: type classes

Before we get into the depths of instance derivation, let's quickly recap on the important aspects of type classes.

Type classes are a programming pattern borrowed from Haskell (the word "class" has nothing to do with classes in object oriented programming). We encode them in Scala using traits and implicit parameters. A *type class* is a generic trait representing some sort of general functionality that we would like to apply to a wide range of types:

```
// Turn a value of type A into a row of cells in a CSV file:
trait CsvEncoder[A] {
```

```
  def encode(value: A): List[String]
}
```

We implement our type class with *instances* for each type we care about:

```
// Helper method for creating CsvEncoder instances:
def createEncoder[A](func: A => List[String]): CsvEncoder[A] =
  new CsvEncoder[A] {
    def encode(value: A): List[String] =
      func(value)
  }

// Custom data type:
case class Employee(name: String, number: Int, manager: Boolean)

// CsvEncoder instance for the custom data type:
implicit val employeeEncoder: CsvEncoder[Employee] =
  createEncoder(e => List(
    e.name,
    e.number.toString,
    if(e.manager) "yes" else "no"
  ))
```

We mark each instance with the keyword `implicit`, and define a generic *entry point* method that accepts an implicit parameter of the corresponding type:

```
def writeCsv[A](values: List[A])(implicit enc: CsvEncoder[A]): String =
  values.map(value => enc.encode(value).mkString(",")).
    mkString("\n")
```

When we call the entry point, the compiler calculates the value of the type parameter and searches for an implicit `CsvWriter` of the corresponding type:

```
val employees: List[Employee] = List(
  Employee("Bill", 1, true),
  Employee("Peter", 2, false),
  Employee("Milton", 3, false)
)

// The compiler inserts a CsvEncoder[Employee] parameter:
```

```scala
writeCsv(employees)
// res7: String =
// Bill,1,yes
// Peter,2,no
// Milton,3,no
```

We can use `writeCsv` with any data type we like, provided we have a corresponding implicit `CsvEncoder` in scope:

```scala
case class IceCream(name: String, numCherries: Int, inCone: Boolean)

implicit val iceCreamEncoder: CsvEncoder[IceCream] =
  createEncoder(i => List(
    i.name,
    i.numCherries.toString,
    if(i.inCone) "yes" else "no"
  ))

val iceCreams: List[IceCream] = List(
  IceCream("Sundae", 1, false),
  IceCream("Cornetto", 0, true),
  IceCream("Banana Split", 0, false)
)

writeCsv(iceCreams)
// res10: String =
// Sundae,1,no
// Cornetto,0,yes
// Banana Split,0,no
```

3.1.1 Resolving instances

Type classes are very flexible but they require us to define instances for every type we care about. Fortunately, the Scala compiler has a few tricks up its sleeve to resolve instances for us given sets of user-defined rules. For example, we can write a rule that creates a `CsvEncoder` for `(A, B)` given `CsvEncoders` for `A` and `B`:

```
implicit def pairEncoder[A, B](
  implicit
  aEncoder: CsvEncoder[A],
  bEncoder: CsvEncoder[B]
): CsvEncoder[(A, B)] =
  createEncoder {
    case (a, b) =>
      aEncoder.encode(a) ++ bEncoder.encode(b)
  }
```

When all the parameters to an `implicit def` are themselves marked as `implicit`, the compiler can use it as a *resolution rule* to create instances from other instances. For example, if we call `writeCsv` and pass in a `List[(Employee, IceCream)]`, the compiler is able to combine `pairEncoder`, `employeeEncoder`, and `iceCreamEncoder` to produce the required `CsvEncoder[(Employee, IceCream)]`:

```
writeCsv(employees zip iceCreams)
// res11: String =
// Bill,1,yes,Sundae,1,no
// Peter,2,no,Cornetto,0,yes
// Milton,3,no,Banana Split,0,no
```

Given a set of rules encoded as `implicit vals` and `implicit defs`, the compiler is capable of *searching* for combinations to give it the required instances. This behaviour, known as "implicit resolution", is what makes the type class pattern so powerful.

Traditionally the only limitation to this has been ADTs. The compiler can't pull apart the types of case classes and sealed traits, so we have always had to define instances for ADTs by hand. Shapeless' generic representations change all of this, allowing us to derive instances for any ADT for free.

3.2 Deriving instances for products

In this section we're going to use shapeless to derive type class instances for products (i.e. case classes). We'll use two intuitions:

1. If we have type class instances for the head and tail of an `HList`, we can derive an instance for the whole `HList`.

2. If we have a case class `A`, a `Generic[A]`, and a type class instance for the generic's `Repr`, we can combine them to create an instance for `A`

Take `CsvEncoder` and `IceCream` as examples:

- `IceCream` has a generic `Repr` of type `String :: Int :: Boolean :: HNil`.

- The `Repr` is made up of a `String`, an `Int`, a `Boolean`, and an `HNil`. If we have `CsvEncoders` for these types, we can create an encoder for the whole thing.

- If we can derive a `CsvEncoder` for the `Repr`, we can create one for `IceCream`.

3.2.1 Instances for *HLists*

Let's start by writing `CsvEncoders` for `String`, `Int`, and `Boolean`. See Section 3.1 for the definition of `createEncoder`:

```scala
implicit val stringEncoder: CsvEncoder[String] =
  createEncoder(str => List(str))

implicit val intEncoder: CsvEncoder[Int] =
  createEncoder(num => List(num.toString))

implicit val booleanEncoder: CsvEncoder[Boolean] =
  createEncoder(bool => List(if(bool) "yes" else "no"))
```

We can combine these building blocks to create an encoder for our `HList`. We'll use two rules: one for an `HNil` and one for `::`:

```scala
import shapeless.{HList, ::, HNil}

implicit val hnilEncoder: CsvEncoder[HNil] =
  createEncoder(hnil => Nil)

implicit def hlistEncoder[H, T <: HList](
  implicit
  hEncoder: CsvEncoder[H],
  tEncoder: CsvEncoder[T]
): CsvEncoder[H :: T] =
  createEncoder {
    case h :: t =>
      hEncoder.encode(h) ++ tEncoder.encode(t)
  }
```

Taken together, these five rules allow us to summon `CsvEncoders` for any `HList` involving `Strings`, `Ints`, and `Booleans`:

```scala
val reprEncoder: CsvEncoder[String :: Int :: Boolean :: HNil] =
  implicitly

reprEncoder.encode("abc" :: 123 :: true :: HNil)
// res8: List[String] = List(abc, 123, yes)
```

3.2.2 Instances for concrete products

We can combine our derivation rules for `HLists` with an instance of `Generic` to produce a `CsvEncoder` for `IceCream`:

```scala
import shapeless.Generic

implicit val iceCreamEncoder: CsvEncoder[IceCream] = {
  val gen = Generic[IceCream]
  val enc = implicitly[CsvEncoder[gen.Repr]]
  createEncoder(iceCream => enc.encode(gen.to(iceCream)))
}
```

and use it as follows:

```scala
writeCsv(iceCreams)
// res10: String =
// Sundae,1,no
// Cornetto,0,yes
// Banana Split,0,no
```

This solution is specific to `IceCream`. Ideally we'd like to have a single rule that handles all case classes that have a `Generic` and a matching `CsvEncoder`. Let's work through the derivation step by step. Here's a first cut:

```scala
implicit def genericEncoder[A](
  implicit
  gen: Generic[A],
  enc: CsvEncoder[???]
): CsvEncoder[A] = createEncoder(a => enc.encode(gen.to(a)))
```

The first problem we have is selecting a type to put in place of the `???`. We want to write the `Repr` type associated with gen, but we can't do this:

```scala
implicit def genericEncoder[A](
  implicit
  gen: Generic[A],
  enc: CsvEncoder[gen.Repr]
): CsvEncoder[A] =
  createEncoder(a => enc.encode(gen.to(a)))
// <console>:26: error: illegal dependent method type: parameter may
     only be referenced in a subsequent parameter section
//          gen: Generic[A],
//          ^
```

The problem here is a scoping issue: we can't refer to a type member of one parameter from another parameter in the same block. We won't dwell on the details here, but the trick to solving this kind of problem is to introduce a new type parameter to our method and refer to it in each of the associated parameters:

```
implicit def genericEncoder[A, R](
  implicit
  gen: Generic[A] { type Repr = R },
  enc: CsvEncoder[R]
): CsvEncoder[A] =
  createEncoder(a => enc.encode(gen.to(a)))
```

We'll cover this coding style in more detail the next chapter. Suffice to say, this definition now compiles and works as expected and we can use it with any case class as expected. Intuitively, this definition says:

> *Given a type A and an `HList` type R, an implicit `Generic` to map A to R, and a `CsvEncoder` for R, create a `CsvEncoder` for A.*

We now have a complete system that handles any case class. The compiler expands a call like:

```
writeCsv(iceCreams)
```

to use our family of derivation rules:

```
writeCsv(iceCreams)(
  genericEncoder(
    Generic[IceCream],
    hlistEncoder(stringEncoder,
      hlistEncoder(intEncoder,
        hlistEncoder(booleanEncoder, hnilEncoder)))))
```

I'm sure you'll agree, it's nice not to have to write this code by hand!

> *Aux type aliases*
>
> Type refinements like `Generic[A] { type Repr = L }` are verbose and difficult to read, so shapeless provides a type alias `Generic.Aux` to rephrase the type member as a type parameter:

```scala
package shapeless

object Generic {
  type Aux[A, R] = Generic[A] { type Repr = R }
}
```

Using this alias we get a much more readable definition:

```scala
implicit def genericEncoder[A, R](
  implicit
  gen: Generic.Aux[A, R],
  env: CsvEncoder[R]
): CsvEncoder[A] =
  createEncoder(a => env.encode(gen.to(a)))
```

Note that the Aux type isn't changing any semantics here—it's just making things easier to read. This pattern is used frequently in the shapeless codebase.

3.2.3 So what are the downsides?

If all of the above seems pretty magical, allow us to provide one significant dose of reality. If things go wrong, the compiler isn't great at telling us why.

There are two main reasons the code above might fail to compile. The first is when we can't find an implicit `Generic` instance. For example, here we try to call `writeCsv` with a non-case class:

```scala
class Foo(bar: String, baz: Int)

writeCsv(List(new Foo("abc", 123)))
// <console>:30: error: could not find implicit value for parameter
     encoder: CsvEncoder[Foo]
//        writeCsv(List(new Foo("abc", 123)))
//                ^
```

In this case the error message is relatively easy to understand. If shapeless can't calculate a `Generic` it means that the type in question isn't an ADT—

somewhere in the algebra there is a type that isn't a case class or a sealed abstract type.

The other potential source of failure is when the compiler can't calculate a `CsvEncoder` for our `HList`. This normally happens because we don't have an encoder for one of the fields in our ADT. For example, so far we haven't defined a `CsvEncoder` for `java.util.Date`, so the following code fails:

```
import java.util.Date

case class Booking(room: String, date: Date)

writeCsv(List(Booking("Lecture hall", new Date())))
// <console>:32: error: could not find implicit value for parameter
     encoder: CsvEncoder[Booking]
//        writeCsv(List(Booking("Lecture hall", new Date())))
//                ^
```

The message we get here isn't very helpful. All the compiler knows is it tried a lot of implicit resolution rules and couldn't make them work. It has no idea which combination came closest to the desired result, so it can't tell us where the source(s) of failure lie.

