



Haskell Tutorial

A guide to Haskell basics

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Contents

1	Introduction	1
1.1	Language Overview	1
1.2	Installation	1
1.2.1	The Haskell Toolchain	1
1.2.2	Install Command	1
2	Variables	2
2.1	Local Name Binding	2
2.1.1	let	2
2.1.2	where	2
3	Functions	3
3.1	Function Definition	3
3.1.1	Infix Functions	3
3.1.2	Pattern Matching	3
3.2	Function Application	4
3.3	Recursion	4
3.3.1	Defined Base Case	4
3.3.2	If-Else Expression	4
3.3.3	Guards	4
3.3.4	Accumulators	5
3.4	Lambdas	5
3.5	Higher Order Functions	5
3.5.1	Useful Higher Order Functions	5
3.6	Currying	6
3.7	Currying	6
3.8	Uncurrying	6
3.8.1	Partial Function Application	6
3.9	Function Composition	7
4	Types	8
4.1	Variable Types	8
4.1.1	Lists	8
4.2	Function Types	8
4.2.1	Type Variables	8
4.3	Type Aliasing	8
4.4	Type Classes	8
4.4.1	Definition	8
4.4.2	Implementation	8
4.4.3	Common Type Classes	9
4.4.4	Instances	9
4.4.5	Derivation	9
4.5	Defining Datatypes	9
4.5.1	Examples	9
4.6	Records	10
4.6.1	Multiple Constructors	10
5	Useful Types	11
5.1	Maybe	11
5.2	Either	11

6	Collections	12
6.1	Lists	12
6.1.1	Construction	12
6.1.2	Pre-defined functions	12
6.1.3	List Comprehension	13
6.1.4	Ranges	13
6.2	Tuples	13
7	Kinds	14
8	Modules	15
8.1	Importing	15
8.1.1	Qualified Imports	15
8.1.2	Aliased Imports	15
8.1.3	Hiding Imports	15
8.2	Importing Datatypes	15
9	Type Classes	16
9.1	Semigroups	16
9.2	Monoid	16
9.2.1	Multiple Monoids	16
9.2.2	Foldable	16
9.3	Functors	17
9.3.1	Fmap	17
9.4	Applicatives	17
9.5	Monads	18
9.5.1	Bind	18
9.5.2	Then	18
9.5.3	Return	19
9.5.4	Fail	19
9.5.5	“do” Syntax	19
9.5.6	Kleisli-Composition	19
10	I/O	20
10.1	The IO Type	20
10.2	Input	20
10.3	Output	20
10.4	Extracting <value>	20
10.5	Environment	20
10.5.1	Command-Line Arguments	20
10.5.2	Environment Variables	21
10.5.3	Error Handling	21

1 Introduction

Haskell is a purely functional programming language. The following sections will give a brief overview of Haskell, and how to install it.

1.1 Language Overview

In Haskell, everything is a *pure* function - that is, they abide by the Mathematical definition of a function; they map inputs to a unique output.

Data is immutable, meaning that our data types cannot be changed in-place. Combined, this means that there are few or no side-effects from functions, which make programming more simple.

Haskell is declarative, meaning that the program defines what the issue is, rather than simply giving an algorithm to solve a problem.

Functional programs are easier to verify as we can use maths to verify an algorithm.

1.2 Installation

Link: <https://www.haskell.org/ghcup/>

I used GHCup to install several components of the Haskell toolchain.

1.2.1 The Haskell Toolchain

The Haskell Toolchain consists of several useful tools for Haskell compilation and development:

- **GHC** - the Glasgow Haskell Compiler;
- **cabal-install** - Cabal installation tool for managing Haskell software;
- **Stack** - a cross-platform program for developing Haskell projects;
 - **Msys2** - provides a UNIX shell and environment which is necessary for executing configuration scripts.
- **haskell-language-server** - a language server which may be integrated into an IDE;

1.2.2 Install Command

The command to use on Windows (in a normal Powershell instance) is

```
1 Set-ExecutionPolicy Bypass -Scope Process -Force; [System.Net.ServicePointManager
  ]::SecurityProtocol = [System.Net.ServicePointManager]::SecurityProtocol -bor
  3072; try { Invoke-Command -ScriptBlock ([ScriptBlock]::Create((
  Invoke-WebRequest https://www.haskell.org/ghcup/sh/bootstrap-haskell.ps1 -
  UseBasicParsing))) -ArgumentList $true } catch { Write-Error $_ }
```

2 Variables

Variables are name-bounded values. Variables in Haskell are immutable - they cannot be changed.

```
name = <value>
```

Variable types are *inferred*. To explicitly assign variables a type,

```
name :: Type
```

In GHCi, the type of a symbol may be retrieved by `:t name`.