There's not much good news here. We have find the source of the error ourselves by a process of elimination. We'll discuss debugging techniques in more detail next chapter. For now, the main redeeming feature is that implicit resolution always fails at compile time. There's little chance that we will end up with code that fails during execution.

3.3 Deriving instances for coproducts

In the last section we created a set of rules to automatically derive a `CsvEncoder` for any product type. In this section we will apply the same patterns to coproducts. Let's return to our shape ADT as an example:

```scala
sealed trait Shape
final case class Rectangle(width: Double, height: Double) extends Shape
final case class Circle(radius: Double) extends Shape
```

The generic representation for `Shape` is `Rectangle :+: Circle :+: CNil`. We can write generic `CsvEncoders` for `:+:` and `CNil` using the same principles we used for `HLists`. Our existing product encoders will take care of `Rectangle` and `Circle`:

```scala
import shapeless.{Coproduct, :+:, CNil, Inl, Inr}

implicit val cnilEncoder: CsvEncoder[CNil] =
  createEncoder(cnil => throw new Exception("Mass hysteria!"))

implicit def coproductEncoder[H, T <: Coproduct](
  implicit
  hEncoder: CsvEncoder[H],
  tEncoder: CsvEncoder[T]
): CsvEncoder[H :+: T] = createEncoder {
  case Inl(h) => hEncoder.encode(h)
  case Inr(t) => tEncoder.encode(t)
}
```

There are two key points of note:

1. Alarmingly, the encoder for `CNil` throws an exception! Don't panic, though. Remember that we can't actually create values of type `CNil`. It's just there as a marker for the compiler. It's ok to fail abruptly here because we should never reach this point.

2. Because `Coproducts` are *disjunctions* of types, the encoder for `:+:` has to *choose* whether to encode a left or right value. We pattern match on the two subtypes of `:+:`—`Inl` for left and `Inr` for right.

With these definitions and our product encoders from Section 3.2, we should be able to serialize a list of shapes. Let's give it a try:

```
val shapes: List[Shape] = List(
  Rectangle(3.0, 4.0),
  Circle(1.0)
)

writeCsv(shapes)
// <console>:33: error: could not find implicit value for parameter
     encoder: CsvEncoder[Shape]
//        writeCsv(shapes)
//                ^
```

Oh no, it failed! The error message is unhelpful as we discussed earlier. The reason for the failure is we don't have a `CsvEncoder` instance for `Double`:

```
implicit val doubleEncoder: CsvEncoder[Double] =
  createEncoder(d => List(d.toString))
```

With this definition in place, everything works as expected:

```
writeCsv(shapes)
// res7: String =
// 3.0,4.0
// 1.0
```

Aligning CSV Output

Our CSV encoder isn't very practical in its current form. It allows fields from `Rectangle` and `Circle` to occupy the same columns in the output. To fix this problem we need to modify the definition of `CsvEncoder` to incorporate the width of the data type and space the output accordingly. We leave this as an exercise to the reader.

3.4 Deriving instances for recursive types

Let's try something more ambitious—a binary tree:

```
sealed trait Tree[A]
case class Branch[A](left: Tree[A], right: Tree[A]) extends Tree[A]
case class Leaf[A](value: A) extends Tree[A]
```

Theoretically we should already have all of the definitions in place to summon a CSV writer for this definition. However, calls to `writeCsv` fail to compile:

```
implicitly[CsvEncoder[Tree[Int]]]
// <console>:24: error: could not find implicit value for parameter e:
     CsvEncoder[Tree[Int]]
//        implicitly[CsvEncoder[Tree[Int]]]
//                  ^
```

The problem is that our type is recursive. The compiler senses an infinite loop applying our derivation rules and gives up.

3.4.1 Implicit Divergence

Implicit resolution is a search process. The compiler uses heuristics to determine whether it is "converging" on a solution. If the heuristics don't yield favorable results for a particular branch of search, the compiler assumes the branch is not converging and moves onto another.

One heuristic is specifically designed to avoid infinite loops. If the compiler sees the same target type twice in a particular branch of search, it gives up and moves on. We can see this happening if we look at the expansion for `CsvEncode[Tree[Int]]` The implicit resolution process goes through the following types:

```
implicitly[CsvEncoder[Tree[Int]]]                          // 1
implicitly[CsvEncoder[Branch[Int] :+: Leaf[Int] :+: CNil]] // 2
implicitly[CsvEncoder[Branch[Int]]]                        // 3
implicitly[CsvEncoder[Tree[Int] :: Tree[Int] :: HNil]]     // 4
implicitly[CsvEncoder[Tree[Int]]]                          // 5 uh oh
```

We see `Tree[A]` twice in lines 1 and 5, so the compiler moves onto another branch of search. The result is failure to find a suitable implicit.

In fact, the situation is worse than this. If the compiler sees the same type constructor twice and the complexity of the type parameters is *increasing*, it assumes that branch of search is "diverging". This is a problem for shapeless because types like `::[H, T]` and `:+:[H, T]` come up in different generic representations and cause the compiler to give up prematurely. Consider the following types:

```
case class Bar(baz: Int, qux: String)
case class Foo(bar: Bar)
```

The expansion for `Foo` looks like this:

```
implicitly[CsvEncoder[Foo]]                     // 1
implicitly[CsvEncoder[Bar :: HNil]]             // 2
implicitly[CsvEncoder[Bar]]                     // 3
implicitly[CsvEncoder[Int :: String :: HNil]] // 4 uh oh
```

The compiler attempts to resolve a `CsvEncoder[::[H, T]]` twice in this branch of search, on lines 2 and 4. The type parameter for `T` is more complex on line 4 than on line 2, so the compiler assumes (incorrectly in this case) that the branch of search is diverging. It moves onto another branch and, again, the result is failure to find a suitable implicit.

3.4.2 *Lazy*

Implicit divergence would be a show-stopper for libraries like shapeless. Fortunately, shapeless provides a type called `Lazy` as a workaround. `Lazy` does two things:

1. it delays resolution of an implicit parameter until it is strictly needed, permitting the derivation of self-referential implicits.

2. it guards against some of the aforementioned over-defensive convergence heuristics.

We use Lazy by wrapping it around specific implicit parameters. As a rule of thumb, it is always a good idea to wrap the "head" parameter of any HList or Coproduct rule and the Repr parameter of any Generic rule in Lazy:

```
implicit def hlistEncoder[H, T <: HList](
  implicit
  hEncoder: Lazy[CsvEncoder[H]],
  tEncoder: CsvEncoder[T]
): CsvEncoder[H :: T] = createEncoder {
  case h :: t =>
    hEncoder.value.encode(h) ++ tEncoder.encode(t)
}

implicit def coproductEncoder[H, T <: Coproduct](
  implicit
  hEncoder: Lazy[CsvEncoder[H]], // wrapped in Lazy
  tEncoder: CsvEncoder[T]
): CsvEncoder[H :+: T] = createEncoder {
  case Inl(h) => hEncoder.value.encode(h)
  case Inr(t) => tEncoder.encode(t)
}

implicit def genericEncoder[A, R](
  implicit
  gen: Generic.Aux[A, R],
  rEncoder: Lazy[CsvEncoder[R]] // wrapped in Lazy
): CsvEncoder[A] = createEncoder { value =>
  rEncoder.value.encode(gen.to(value))
}
```

This prevents the compiler giving up prematurely, and enables the solution to work on complex/recursive types like Tree:

```
implicitly[CsvEncoder[Tree[Int]]]
// res2: CsvEncoder[Tree[Int]] = $anon$1@3aa2df25
```

3.5 Summary

In this chapter we discussed how to use Generic, HLists, and Coproducts to automatically derive type class instances. We also covered the Lazy type as a means of handling complex/recursive types. Taking all of this into account, we can write a common skeleton for deriving type class instances as follows.

First, define the type class:

```scala
import shapeless._

trait MyTC[A]
```

Define basic instances:

```scala
implicit def intInstance: MyTC[Int] = ???
implicit def stringInstance: MyTC[String] = ???
implicit def booleanInstance: MyTC[Boolean] = ???
```

Define instances for `HList`:

```scala
implicit def hnilInstance: MyTC[HNil] = ???

implicit def hlistInstance[H, T <: HList](
  implicit
  hInstance: Lazy[MyTC[H]], // wrap in Lazy
  tInstance: MyTC[T]
): MyTC[H :: T] = ???
```

If required, define instances for `Coproduct`:

```scala
implicit def cnilInstance: MyTC[CNil] = ???

implicit def coproductInstance[H, T <: Coproduct](
  implicit
  hInstance: Lazy[MyTC[H]], // wrap in Lazy
  tInstance: MyTC[T]
): MyTC[H :+: T] = ???
```

Finally, define an instance for `Generic`:

```scala
implicit def genericInstance[A, R](
  implicit
  generic: Generic.Aux[A, R],
  rInstance: Lazy[MyTC[R]] // wrap in Lazy
): MyTC[A] = ???
```

In the next chapter we'll cover some useful theory, programming patterns, and debugging techniques to help write code in this style. In Chapter 5 we will revisit type class derivation using a variant of `Generic` that allows us to inspect field and type names in our ADTs.

Chapter 4

Working with types and implicits

In the last chapter we saw one of the most compelling use cases for shapeless: automatically deriving type class instances. There are plenty of even more powerful examples coming later. However, before we move on, we should take time to dicuss some of theory we've overlooked and establish a set of patterns for writing and debugging type- and implicit-heavy code.

4.1 Theory: dependent types

Last chapter we spent a lot of time using `Generic`, the type class for mapping ADT types to generic representations. However, we haven't yet discussed an important bit of theory that underpins `Generic` and much of shapeless: *dependent types*.

To illustrate this, let's take a closer look at `Generic`. Here's a simplified version of the definition:

```
package shapeless

trait Generic[A] {
  type Repr
  def to(value: A): Repr
```

```
  def from(value: Repr): A
}
```

Instances of `Generic` reference two other types: a type parameter `A` and a type member `Repr`. Suppose we implement a method `getRepr` as follows. What type will we get back?

```
import shapeless.Generic

def getRepr[A](value: A)(implicit gen: Generic[A]) =
  gen.to(value)
```

The answer is it depends on the instance we get for `gen`. In expanding the call to `getRepr`, the compiler will search for a `Generic[A]` and the result type will be whatever `Repr` is defined in that instance:

```
case class Vec(x: Int, y: Int)
case class Rect(origin: Vec, size: Vec)

getRepr(Vec(1, 2))
// res1: shapeless.::[Int,shapeless.::[Int,shapeless.HNil]] = 1 :: 2 ::
     HNil

getRepr(Rect(Vec(0, 0), Vec(5, 5)))
// res2: shapeless.::[Vec,shapeless.::[Vec,shapeless.HNil]] = Vec(0,0)
     :: Vec(5,5) :: HNil
```

What we're seeing here *dependent typing*: the return type of `getRepr` is dependent on types defined in its value parameters. Suppose we had specified `Repr` as type parameter on `Generic` instead of a type member:

```
trait Generic2[A, Repr]

def getRepr2[A, R](value: A)(implicit generic: Generic2[A, R]): R =
  ???
```

We would have had to pass the desired value of `Repr` to `getRepr` as a type parameter, effectively making `getRepr` useless.

The intuitive take-away from this is that type parameters are useful as "inputs" and type members are useful as "outputs".

4.2 Dependently typed functions

Shapeless uses dependent types all over the place: in `Generic`, in `Witness` (which we will see next chapter), and in a host of other implicit values that operate on `HLists`.

For example, shapeless provides a type class called `Last` that returns the last element in an `HList`. Here's a simplified version of its definition:

```
package shapeless.ops.hlist

trait Last[L <: HList] {
  type Out
  def apply(in: L): Out =
    ??? // definition omitted for brevity
}
```

We can summon instances of `Last` to inspect `HLists` in our code. In the two examples below note that the `Out` types are dependent on the `HList` types we started with:

```
import shapeless.{HList, ::, HNil}

import shapeless.ops.hlist.Last

val last1 = implicitly[Last[String :: Int :: HNil]]
// last1: shapeless.ops.hlist.Last[shapeless.::[String,shapeless.::[Int,
     shapeless.HNil]]] = shapeless.ops.hlist$Last$$anon$34@1e541e23

val last2 = implicitly[Last[Int :: String :: HNil]]
// last2: shapeless.ops.hlist.Last[shapeless.::[Int,shapeless.::[String,
     shapeless.HNil]]] = shapeless.ops.hlist$Last$$anon$34@733e0cad
```

Once we have summoned instances of `Last`, we can use them at the value level:

```
last1("foo" :: 123 :: HNil)
// res1: last1.Out = 123

last2(321 :: "bar" :: HNil)
// res2: last2.Out = bar
```

We get two forms of protection against errors. The implicits defined for `Last` ensure we can only summon instances if the input `HList` has at least one element:

```
implicitly[Last[HNil]]
// <console>:15: error: Implicit not found: shapeless.Ops.Last[shapeless
     .HNil]. shapeless.HNil is empty, so there is no last element.
//        implicitly[Last[HNil]]
//                  ^
```

In addition, the type parameters on the instances of `Last` check whether we pass in the expected type of `HList`:

```
last1(321 :: "bar" :: HNil)
// <console>:16: error: type mismatch;
//  found   : shapeless.::[Int,shapeless.::[String,shapeless.HNil]]
//  required: shapeless.::[String,shapeless.::[Int,shapeless.HNil]]
//        last1(321 :: "bar" :: HNil)
//                  ^
```

As a further example, let's implement our own type class, called `Second`, that returns the second element in an `HList`:

```
trait Second[H <: HList] {
  type Out
  def apply(value: H): Out
}

implicit def hlistSecond[A, B, Rest <: HList]: Second[A :: B :: Rest] =
  new Second[A :: B :: Rest] {
    type Out = B
    def apply(value: A :: B :: Rest): B =
```

```
    value.tail.head
}
```

We can summon instances of `Second` subject to similar constraints to `Last`:

```
val second1 = implicitly[Second[String :: Boolean :: Int :: HNil]]
// second1: Second[shapeless.::[String,shapeless.::[Boolean,shapeless
     .::[Int,shapeless.HNil]]]] = $anon$1@6fa24e1c

val second2 = implicitly[Second[String :: Int :: Boolean :: HNil]]
// second2: Second[shapeless.::[String,shapeless.::[Int,shapeless.::[
     Boolean,shapeless.HNil]]]] = $anon$1@30137674

implicitly[Second[String :: HNil]]
// <console>:17: error: could not find implicit value for parameter e:
     Second[shapeless.::[String,shapeless.HNil]]
//        implicitly[Second[String :: HNil]]
//                  ^
```

And use them at the value level in the same way:

```
second1("foo" :: true :: 123 :: HNil)
// res7: second1.Out = true

second2("bar" :: 321 :: false :: HNil)
// res8: second2.Out = 321

second1("baz" :: HNil)
// <console>:18: error: type mismatch;
//  found   : shapeless.::[String,shapeless.HNil]
//  required: shapeless.::[String,shapeless.::[Boolean,shapeless.::[Int,
     shapeless.HNil]]]
//        second1("baz" :: HNil)
//                      ^
```

4.2.1 Chaining dependent functions

Dependently typed functions provide a means of calculating one type from another. We can *chain* dependently typed functions to perform calculations involving multiple steps. For example, we should be able to use a `Generic` to calculate a Repr for a case class, and use a Last to calculate the type of the last element. Let's try coding this:

```
def lastField[A](input: A)(
  implicit
  gen: Generic[A],
  last: Last[gen.Repr]
): last.Out = last.apply(gen.to(input))
// <console>:19: error: illegal dependent method type: parameter may
     only be referenced in a subsequent parameter section
//          gen: Generic[A],
//          ^
```

Unfortunately our code doesn't compile. This is the same problem we had in Section 3.2.2 with our definition of genericEncoder. We worked around the problem by lifting the free type variable out as a type parameter:

```
def lastField[A, Repr <: HList](input: A)(
  implicit
  gen: Generic.Aux[A, Repr],
  last: Last[Repr]
): last.Out = last.apply(gen.to(input))

lastField(Rect(Vec(1, 2), Vec(3, 4)))
// res10: Vec = Vec(3,4)
```

As a general rule, we always write code in this style. By encoding all the free variables as type parameters, we enable the compiler to unify them with appropriate types. This goes for more subtle constraints as well. For example, suppose we wanted to summon a Generic for a case class of exactly one field. We might be tempted to write this:

```
def getWrappedValue[A, Head](input: A)(
  implicit
  gen: Generic.Aux[A, Head :: HNil]
): Head = gen.to(input).head
```

The result here is more insidious. The method definition compiles but the compiler can never find the implicits its needs at the call site:

```scala
case class Wrapper(value: Int)

getWrappedValue(Wrapper(42))
// <console>:21: error: could not find implicit value for parameter gen:
      shapeless.Generic.Aux[Wrapper,shapeless.::[Head,shapeless.HNil]]
//        getWrappedValue(Wrapper(42))
//                       ^
```

The error message hints at the problem:

> error: could not find implicit value for parameter gen:
>
> `Generic.Aux[Wrapper, Head :: HNil]`

The clue is in the appearance of the type `Head`. This is the name of a type parameter in the method: it shouldn't be appearing in the type the compiler is trying to unify. The problem is that the `gen` parameter is over-constrained: the compiler can't find a `Repr` *and* ensure its length at the same time. `Nothing` also often provides a clue, appearing when the compiler fails to unify covariant type parameters.

The solution to our problem above is to separate implicit resolution into steps:

1. find a `Generic` with a suitable `Repr` for `A`;
2. provide that the `Repr` has a `Head` type.

Here's a revised version of the method using `=:=` to constrain `Repr`:

```scala
def getWrappedValue[A, Repr <: HList, Head, Tail <: HList](input: A)(
  implicit
  gen: Generic.Aux[A, Repr],
  ev: (Head :: Tail) =:= Repr
): Head = gen.to(input).head
// <console>:21: error: could not find implicit value for parameter c:
     shapeless.ops.hlist.IsHCons[gen.Repr]
//        ): Head = gen.to(input).head
//                                ^
```

This doesn't compile because the head method in the method body requires an implicit parameter of type `IsHCons`. This is a much simpler error message to fix—we just need to learn a tool from shapeless' toolbox. `IsHCons` is a shapeless type class that splits an `HList` into a `Head` and `Tail`. We can use `IsHCons` instead of `=:=`:

```
import shapeless.ops.hlist.IsHCons

def getWrappedValue[A, Repr <: HList, Head, Tail <: HList](in: A)(
  implicit
  gen: Generic.Aux[A, Repr],
  isHCons: IsHCons.Aux[Repr, Head, Tail]
): Head = gen.to(in).head
```

This fixes the bug. Both the method definition and the call site now compile as expected:

```
getWrappedValue(Wrapper(42))
// res13: Int = 42
```

The take home point here isn't that we solved the problem using `IsHCons`. Shapeless provides a lot of tools like this, and we can supplement them where necessary with our own type classes. The important point is the process we used to write code that compiles and is capable of finding solutions. We'll finish off this section with a step-by-step guide summarising our findings so far.

4.3 Summary

When coding with shapeless, we are often trying to find a target type that depends on the types we start with. This relationship is called *dependent typing*.

Problems involving dependent types can be conveniently expressed using implicit search, allowing the compiler to resolve intermediate and target types given a starting point at the call site.

We often have to use multiple steps to calculate a result (e.g. using a `Generic` to get a `Repr`, then using another type class to get to another type). When we do this, there are a few rules we can follow to ensure our code compiles and works as expected:

1. We should extract every intermediate type out to a type parameter. Many type parameters won't be used in the result, but the compiler needs them to know which types it has to unify.

2. The compiler resolves implicits from left to right, backtracking if it can't find a working combination. We should write implicits in the order we need them, using one or more type variables to connect them to previous implicits.

3. The compiler can only solve for one constraint at a time, so we mustn't over-constrain any single implicit.

4. We should state the return type explicitly, specifying any type parameters and type members that may ne needed elsewhere. Type members are often important. If we don't state them in the return type, they won't be available to the compiler for further implicit resolution.

5. The `Aux` type alias pattern is useful for keeping code readable. We should look out for `Aux` aliases when using tools from the shapeless toolbox, and implement `Aux` aliases on our own dependently typed functions.

> TODO: Section on debugging using `implicitly`?
>
> Section on debugging using `reify`?

Chapter 5

Accessing names during implicit derivation

Often, the type class instances we define need access to more than just types. In this chapter we will look at a variant of `Generic` called `LabelledGeneric` that gives us access to field names and type names.

To begin with we have some theory to cover. `LabelledGeneric` uses some clever techniques to expose name information at the type level. To understand these techniques we must discuss *literal types*, *singleton types*, *phantom types*, and *type tagging*.

5.1 Literal types

As Scala developers, we are used to the notion that a value may have multiple types. For example, the string `"hello"` has at least three types: `String`, `AnyRef`, and `Any`[1]:

[1]`String` has a bunch of other types like `Serializable` and `Comparable` but let's ignore those for now.

```
"hello" : String
// res0: String = hello

"hello" : AnyRef
// res1: AnyRef = hello

"hello" : Any
// res2: Any = hello
```

Interestingly, `"hello"` also has another type: a "singleton type" that belongs exclusively to that one value. This is similar to the singleton type we get when we define a companion object:

```
object Foo

Foo
// res3: Foo.type = Foo$@23c925d4
```

Singleton types applied to literal values are called *literal types*. We don't normally interact with them because the default behaviour of the compiler is to "cast" literals to their nearest non-singleton type. So, for example, these two expressions are essentially equivalent:

```
"hello"
// res4: String = hello

("hello" : String)
// res5: String = hello
```

Shapeless provides a few tools for working with literal types. First, there is a `narrow` macro that converts a literal expression into a singleton-typed literal expression:

```
import shapeless.syntax.singleton._

var x = 42.narrow
// x: Int(42) = 42
```

Note the type of `x` here: `Int(42)` is a literal type. It is a subtype of `Int` that only contains the value 42. If we attempt to assign a different number to x, we get a compile error:

```
x = 43
// <console>:16: error: type mismatch;
//  found   : Int(43)
//  required: Int(42)
//        x = 43
//            ^
```

However, x is still an `Int` according to normal subtyping rules. If we operate on x we get a regular type of result:

```
x + 1
// res6: Int = 43
```

We can use `narrow` on any literal in Scala:

```
1.narrow
// res7: Int(1) = 1

true.narrow
// res8: Boolean(true) = true

"hello".narrow
// res9: String("hello") = hello

// and so on...
```

However, we can't use it on compound expressions: the compiler has to be able to determine the literal value straight from the source:

```
math.sqrt(4).narrow
// <console>:17: error: Expression scala.math.`package`.sqrt(4.0) does
     not evaluate to a constant or a stable reference value
//        math.sqrt(4).narrow
//                 ^
// <console>:17: error: value narrow is not a member of Double
//        math.sqrt(4).narrow
```

```
//                       ^
```

Literal types in Scala

Until recently, Scala had no syntax for writing literal types. The types were there in the compiler, but we couldn't express them directly in code. As of Lightbend Scala 2.12.1[a], Lightbend Scala 2.11.9, and Typelevel Scala 2.11.8[b], however, we now have direct syntax support for literal types. In these versions of Scala we can write declarations like the following:

```
val theAnswer: 42 = 42
```

[a] https://github.com/scala/scala/pull/5310
[b] https://github.com/typelevel/scala#typelevel-scala-2118

The type 42 is the same as the type `Int(42)` we saw in printed output earlier. You'll still see `Int(42)` in output for legacy reasons, but the canonical syntax going forward is 42.

5.2 Type tagging and phantom types

Shapeless uses literal types to model the names of fields in case classes. It does this by "tagging" the types of the fields with the literal types of their names. Before we see how shapeless does this, we'll do it ourselves to show that there's no magic (well... minimal magic, at any rate). Suppose we have a number:

```
val number = 42
```

This number is an `Int` in two worlds: at runtime, where it has methods like + and *, and at compile-time, where the compiler uses the type to calculate which pieces of code work together and to search for implicits.

We can modify the type of `number` at compile time without modifying its run-time behaviour by "tagging" it with a "phantom type". Phantom types are types with no run-time semantics, like this:

```
trait Cherries
```

We can tag `number` using `asInstanceOf`. We end up with a value that is both an `Int` and a `Cherries` at compile-time, and an `Int` at run-time:

```
val numCherries = number.asInstanceOf[Int with Cherries]
// numCherries: Int with Cherries = 42
```

Shapeless uses this trick to tag the types of fields in a case classes with the singleton types of their names. If you find using `asInstanceOf` uncomfortable then don't worry: there's explicit syntax for tagging that avoids such unsavoriness:

```
import shapeless.labelled.{KeyTag, FieldType}
import shapeless.syntax.singleton._

val someNumber = 123

val numCherries = "numCherries" ->> someNumber
// numCherries: Int with shapeless.labelled.KeyTag[String("numCherries")
     ,Int] = 123
```

Here we are tagging `someNumber` with the phantom type `KeyTag["numCherries", Int]`. The tag encodes both the name and type of the field, both of which are useful when searching for entries in a `Repr` using implicit resolution. Shapeless also provides us with the `FieldType` type alias to make it easy to extract the key tag and value from a type:

```
type FieldType[K, V] = V with KeyTag[K, V]
```

Now we understand how shapeless tags the type of a value with its field name. But the key tag is just a phantom type: how do we convert it to a value we can use at runtime? Shapeless provides a type class called `Witness` for this purpose. If we combine `Witness` and `FieldType`, we get something very compelling—the ability extract the field name from a tagged field:

```
import shapeless.Witness

val numCherries = "numCherries" ->> 123
// numCherries: Int with shapeless.labelled.KeyTag[String("numCherries")
     ,Int] = 123

// Get the tag from a tagged value:
def getFieldName[K, V](value: FieldType[K, V])
    (implicit witness: Witness.Aux[K]): K =
  witness.value

getFieldName(numCherries)
// res14: String = numCherries

// Get the untagged value from a tagged value:
def getFieldValue[K, V](value: FieldType[K, V]): V =
  value

getFieldValue(numCherries)
// res16: Int = 123
```

5.2.1 Records and *LabelledGeneric*

Shapeless includes a set of tools for working with data structures called *records*. Records are `HLists` of items that are each tagged with type-level identifiers:

```
import shapeless.{HList, ::, HNil}

val garfield = ("cat" ->> "Garfield") ::  ("orange" ->> true) :: HNil
// garfield: shapeless.::[String with shapeless.labelled.KeyTag[String("
     cat"),String],shapeless.::[Boolean with shapeless.labelled.KeyTag[
     String("orange"),Boolean],shapeless.HNil]] = Garfield :: true ::
     HNil
```

For clarity, the type of `garfield` is as follows:

```
// FieldType["cat",    String]  ::
// FieldType["orange", Boolean] ::
// HNil
```

TODO: Insert link to records chapter if we have one.

We don't need to go into depth regarding records here, suffice to say that records are the generic representation used by the `LabelledGeneric` type class that we will discuss next. `LabelledGeneric` tags each item in a product or coproduct with the corresponding field or type name from the concrete ADT (although the names are represented as `Symbols`, not `Strings`). Accessing names without using reflection is incredibly compelling, so let's derive some type class instances using `LabelledGeneric`.

5.3 Deriving product instances with *LabelledGeneric*

We'll use a running example of JSON encoding to illustrate `LabelledGeneric`. We'll define a `JsonEncoder` type class that converts values to a JSON AST. This is the approach taken by argonaut[2], circe[3], play-json[4], spray-json[5], and many other Scala JSON libraries.

First we'll define our JSON data type:

```
sealed trait JsonValue
case class JsonObject(fields: List[(String, JsonValue)]) extends
     JsonValue
case class JsonArray(items: List[JsonValue]) extends JsonValue
case class JsonString(value: String) extends JsonValue
case class JsonNumber(value: Double) extends JsonValue
```

[2]https://argonaut.io
[3]https://github.com/travisbrown/circe
[4]https://www.playframework.com/documentation/2.5.x/ScalaJson
[5]https://github.com/spray/spray-json

```
case class JsonBoolean(value: Boolean) extends JsonValue
case object JsonNull extends JsonValue
```

then the type class for encoding values as JSON:

```
trait JsonEncoder[A] {
  def encode(value: A): JsonValue
}
```

then a few basic instances:

```
def createEncoder[A](func: A => JsonValue): JsonEncoder[A] =
  new JsonEncoder[A] {
    def encode(value: A): JsonValue =
      func(value)
  }

implicit val stringEncoder: JsonEncoder[String] =
  createEncoder(str => JsonString(str))

implicit val doubleEncoder: JsonEncoder[Double] =
  createEncoder(num => JsonNumber(num))

implicit val intEncoder: JsonEncoder[Int] =
  createEncoder(num => JsonNumber(num))

implicit val booleanEncoder: JsonEncoder[Boolean] =
  createEncoder(bool => JsonBoolean(bool))

implicit def listEncoder[A]
    (implicit enc: JsonEncoder[A]): JsonEncoder[List[A]] =
  createEncoder(list => JsonArray(list.map(enc.encode)))

implicit def optionEncoder[A]
    (implicit enc: JsonEncoder[A]): JsonEncoder[Option[A]] =
  createEncoder(opt => opt.map(enc.encode).getOrElse(JsonNull))
```

Ideally, when we encode ADTs as JSON, we would like to use the correct field names in the output JSON:

```scala
case class IceCream(name: String, numCherries: Int, inCone: Boolean)

val iceCream = IceCream("Sundae", 1, false)

// Ideally we'd like to produce something like this:
val iceCreamJson: JsonValue =
  JsonObject(List(
    "name"        -> JsonString("Sundae"),
    "numCherries" -> JsonNumber(1),
    "inCone"      -> JsonBoolean(false)
  ))
```

This is where `LabelledGeneric` comes in. Let's summon an instance for `IceCream` and see what kind of representation it produces:

```scala
import shapeless.LabelledGeneric

val gen = LabelledGeneric[IceCream].to(iceCream)
// gen: shapeless.::[String with shapeless.labelled.KeyTag[Symbol with
     shapeless.tag.Tagged[String("name")],String],shapeless.::[Int with
     shapeless.labelled.KeyTag[Symbol with shapeless.tag.Tagged[String("
     numCherries")],Int],shapeless.::[Boolean with shapeless.labelled.
     KeyTag[Symbol with shapeless.tag.Tagged[String("inCone")],Boolean],
     shapeless.HNil]]] = Sundae :: 1 :: false :: HNil
```

For clarity, the full type of the `HList` is:

```scala
// String  with KeyTag[Symbol with Tagged["name"], String]     ::
// Int     with KeyTag[Symbol with Tagged["numCherries"], Int] ::
// Boolean with KeyTag[Symbol with Tagged["inCone"], Boolean]  ::
// HNil
```

The type here is slightly more complex than we have seen. Instead of representing the field names with literal string types, shapeless is representing them with symbols tagged with literal string types. The details of the implementation aren't particularly important: we can still use `Witness` and `FieldType` to extract the tags, but they come out as `Symbols` instead of `Strings`.

5.3.1 Instances for *HLists*

Let's define `JsonEncoder` instances for `HNil` and `::`. These encoders are going to generate and manipulate `JsonObjects`, so we'll introduce a new type of encoder to make that easier:

```
trait JsonObjectEncoder[A] extends JsonEncoder[A] {
  def encode(value: A): JsonObject
}

def createObjectEncoder[A](fn: A => JsonObject): JsonObjectEncoder[A] =
  new JsonObjectEncoder[A] {
    def encode(value: A): JsonObject =
      fn(value)
  }
```

The definition for `HNil` is then straightforward:

```
import shapeless.{HList, ::, HNil, Lazy}

implicit val hnilEncoder: JsonObjectEncoder[HNil] =
  createObjectEncoder(hnil => JsonObject(Nil))
```

The definition of `hlistEncoder` involves a few moving parts so we'll go through it piece by piece. We'll start with the definition we might expect if we were using regular `Generic`:

```
implicit def hlistObjectEncoder[H, T <: HList](
  implicit
  hEncoder: Lazy[JsonEncoder[H]],
  tEncoder: JsonObjectEncoder[T]
): JsonEncoder[H :: T] = ???
```

`LabelledGeneric` will give us an `HList` of tagged types, so let's start by introducing a new type variable for the key type:

```scala
import shapeless.Witness
import shapeless.labelled.FieldType

implicit def hlistObjectEncoder[K, H, T <: HList](
  implicit
  hEncoder: Lazy[JsonEncoder[H]],
  tEncoder: JsonObjectEncoder[T]
): JsonObjectEncoder[FieldType[K, H] :: T] = ???
```

In the body of our method we're going to need the value associated with K. We'll add an implicit `Witness[K]` to do this for us:

```scala
implicit def hlistObjectEncoder[K, H, T <: HList](
  implicit
  witness: Witness.Aux[K],
  hEncoder: Lazy[JsonEncoder[H]],
  tEncoder: JsonObjectEncoder[T]
): JsonObjectEncoder[FieldType[K, H] :: T] = {
  val fieldName = witness.value
  ???
}
```

We can access the value of K using `witness.value`, but the compiler has no way of knowing what type of tag we're going to get. `LabelledGeneric` uses `Symbols` as the tag types, so we'll put a type bound on K and use `symbol.name` to convert it to a `String`:

```scala
implicit def hlistObjectEncoder[K <: Symbol, H, T <: HList](
  implicit
  witness: Witness.Aux[K],
  hEncoder: Lazy[JsonEncoder[H]],
  tEncoder: JsonObjectEncoder[T]
): JsonObjectEncoder[FieldType[K, H] :: T] = {
  val fieldName: String = witness.value.name
  ???
}
```

The rest of the definition uses the principles we covered in Chapter 3:

```scala
implicit def hlistObjectEncoder[K <: Symbol, H, T <: HList](
  implicit
  witness: Witness.Aux[K],
  hEncoder: Lazy[JsonEncoder[H]],
  tEncoder: JsonObjectEncoder[T]
): JsonObjectEncoder[FieldType[K, H] :: T] = {
  val fieldName: String = witness.value.name
  createObjectEncoder { hlist =>
    val head = hEncoder.value.encode(hlist.head)
    val tail = tEncoder.encode(hlist.tail)
    JsonObject((fieldName, head) :: tail.fields)
  }
}
```

5.3.2 Instances for concrete products

Finally let's turn to our generic instance. This is identical to the definitions we've seen before, except that we're using `LabelledGeneric` instead of `Generic`:

```scala
import shapeless.LabelledGeneric

implicit def genericObjectEncoder[A, H <: HList](
  implicit
  generic: LabelledGeneric.Aux[A, H],
  hEncoder: Lazy[JsonObjectEncoder[H]]
): JsonEncoder[A] =
  createObjectEncoder { value =>
    hEncoder.value.encode(generic.to(value))
  }
```

And that's all we need! With these definitions in place we can serialize instances of any case class and retain the field names in the resulting JSON:

```scala
implicitly[JsonEncoder[IceCream]].encode(iceCream)
// res14: JsonValue = JsonObject(List((name,JsonString(Sundae)), (
    numCherries,JsonNumber(1.0)), (inCone,JsonBoolean(false))))
```

5.4 Deriving coproduct instances with *LabelledGeneric*

Applying `LabelledGeneric` with `Coproducts` involves a mixture of the concepts we've covered already. Let's start by examining a `Coproduct` type derived by `LabelledGeneric`. We'll re-visit our `Shape` ADT from Chapter 3:

```
import shapeless.LabelledGeneric

sealed trait Shape
final case class Rectangle(width: Double, height: Double) extends Shape
final case class Circle(radius: Double) extends Shape

LabelledGeneric[Shape].to(Circle(1.0))
// res5: shapeless.:+:[Rectangle with shapeless.labelled.KeyTag[Symbol
     with shapeless.tag.Tagged[String("Rectangle")],Rectangle],shapeless
     .:+:[Circle with shapeless.labelled.KeyTag[Symbol with shapeless.
     tag.Tagged[String("Circle")],Circle],shapeless.CNil]] = Inr(Inl(
     Circle(1.0)))
```

Here is that `Coproduct` type in a more readable format:

```
// Rectangle with KeyTag[Symbol with Tagged["Rectangle"], Rectangle] :+:
// Circle    with KeyTag[Symbol with Tagged["Circle"],    Circle]    :+:
// CNil
```

As you can see, the result is a `Coproduct` of the subtypes of `Shape`, each tagged with the type name. We can use this information to write `JsonEncoders` for `:+:` and `CNil`:

```
import shapeless.{Coproduct, :+:, CNil, Inl, Inr, Witness, Lazy}
import shapeless.labelled.FieldType

implicit val cnilObjectEncoder: JsonObjectEncoder[CNil] =
  createObjectEncoder(cnil => throw new Exception("Mass hysteria!"))

implicit def coproductObjectEncoder[K <: Symbol, H, T <: Coproduct](
  implicit
  witness: Witness.Aux[K],
  hEncoder: Lazy[JsonEncoder[H]],
```

```scala
  tEncoder: JsonObjectEncoder[T]
): JsonObjectEncoder[FieldType[K, H] :+: T] = {
  val typeName = witness.value.name
  createObjectEncoder {
    case Inl(h) =>
      JsonObject(List(typeName -> hEncoder.value.encode(h)))

    case Inr(t) =>
      tEncoder.encode(t)
  }
}
```

`coproductEncoder` follows the same pattern as `hlistEncoder`. We have three type parameters: `K` for the type name, `H` for the value at the head of the `HList`, and `T` for the value at the tail. We use `FieldType` and `:+:` in the result type to declare the relationships between the three, and we use a `Witness` to access the runtime value of the type name. The result is an object containing a single key/value pair: the key being the type name and the value the result:

```scala
val shape: Shape = Circle(1.0)

implicitly[JsonEncoder[Shape]].encode(shape)
// res8: JsonValue = JsonObject(List((Circle,JsonObject(List((radius,
     JsonNumber(1.0)))))))
```

5.5 Summary

In this chapter we discussed `LabelledGeneric`, a variant of `Generic` that exposes type and field names in its generic representations.

The names exposed by `LabelledGeneric` are encoded at as type-level tags, so we can target them during implicit resolution. We started the chapter discussing *literal types* and the way shapeless uses them in its tags. We also discussed the `Witness` type class, which is used to reify literal types as values.

Finally, we brought `LabelledGeneric`, literal types, and `Witness` together to build a `JsonEcoder` library that includes sensible names in its output.

The key take home point from this chapter is that none of this code uses run-time reflection: it's all done with types, implicits, and a small set of macros that are internal to shapeless. The code we're generating is consequently very fast and reliable at runtime.

Chapter 6

Working with HLists and Coproducts

We have now seen several examples of type class derivation. In each case we convert an ADT to an `HList` or `Coproduct` and recurse over it in some manner to calculate our output.

In this chapter we'll look at some built-in type classes that shapeless provides for manipulating `HLists` and `Coproducts`. We can use these in two ways. If we're creating our own type classes We can build our own type classes on top of them, or we can use them directly via *extension methods* on `HList` and `Coproduct`.

There are three general sets of type classes, available from three packages:

`shapeless.ops.hlist` defines type classes for `HLists`. Many can be used directly via extension methods on `HList`, defined in `shapeless.syntax.hlist`.

`shapeless.ops.coproduct` defines type classes for `Coproducts`. Many can be used directly via extension methods on `Coproduct`, defined in `shapeless.syntax.coproduct`.

`shapeless.ops.record` defines type classes for `HLists` whose elements are tagged with key types (see Section 5.2). Many can be used directly via extension methods on `HList`, defined in `shapeless.syntax.record`.

There are a huge number of these "ops" type classes, all written in a consistent style and many defined for both `HLists` and `Coproducts`. Rather than cover them all (which would make this book significantly larger), we will walk through a few worked examples, cover the main theory points, and show you how to extract further information from the shapeless codebase.

6.1 Simple ops examples

`HList` has `init` and `last` extension methods based on two type classes: `shapeless.ops.hlist.Init` and `shapeless.ops.hlist.Last`. `Coproduct` has similar methods and type classes. These serve as perfect simple examples of the ops pattern. Here are simplified definitions of the extension methods:

```
package shapeless
package syntax

implicit class HListOps[L <: HList](l : L) {
  def last(implicit last: Last[L]): last.Out = last.apply(l)
  def init(implicit init: Init[L]): init.Out = init.apply(l)
}
```

The return type of each method is determined by a dependent type on the type class parameter. The resolution of the type class instance inspects the `HList` type and calculates the result type. Here's the definition of `Last` as an example:

```
trait Last[L <: HList] {
  type Out
  def apply(in: L): Out
}

object Last {
  type Aux[L <: HList, O] = Last[L] { type Out = O }
  implicit def pair[H]: Aux[H :: HNil, H] = ???
```

```
  implicit def list[H, T <: HList]
    (implicit last: Last[T]): Aux[H :: T, last.Out] = ???
}
```

We can make a few interesting observations about this implementation. First, we can typically implement ops type classes with a small number of instances (two in the case of `Last` and `Init`). All of the instances are generally packaged in the companion object of the type class, allowing us to call the corresponding extension methods without additional imports:

```
import shapeless._

("Hello" :: 123 :: true :: HNil).last
// res0: Boolean = true

("Hello" :: 123 :: true :: HNil).init
// res1: shapeless.::[String,shapeless.::[Int,shapeless.HNil]] = Hello
     :: 123 :: HNil
```

Second, the type class is only defined for `HLists` with at least one element. This gives us a degree of static checking. If we try to call `last` on an empty `HList`, we get a compile error:

```
HNil.last
// <console>:16: error: Implicit not found: shapeless.Ops.Last[shapeless
     .HNil.type]. shapeless.HNil.type is empty, so there is no last
     element.
//        HNil.last
//             ^

HNil.init
// <console>:16: error: Implicit not found: shapeless.Ops.Init[shapeless
     .HNil.type]. {L} is empty, so there is no first element.
//        HNil.init
//             ^
```

6.2 Creating a custom op

As an exercise, let's work through the creation of our own op. We'll combine the power of `Last` and `Init` to create a `Penultimate` type class that retrieves the second-to-last element in an `HList`. Here's the type class definition:

```
import shapeless._

trait Penultimate[L] {
  type Out
  def apply(l: L): Out
}

object Penultimate {
  type Aux[L, O] = Penultimate[L] { type Out = O }

  def apply[L](implicit inst: Penultimate[L]): Aux[L, inst.Out] =
    inst
}
```

We can create the only instance we require by combining `Init` and `Last` using the techniques covered in Section 4.2.1:

```
import shapeless.ops.hlist

implicit def hlistPenultimate[L <: HList, M <: HList, O](
  implicit
  init: hlist.Init.Aux[L, M],
  last: hlist.Last.Aux[M, O]
): Penultimate.Aux[L, O] =
  new Penultimate[L] {
    type Out = O
    def apply(l: L): O =
      last.apply(init.apply(l))
  }
```

This gives us a `Penultimate` type class that we can re-use in other type class definitions:

```scala
type BigList = String :: Int :: Boolean :: Double :: HNil

val bigList = "foo" :: 123 :: true :: 456.0 :: HNil

Penultimate[BigList].apply(bigList)
// res4: Boolean = true
```

Summoning an instance of `Penultimate` depends on summoning instances for `Last` and `Init`, so we inherit the same level of type checking on short `HLists`:

```scala
type TinyList = String :: HNil

val tinyList = "bar" :: HNil

Penultimate[TinyList].apply(tinyList)
// <console>:22: error: could not find implicit value for parameter inst
     : Penultimate[TinyList]
//        Penultimate[TinyList].apply(tinyList)
//                   ^
```

We can make things more convenient for end users by defining an extension method on `HList`:

```scala
implicit class PenultimateOps[A](a: A) {
  def penultimate(implicit inst: Penultimate[A]): inst.Out =
    inst.apply(a)
}

bigList.penultimate
// res7: Boolean = true
```

Finally, if we add a second type class instance for `Generic`, we can access the penultimate fields of arbitrary product types:

```scala
implicit def genericPenultimate[A, R, O](
  implicit
  generic: Generic.Aux[A, R],
  penultimate: Penultimate.Aux[R, O]
): Penultimate.Aux[A, O] =
```

```scala
  new Penultimate[A] {
    type Out = O
    def apply(a: A): O =
      penultimate.apply(generic.to(a))
  }

case class IceCream(name: String, numCherries: Int, inCone: Boolean)

IceCream("Sundae", 1, false).penultimate
// res9: Int = 1
```

6.3 Case study: case class migrations

We'll finish this chapter with a more useful example: a type class for performing "migrations" (aka "evolutions") on case classes[1]. For example, suppose version 1 of our app has a case class:

```scala
case class IceCreamV1(name: String, numCherries: Int, inCone: Boolean)
```

our type class will let us perform certain mechanical "upgrades" for free:

```scala
// Remove fields:
case class IceCreamV2a(name: String, inCone: Boolean)

// Reorder fields:
case class IceCreamV2b(name: String, inCone: Boolean, numCherries: Int)

// Add fields (provided we can determine a default value):
case class IceCreamV2c(
  name: String, inCone: Boolean, numCherries: Int, numWaffles: Int)
```

Ideally we'd like to be able to write code like this:

```scala
IceCreamV1("Sundae", 1, false).migrateTo[IceCreamV2a]
```

The type class should take care of the migration without additional boilerplate.

[1]The term "migration" is stolen from "database migration"—an SQL script that automates an upgrade to a database schema to keep it in line with a change in a corresponding application.

6.3.1 The type class

The `Migration` type class represents a transformation from a source to a destination type. Both of these are going to be "input" types in our derivation, so we model both as type parameters. We don't need an `Aux` type alias because there are no type members to expose as parameters:

```
trait Migration[A, B] {
  def apply(a: A): B
}
```

We'll introduce syntax for `Migration` now to make later examples more readable:

```
implicit class MigrationOps[A](a: A) {
  def migrateTo[B](implicit migration: Migration[A, B]): B =
    migration.apply(a)
}
```

6.3.2 Step 1. Removing fields

Let's build up the solution piece by piece, starting with field removal. We can do this in several steps:

1. convert `A` to its generic representation;
2. filter the `HList` from step 1—only retain fields that are also in `B`;
3. convert the output of step 2 to `B`.

We can implement steps 1 and 3 with `Generic` or `LabelledGeneric`, and step 2 with an existing op called `Intersection`:

```
import shapeless._
import shapeless.ops.hlist

implicit def genericMigration[A, B, ARepr <: HList, BRepr <: HList](
  implicit
  aGen    : LabelledGeneric.Aux[A, ARepr],
```

```
  bGen    : LabelledGeneric.Aux[B, BRepr],
  inter   : hlist.Intersection.Aux[ARepr, BRepr, BRepr]
): Migration[A, B] = new Migration[A, B] {
  def apply(a: A): B =
    bGen.from(inter.apply(aGen.to(a)))
}
```

The `Intersection.Aux` type takes three type parameters: two input `HLists` and one output for the intersection type. In the example above we are specifying `ARepr` and `BRepr` as the input types and `BRepr` as the output type. This means type class resolution will only work if `B` has an exact subset of the fields of `A`, specified with the exact same names in the same order:

```
IceCreamV1("Sundae", 1, true).migrateTo[IceCreamV2a]
// res6: IceCreamV2a = IceCreamV2a(Sundae,true)
```

If we try to use `Migration` with non-conforming types, implicit resolution will fail:

```
IceCreamV1("Sundae", 1, true).migrateTo[IceCreamV2b]
// <console>:24: error: could not find implicit value for parameter
     migration: Migration[IceCreamV1,IceCreamV2b]
//        IceCreamV1("Sundae", 1, true).migrateTo[IceCreamV2b]
//                                               ^
```

Field uniqueness

What would have happened if we had used `Generic` above instead of `LabelledGeneric`? Both type classes return `HLists`—the only difference is that `LabelledGeneric` refines the types of the members with the singleton types of their identifiers.

We're not using field names directly in this example, but they are having an effect on the way other type classes work. `Intersection`, for example, calculates a list of common elements based on their types. The types generated by `LabelledGeneric` are different if the field names

> are different, so `Intersection` is taking the names into account. If we had used regular `Generic`, the behaviour would be different.

6.3.3 Step 2. Reordering fields

To add support for field reordering we need to lean on another ops type class. The `Align` type class allows us reorder the fields in an `HList` so they are in the same order as another `HList`. We can use `Align` to redefine our instance as follows:

```scala
implicit def genericMigration[
  A, B,
  ARepr <: HList, BRepr <: HList,
  Unaligned <: HList
](
  implicit
  aGen    : LabelledGeneric.Aux[A, ARepr],
  bGen    : LabelledGeneric.Aux[B, BRepr],
  inter   : hlist.Intersection.Aux[ARepr, BRepr, Unaligned],
  align   : hlist.Align[Unaligned, BRepr]
): Migration[A, B] = new Migration[A, B] {
  def apply(a: A): B =
    bGen.from(align.apply(inter.apply(aGen.to(a))))
}
```

We introduce a new type parameter called `Unaligned` to represent the intersection of `ARepr` and `BRepr` before alignment, and use `Align` to convert `Unaligned` to `BRepr`. Note that, like `Migration`, `Align` doesn't have any type members and doesn't require an `Aux` type alias.

With this modified type class instance we can support the removal and reordering of fields:

```scala
IceCreamV1("Sundae", 1, true).migrateTo[IceCreamV2a]
// res8: IceCreamV2a = IceCreamV2a(Sundae,true)

IceCreamV1("Sundae", 1, true).migrateTo[IceCreamV2b]
// res9: IceCreamV2b = IceCreamV2b(Sundae,true,1)
```

However, we still get a failure if we try to add fields:

```
IceCreamV1("Sundae", 1, true).migrateTo[IceCreamV2c]
// <console>:26: error: could not find implicit value for parameter
     migration: Migration[IceCreamV1,IceCreamV2c]
//        IceCreamV1("Sundae", 1, true).migrateTo[IceCreamV2c]
//                                               ^
```

6.3.4 Step 3. Adding new fields

To allow the user to add new fields during a migration, we need a mechanism for calculating default values. Shapeless doesn't provide a type class for this, so we'll make our own:

```
trait Empty[A] {
  def get: A
}

def createEmpty[A](body: => A): Empty[A] =
  new Empty[A] {
    def get: A = body
  }
```

We can define instances for `Empty` using the techniques from Chapter 5. We need instances for a few core types, `HNil`, and record `HLists` with tagged head types:

```
import shapeless.labelled.{field, FieldType}

implicit val emptyInt     : Empty[Int]     = createEmpty(0)
implicit val emptyDouble  : Empty[Double]  = createEmpty(0.0)
implicit val emptyBoolean : Empty[Boolean] = createEmpty(false)
implicit val emptyString  : Empty[String]  = createEmpty("")
implicit val emptyHnil    : Empty[HNil]    = createEmpty(HNil)
implicit def emptyHList[K <: Symbol, H, T <: HList](
  implicit
  hEmpty: Lazy[Empty[H]],
  tEmpty: Empty[T]
): Empty[FieldType[K, H] :: T] =
```

```scala
createEmpty(field[K](hEmpty.value.get) :: tEmpty.get)
```

We need to combine `Empty` with a couple of other ops type classes to complete our final implementation of `Migration`. Here's the full list of steps:

1. use `LabelledGeneric` to convert `A` to its generic representation;
2. use `Intersection` to calculate an `HList` of fields common to `A` and `B`;
3. calculate the type of fields that appear in `B` but not in `A`;
4. use `Empty` to calculate an empty `HList` of the type from step 3;
5. append the common fields from step 2 to the new fiewld from step 4;
6. use `Align` to reorder the fields from step 5 in the same order as `B`;
7. use `LabelledGeneric` to convert the output of step 6 to `B`.

We've already seen how to implement steps 1, 2, 4, 6, and 7. We can implement step 3 using an ops type class called `Diff` that works very similarly to `Intersection`, and we can implement step 5 using another ops type class called `Prepend`. Here's the complete solution:

```scala
implicit def genericMigration[
  A, B, ARepr <: HList, BRepr <: HList,
  Common <: HList, Added <: HList, Unaligned <: HList
](
  implicit
  aGen    : LabelledGeneric.Aux[A, ARepr],
  bGen    : LabelledGeneric.Aux[B, BRepr],
  inter   : hlist.Intersection.Aux[ARepr, BRepr, Common],
  diff    : hlist.Diff.Aux[BRepr, Common, Added],
  empty   : Empty[Added], // see below
  prepend : hlist.Prepend.Aux[Added, Common, Unaligned],
  align   : hlist.Align[Unaligned, BRepr]
): Migration[A, B] =
  new Migration[A, B] {
    def apply(a: A): B =
      bGen.from(align(prepend(empty.get, inter(aGen.to(a)))))
  }
```

Note that we don't end up using all the type class parameters at the value level. We use `Diff` to calculate the `Added` data type, but we don't actually need it at run time. Instead we use `Empty` to summon an instance of `Added`.

With this final version of the type class instance in place we can use `Migration` for all the use cases we set out at the beginning of the case study:

```
IceCreamV1("Sundae", 1, true).migrateTo[IceCreamV2a]
// res13: IceCreamV2a = IceCreamV2a(Sundae,true)

IceCreamV1("Sundae", 1, true).migrateTo[IceCreamV2b]
// res14: IceCreamV2b = IceCreamV2b(Sundae,true,1)

IceCreamV1("Sundae", 1, true).migrateTo[IceCreamV2c]
// res15: IceCreamV2c = IceCreamV2c(Sundae,true,1,0)
```

This is a mighty utilty, indeed, and we generated the entire thing with a single type class instance based on the powerful type classes built in to `shapeless.ops.hlist`.

6.4 Summary

In this chapter we looked at a few of the "ops" type classes that shapeless provides in `shapeless.ops.hlist` and `shapeless.ops.coproduct`. These type classes, together with their extension methods defined in `shapeless.syntax.hlist` and `shapeless.syntax.coproduct`, provide a wealth of functionality that we can use in the definitions of our own type classes.

We didn't discuss the type classes in `shapeless.ops.record`, which provide `Map`-like operations on `HLists` of tagged types. We've already covered all of the theory required to understand these type classes, so we'll leave it as an exercise to the reader to find out more about them.

In the next chapters we will discuss two more suites of ops type classes that with some associated theory. Chapter **??** discusses how to implement functional operations such as `map` and `flatMap` on `HLists`, and Chapter **??** discusses how to implement type classes that require type level representations of numbers.

Chapter 7

Functional operations on HLists

Regular Scala programs make heavy use of functional operations like `map` and `flatMap`. A question arises: can we perform similar operations on `HLists` and `Coproducts`? The answer is "yes", but the code looks a little different to regular Scala code. Unsurprisingly, the mechanisms are type class based and there are a suite of ops type classes to help us out.

Before we delve in to the type classes themselves, however, we need to discuss some theory to understand what operations involving functions look like when applied to heterogeneously typed data structures.

7.1 Motivation: mapping over an HList

Let's take the `map` method as an example. Figure 7.1 shows a type chart for mapping over a regular list. We start with a `List[A]`, supply a function `A => B`, and end up with a `List[B]`.

This model breaks down for `HLists` and `Coproducts` because of the heterogenous nature of the element types. Ideally we'd like a mapping like the one shown in Figure 7.2, which inspects the type of each input element and uses it to determine the type of each output element. This gives us a closed, composable transformation.

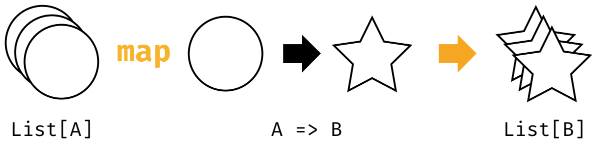

Figure 7.1: Mapping over a regular list ("monomorphic" map)

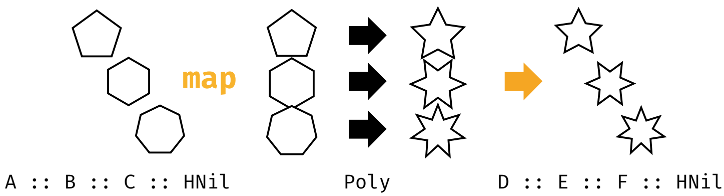

Figure 7.2: Mapping over a heterogeneous list ("polymorphic" map)

Unfortunately, Scala functions are subject to a few restrictions: they are not polymorphic and they can't have implicit parameters. In other words, we can't choose an output type based on input type of a regular function. We need some new infrastructure to solve this problem.

7.2 Polymorphic functions

Shapeless provides the `Poly` datatype for representing polymorphic functions. At its core, a `Poly` is an object with an `apply` method that accepts an implicit `Case` parameter to map input types to output types. Here is a simplified explanation of how it all works. Note that this isn't real shapeless code—we're eliding a lot of extra stuff that makes real shapeless `Polys` much more flexible and easier to use.

7.2.1 How Polys work

The implementation of `Poly` boils down to the following. The `apply` method delegates all concrete functionality to a type class, `Case`:

```scala
// This is not real shapeless code.
// It is purely for illustration.

trait Case[P, A] {
  type Result
  def apply(a: A): Result
}

trait Poly {
  def apply[A](arg: A)(implicit cse: Case[this.type, A]): cse.Result =
    cse.apply(arg)
}
```

We'll define some extra helpers to simplify the examples below:

```scala
type CaseAux[P, A, R] = Case[P, A] { type Result = R }

def createCase[P, A, R](func: A => R): CaseAux[P, A, R] =
  new Case[P, A] {
    type Result = R
    def apply(a: A): R = func(a)
  }
```

`Case` maps an input type A to an output type `Result`. It also has a second type parameter P referincing the singleton type of the `Poly` it is supporting (we'll come to this in a moment). When we create a `Poly`, we define the `Cases` as `implicit vals` within its body:

```scala
// This is not real shapeless code.
// It is purely for illustration.

object myPoly extends Poly {
  implicit def intCase: CaseAux[this.type, Int, Double] =
    createCase(num => num / 2.0)

  implicit def stringCase: CaseAux[this.type, String, Int] =
    createCase(str => str.length)
}
```

The `Cases` define the behaviour for each input type. When we call `myPoly.apply`, the compiler searches for the relevant implicit `Case` and fills it in as usual:

```
myPoly.apply(123) // search for a `Case[myPoly.type, Int]`
```

But how do the `Cases` end up in implicit scope? There is some subtle behaviour that makes this work. The implicit scope for `Case[P, A]` includes the companion objects for `Case`, `P`, and `A`. We defined `P` as the singleton type `myPoly.type` and it turns out that the companion object for `myPoly.type` is `myPoly` itself, so the `Cases` defined in the body of the `Poly` are always in implicit scope:

```
myPoly.apply(123)     // search for a `Case[myPoly.type, Int]`
// res8: Double = 61.5

myPoly.apply("hello") // search for a `Case[myPoly.type, String]`
// res9: Int = 5
```

7.2.2 Poly syntax

The code so far this chapter hasn't been real shapeless code. Here's our demo function from above rewritten in proper syntax:

```
import shapeless._

object myPoly extends Poly1 {
  implicit val intCase: Case.Aux[Int, Double] =
    at(num => num / 2.0)

  implicit val stringCase: Case.Aux[String, Int] =
    at(str => str.length)
}
```

There are a few key differences with our earlier toy syntax:

1. We're extending a trait called `Poly1` instead of `Poly`. Shapeless has a `Poly` type and a set of subtypes, `Poly1` through `Poly2`, supporting different arities of polymorphic function.

2. The `Case` and `Case.Aux` types don't include the singleton type of the `Poly`. In this context `Case` actually refers to a type alias defined within the body of `Poly1`. The singleton type is there—we just don't see it.

3. We're using a helper method, `at`, to define cases.

These syntactic differences aside, the shapeless version of `myPoly` is functionally identical to our toy version. We can call it with an `Int` or `String` parameter and get back a result of the corresponding return type:

```
myPoly.apply(123)
// res11: myPoly.intCase.Result = 61.5

myPoly.apply("hello")
// res12: myPoly.stringCase.Result = 5
```

Shapeless also supports `Poly`s with more than one parameter. Here is a binary example:

```
object multiply extends Poly2 {
  implicit val intIntCase: Case.Aux[Int, Int, Int] =
    at((a, b) => a * b)

  implicit val intStrCase: Case.Aux[Int, String, String] =
    at((a, b) => b.toString * a)
}

multiply(3, 4)
// res13: multiply.intIntCase.Result = 12

multiply(3, "4")
// res14: multiply.intStrCase.Result = 444
```

Because `Case`s are just implicit values, we can define cases based on type classes and do all of the advanced implicit resolution covered in previous chapters. Here's a simple example that totals numbers in different contexts:

```scala
import scala.math.Numeric

object total extends Poly1 {
  implicit def baseCase[A](implicit num: Numeric[A]): Case.Aux[A, Double
     ] =
    at(num.toDouble)

  implicit def optionCase[A](implicit num: Numeric[A]): Case.Aux[Option[
     A], Double] =
    at(opt => opt.map(num.toDouble).getOrElse(0.0))

  implicit def listCase[A](implicit num: Numeric[A]): Case.Aux[List[A],
     Double] =
    at(list => num.toDouble(list.sum))
}

total(10)
// res16: Double = 10.0

total(Option(20.0))
// res17: Double = 20.0

total(List(1L, 2L, 3L))
// res18: Double = 6.0
```

7.3 Mapping and flatMapping using Poly

`HList` has a `map` method that accepts a `Poly` as the mapping function. Here's an example:

```scala
import shapeless._

object sizeOf extends Poly1 {
  implicit val intCase: Case.Aux[Int, Int] =
    at(identity)

  implicit val stringCase: Case.Aux[String, Int] =
    at(_.length)

  implicit val booleanCase: Case.Aux[Boolean, Int] =
```

```
    at(bool => if(bool) 1 else 0)
}

(10 :: "hello" :: true :: HNil).map(sizeOf)
// res1: shapeless.::[Int,shapeless.::[Int,shapeless.::[Int,shapeless.
     HNil]]] = 10 :: 5 :: 1 :: HNil
```

We can use map provided the Poly provides Cases for every member of the HList. If the compiler can't find a Case for a particular member, we get a compile error:

```
(1.5 :: HNil).map(sizeOf)
// <console>:17: error: could not find implicit value for parameter
     mapper: shapeless.ops.hlist.Mapper[sizeOf.type,shapeless.::[Double,
     shapeless.HNil]]
//        (1.5 :: HNil).map(sizeOf)
//                         ^
```

We can also flatMap over an HList provided every corresponding case in our Poly returns another HList:

```
object valueAndSizeOf extends Poly1 {
  implicit val intCase: Case.Aux[Int, Int :: Int :: HNil] =
    at(num => num :: num :: HNil)

  implicit val stringCase: Case.Aux[String, String :: Int :: HNil] =
    at(str => str :: str.length :: HNil)

  implicit val booleanCase: Case.Aux[Boolean, Boolean :: Int :: HNil] =
    at(bool => bool :: (if(bool) 1 else 0) :: HNil)
}

(10 :: "hello" :: true :: HNil).flatMap(valueAndSizeOf)
// res3: shapeless.::[Int,shapeless.::[Int,shapeless.::[String,shapeless
     .::[Int,shapeless.::[Boolean,shapeless.::[Int,shapeless.HNil]]]]]]
     = 10 :: 10 :: hello :: 5 :: true :: 1 :: HNil
```

If there is a missing case or one of the cases doesn't return an HList, we get a compilation error:

```
// Using the wrong Poly with flatMap:
(10 :: "hello" :: true :: HNil).flatMap(sizeOf)
// <console>:18: error: could not find implicit value for parameter
     mapper: shapeless.ops.hlist.FlatMapper[sizeOf.type,shapeless.::[Int
     ,shapeless.::[String,shapeless.::[Boolean,shapeless.HNil]]]]
//        (10 :: "hello" :: true :: HNil).flatMap(sizeOf)
//                                               ^
```

7.4 Folding using Poly

In addition to map and flatMap, shapeless also provides foldLeft and foldRight operations on HLists:

```
import shapeless._

object sum extends Poly2 {
  implicit val intIntCase: Case.Aux[Int, Int, Int] =
    at((a, b) => a + b)

  implicit val intStringCase: Case.Aux[Int, String, Int] =
    at((a, b) => a + b.length)
}

(10 :: "hello" :: 100 :: HNil).foldLeft(0)(sum)
// res7: Int = 115
```

We can also reduceLeft, reduceRight, foldMap, and so on. Each operation has its own associated type class. We'll leave it as an exercise to the reader to investigate the available operations.

7.5 Defining type classes using Poly

We can use Poly and type classes such as Mapper and FlatMapper in the definitions of our own type classes. As an example let's build a type class for mapping from one case class to another:

```scala
trait ProductMapper[A, B, P] {
  def apply(a: A): B
}
```

We can create a type class instance using a `Mapper` and a pair of `Generics`:

```scala
import shapeless._
import shapeless.ops.hlist

implicit def genericProductMapper[
  A, B,
  P <: Poly,
  ARepr <: HList,
  BRepr <: HList
](
  implicit
  aGen: Generic.Aux[A, ARepr],
  bGen: Generic.Aux[B, BRepr],
  mapper: hlist.Mapper.Aux[P, ARepr, BRepr]
): ProductMapper[A, B, P] =
  new ProductMapper[A, B, P] {
    def apply(a: A): B =
      bGen.from(mapper.apply(aGen.to(a)))
  }
```

Interestingly, the value of the `Poly` does not appear in this code. The `Mapper` type class uses implicit resolution to find `Cases`, so we only need to know the singleton type of the `Poly` to do the mapping.

We can create an extension method to make the type class easy to use. We only want the user to specify the type of `B` at the call site, so we use some indirection to allow the compiler to infer the type of the `Poly` from a value parameter:

```scala
implicit class ProductMapperOps[A](a: A) {
  class Builder[B] {
    def apply[P <: Poly](poly: P)
        (implicit prodMap: ProductMapper[A, B, P]): B =
      prodMap(a)
  }
```

```scala
  def mapTo[B]: Builder[B] =
    new Builder[B]
}
```

The resulting `mapTo` syntax looks like a single method call, but is actually two calls: one call to `mapTo` to fix the `B` type parameter, and one call to `Builder.apply` to specify the `Poly`:

```scala
object conversions extends Poly1 {
  implicit val intCase:  Case.Aux[Int, Boolean]   = at(_ > 0)
  implicit val boolCase: Case.Aux[Boolean, Int]   = at(if(_) 1 else 0)
  implicit val strCase:  Case.Aux[String, String] = at(identity)
}

case class IceCream1(name: String, numCherries: Int, inCone: Boolean)
case class IceCream2(name: String, hasCherries: Boolean, numCones: Int)

IceCream1("Sundae", 1, false).mapTo[IceCream2](conversions)
// res2: IceCream2 = IceCream2(Sundae,true,0)
```

7.6 Summary

In this chapter we discussed *polymorphic functions* whose return types vary based on the types of their parameters. We discussed shapeless' `Poly` type that specifies cases as implicit values, and saw how it is used to implement functional operations such as `map`, `flatMap`, `foldLeft`, and `foldRight`.

Each operation is implemented as an extension method on `HList`, based on a corresponding type class: `Mapper`, `FlatMapper`, `LeftFolder`, and so on. We can use these type classes, `Poly`, and the techniques from Section 4.2.1 to create our own type classes involving sequences of sophisticated transformations.

Chapter 8

Counting with types

From time to time we need to count things at the type level. For example, we may need to know the length of an `HList` or the number of terms we have expanded so far in a computation. This chapter covers the theory behind counting with types, and provides some use cases related to type class derivation.

8.1 Representing numbers as types

Shapeless uses "church encoding" to represent natural numbers at the type level. It provides a type `Nat` with two subtypes: `_0` representing zero, and `Succ[N]` representing the successor of `N`:

```
import shapeless.{Nat, Succ}

type Zero = Nat._0
type One  = Succ[Zero]
type Two  = Succ[One]
// etc...
```

shapeless provides aliases for the first 22 `Nat`s as `Nat._N`:

```
Nat._1
Nat._2
Nat._3
// etc...
```

Nat has no runtime semantics. We have to use the ToInt type class to convert a Nat to a runtime Int:

```
import shapeless.ops.nat.ToInt

val toInt = implicitly[ToInt[Two]]

toInt.apply()
// res7: Int = 2
```

The Nat.toInt method provides convenient shorthand for calling nat.apply():

```
Nat.toInt[Succ[Succ[Succ[Nat._0]]]]
// res8: Int = 3
```

8.2 Sizing generic representations

One use case for Nat is determining the size of HLists and Coproducts. Shapeless provides the shapeless.ops.hlist.Length and shapeless.ops.coproduct.Length type classes for this.

Because of the similarity of the names, we typically import the hlist and coproduct packages refer to the relevant type classes as package.Length:

```
import shapeless._
import shapeless.ops.nat.ToInt
import shapeless.ops.{hlist, coproduct}

val hlistLength = hlist.Length[String :: Int :: Boolean :: HNil]
// hlistLength: shapeless.ops.hlist.Length[shapeless.::[String,shapeless
     .::[Int,shapeless.::[Boolean,shapeless.HNil]]]]{type Out =
     shapeless.Succ[shapeless.Succ[shapeless.Succ[shapeless._0]]]} =
```

```
    shapeless.ops.hlist$Length$$anon$3@6b415bd2

val coproductLength = coproduct.Length[Double :+: Char :+: CNil]
// coproductLength: shapeless.ops.coproduct.Length[shapeless.:+:[Double,
    shapeless.:+:[Char,shapeless.CNil]]]{type Out = shapeless.Succ[
    shapeless.Succ[shapeless._0]]} = shapeless.ops.
    coproduct$Length$$anon$29@5e953019
```

Instances of `Length` have a type member `Out` that represents the length as a `Nat`. We can either summon a `ToInt` ourselves to turn the `Nat` into an `Int`:

```
implicitly[ToInt[hlistLength.Out]].apply()
// res0: Int = 3
```

or use the `Nat.toInt` helper:

```
Nat.toInt[coproductLength.Out]
// res1: Int = 2
```

Let's use this in a concrete example. We'll create a `SizeOf` type class that counts the number of fields in a case class and exposes it as a simple `Int`:

```
trait SizeOf[A] {
  def value: Int
}
```

To create an instance of `SizeOf` we need three things:

1. a `Generic` to calculate the corresponding `HList` type;
2. a `Length` to calculate the length of the `HList` as a `Nat`;
3. a `ToInt` to convert the `Nat` to an `Int`.

Here's a working implementation written in the style described in Chapter 4:

```
implicit def genericSizeOf[A, L <: HList, N <: Nat](
  implicit
  generic: Generic.Aux[A, L],
  size: hlist.Length.Aux[L, N],
  sizeToInt: ToInt[N]
): SizeOf[A] =
  new SizeOf[A] {
    val value = sizeToInt.apply()
  }
```

We can test our code as follows:

```
def sizeOf[A](implicit size: SizeOf[A]): Int =
  size.value

case class IceCream(name: String, numCherries: Int, inCone: Boolean)

sizeOf[IceCream]
// res3: Int = 3
```

8.3 Case study: random value generator

Property-based testing libraries like Scalacheck[1] use type classes to generate random data for use in unit tests. For example, Scalacheck has the `Arbitrary` type class that we can use as follows:

```
import org.scalacheck._

for(i <- 1 to 3) println(Arbitrary.arbitrary[Int].sample)
// Some(-1983727495)
// Some(-1)
// Some(0)

for(i <- 1 to 3) println(Arbitrary.arbitrary[(Boolean, Byte)].sample)
// Some((false,127))
// Some((false,-29))
// Some((true,1))
```

[1] https://scalacheck.org/

Scalacheck provides built-in instances of `Arbitrary` for a wide range of standard Scala types. However, creating instances of `Arbitrary` for user ADTs is still a time-consuming manual process. This makes shapeless integration via libraries like scalacheck-shapeless[2] very attractive.

In this section we will create a simple `Random` type class to generate random values of user-defined ADTs. We will show how `Length` and `Nat` form a crucial part of the implementation:

```
trait Random[A] {
  def get: A
}

def random[A](implicit r: Random[A]): A =
  r.get
```

8.3.1 Simple random values

Let's start with some basic instances of `Random`:

```
// Helper method for creating instances:
def createRandom[A](func: () => A): Random[A] =
  new Random[A] {
    def get = func()
  }

// Random numbers from 0 to 9:
implicit val intRandom: Random[Int] =
  createRandom(() => scala.util.Random.nextInt(10))

// Random characters from A to Z:
implicit val charRandom: Random[Char] =
  createRandom(() => ('A'.toInt + scala.util.Random.nextInt(26)).toChar)

// Random booleans:
implicit val booleanRandom: Random[Boolean] =
  createRandom(() => scala.util.Random.nextBoolean)
```

We can use these simple generators via the `random` method as follows:

[2] https://github.com/alexarchambault/scalacheck-shapeless

```scala
for(i <- 1 to 3) println(random[Int])
// 0
// 8
// 9

for(i <- 1 to 3) println(random[Char])
// V
// N
// J
```

8.3.2 Random products

We can create random values for products using the `Generic` and `HList` techniques from Chapter 3:

```scala
import shapeless._

implicit def genericRandom[A, R](
  implicit
  gen: Generic.Aux[A, R],
  random: Lazy[Random[R]]
): Random[A] =
  createRandom(() => gen.from(random.value.get))

implicit val hnilRandom: Random[HNil] =
  createRandom(() => HNil)

implicit def hlistRandom[H, T <: HList](
  implicit
  hRandom: Random[H],
  tRandom: Lazy[Random[T]]
): Random[H :: T] =
  createRandom(() => hRandom.get :: tRandom.value.get)
```

This gets us as far as summoning random instances for case classes:

```scala
case class Cell(col: Char, row: Int)

for(i <- 1 to 5) println(random[Cell])
// Cell(H,1)
```

```
// Cell(D,4)
// Cell(D,7)
// Cell(V,2)
// Cell(R,4)
```

8.3.3 Random coproducts

This is where we start hitting problems. Generating a random instance of a coproduct involves choosing a random subtype. Let's start with a naïve implementation:

```
implicit val cnilRandom: Random[CNil] =
  createRandom(() => throw new Exception("Mass hysteria!"))
// cnilRandom: Random[shapeless.CNil] = $anon$1@38ebbd84

implicit def coproductRandom[H, T <: Coproduct](
  implicit
  hRandom: Random[H],
  tRandom: Lazy[Random[T]]
): Random[H :+: T] =
  createRandom { () =>
    val chooseH = scala.util.Random.nextDouble < 0.5
    if(chooseH) Inl(hRandom.get) else Inr(tRandom.value.get)
  }
// coproductRandom: [H, T <: shapeless.Coproduct](implicit hRandom:
     Random[H], implicit tRandom: shapeless.Lazy[Random[T]])Random[
     shapeless.:+:[H,T]]
```

There problems with this implementation lie in the 50/50 choice in calculating `chooseH`. This creates an uneven probability distribution. For example, consider the following type:

```
sealed trait Light
case object Red extends Light
case object Amber extends Light
case object Green extends Light
```

The `Repr` for `Light` is `Red :+: Amber :+: Green :+: CNil`. An instance of `Random` for this type will choose `Red` 50% of the time and `Amber :+: Green`

`:+: CNil` 50% of the time. A correct distribution would be 33% `Red` and 67% `Amber :+: Green :+: CNil`.

And that's not all. If we look at the overall probability distribution we see something even more alarming:

- `Red` is chosen 50% of the time
- `Amber` is chosen 25% of the time
- `Green` is chosen 12.5% of the time
- `CNil` is chosen 6.75% of the time

Our coproduct instances will throw exceptions 6.75% of the time!

```
for(i <- 1 to 100) random[Light]
// java.lang.Exception: Mass hysteria!
//   ...
```

To fix this problem we have to alter the probability of choosing `H` over `T`. The correct behaviour should be to choose `H` `1/n`th of the time, where `n` is the length of the coproduct. This ensures an even probability distribution across the subtypes of the coproduct and ensures we will never call `cnilProduct.get`. Here's an updated implementation:

```
import shapeless.ops.coproduct
import shapeless.ops.nat.ToInt

implicit def coproductRandom[H, T <: Coproduct, L <: Nat](
  implicit
  hRandom: Random[H],
  tRandom: Lazy[Random[T]],
  tLength: coproduct.Length.Aux[T, L],
  tLengthAsInt: ToInt[L]
): Random[H :+: T] = {
  createRandom { () =>
    val length = 1 + tLengthAsInt()
    val chooseH = scala.util.Random.nextDouble < (1.0 / length)
    if(chooseH) Inl(hRandom.get) else Inr(tRandom.value.get)
```

```
  }
}
```

With these modifications we can generate random values of any product or coproduct:

```
for(i <- 1 to 5) println(random[Light])
// Green
// Red
// Red
// Red
// Green
```

8.4 Other operations involving Nat

Shapeless provides a suite of other operations based on `Nat`. The `apply` methods on `HList` and `Coproduct` and can accept `Nats` as value or type parameters:

```
import shapeless._

val hlist = 123 :: "foo" :: true :: 'x' :: HNil

hlist.apply[Nat._1]
// res1: String = foo

hlist.apply(Nat._3)
// res2: Char = x
```

There are also operations such as `take`, `drop`, `slice`, and `updatedAt`:

```
hlist.take(Nat._3).drop(Nat._1)
// res3: shapeless.::[String,shapeless.::[Boolean,shapeless.HNil]] = foo
      :: true :: HNil

hlist.updatedAt(Nat._1, "bar").updatedAt(Nat._2, "baz")
// res4: shapeless.::[Int,shapeless.::[String,shapeless.::[String,
     shapeless.::[Char,shapeless.HNil]]]] = 123 :: bar :: baz :: x ::
```

```
HNil
```

These operations and their associated type classes are useful for manipulating individual elements within a product or coproduct.

8.5 Summary

In this chapter we discussed how shapeless represents natural numbers and how to calculate the length of an `HList` or `Coproduct`.

Such calculations involve two parts: one at the type level involving the `Length` type classes and the `Nat` type, and one at the value level involving the `ToInt` type class and regular `Ints`.

Chapter 9

TODOs

Still to do:

- Mention SI-7046 in Chapter 3
- Complete the "debugging" section in Chapter 4
- Maybe type class instance selection in Chapter 4
  - Low and high priority
  - `LowPriorityImplicit`
- **DONE** Built-in `HList` and `Coproduct` operations
  - **DONE** Migrating case class as a basic example
- **DONE** Polymorphic functions
  - **DONE** Mapping over `HLists` as an example
- **DONE** Counting with `Nat`
  - **DONE** Generating `Arbitrary` instances as an example
- Callout box on quirkiness of type inference with poly:
  - `val len1: Int = lengthPoly("foo")` fails, but…
  - `val len2      = lengthPoly("foo")` compiles, but…

  - `val len3: Int = lengthPoly[String]("foo")` fails

- Generic applied to tuples
- Built-in record operations
- Performance
  - `cachedImplicit`
  - Maybe `Cached`
  - Maybe
- Check cross references
- Final summary
- **SHIP IT!**