2.1 Local Name Binding

Two methods are provided to bind a symbol to a value in a local scope: `let` and `where`. Each follow a “main” expression.

2.1.1 `let`

Syntax:

```
1  let
2    <symbol> = <expr>
3    <symbol2> = <expr2>
4    ...
5  in
6    <main_expr>
```

For example, re-define `in_range` as follows:

```
1  in_range x min max =
2    let
3      in_lb = min <= x
4      in_ub = max > x
5    in
6      in_lb && in_ub
```

2.1.2 `where`

Syntax:

```
1  <main_expr>
2  where
3    <symbol> = <expr>
4    <symbol2> = <expr2>
5    ...
```

For example, re-define `in_range` as follows:

```
1  in_range x min max = in_lb && in_ub
2  where
3    in_lb = min <= x
4    in_ub = max > x
```

3 Functions

Functions are defined to map a value from an input set - the *domain* - into an output set - the *co-domain*. Every output of the function is contained in a subset of the co-domain, called the *range*. **Pure** mathematical functions must be able to map every value from the domain, and each input value must map to only one output value.

In Haskell, occurrences of functions are expanded into their RHS.

3.1 Function Definition

Functions are defined by providing its name, a list of arguments, and setting it equal to an expression.

```
name arg1 arg2 ...argn = <expr>
```

The arguments may be set to constants, or may be given a name to accept a variable value.

The type of a function is specified by an arrow (\rightarrow) separated list of its argument types and its return type:

```
func :: type1 -> type2 -> ...-> typen -> typereturn
```

For an example, take a function which returns the sum of the elements of an array:

```
1 sum :: [a] -> Int -- Takes an array of arbitrary type and returns an integer
2 sum [] = 0 -- Define the sum of an empty array to be zero
3 sum (h:t) = h + sum t -- Define the sum of an array to be the head plus the sum
   of the tail
```

3.1.1 Infix Functions

A good example of infix functions are operators such as $+$. Functions which take two arguments may be written between the arguments instead.

For example, say we had `add a b = a + b`. Then `add 5 7` and `5 `add` 7` are equivalent.

To reference the function defined by an operator i.e. $+$, surround it with parenthesis i.e. $(+)$.

The associativity and precedence of infix operators may be changed via `infixr/infixl <prec>` `<function name>` where $0 < \text{prec} \leq 9$.

3.1.2 Pattern Matching

Parameters of functions may be matched against a pattern. Note that order matters: more specific patterns should be defined first, with general cases last.

- Accept any value by using a symbol e.g. `f x = ...`.
- Accept a certain value e.g. `f 0 = ...`, `g [] = ...`.
- List splicing using `(x:xs)` where `x` is the head, `xs` is the tail.
- Tuple unpacking e.g. `(Int, Int)` could be unpacked using `(x, y)`.
- Accept and extract a custom types. E.g., say we had `type Pos = (Int, Int)`, we would define `getX (x, y) = x`.
- Accept and extract a custom datatype. E.g., say we had `data Num = Zero | Succ Num`. We could then define `f Zero = ...` and `f (Succ n) = ...`.

Pattern matching may also be done using `case ... of ...` construct.

3.2 Function Application

A function is applied (called) to some arguments as follows:

```
name arg1 arg2 ...argn
```

For example, consider the function `in_range` `x min max = x >= min && x < max`, an implementation of $x \in [min, max)$.

Then, `in_range 3 0 5` would evaluate to `True`, but `in_range 5 0 5` would evaluate to `False`.

3.3 Recursion

Recursion is the process of a function calling itself. Recursion requires a *base case* to stop the function recursing indefinitely.

There are many ways to implement recursion, which will be demonstrated using the *factorial*, defined as

$$n! = n \cdot (n-1) \cdot \dots \cdot 1 = \prod_{k=1}^n k$$

3.3.1 Defined Base Case

We can hard-code the case where the function is called with the base case:

```
1 fac 1 = 1
2 fac n = n * fib (n-1)
```

3.3.2 If-Else Expression

We can use the if-else expression:

```
if <expr> then <ifTrue> else <ifFalse>
```

For example,

```
1 fac n = if n <= 1 then 1 else n * fac (n-1)
```

3.3.3 Guards

Guards are similar to piece-wise functions.

```
1 <main_expr>
2 | <expr> = <value>
3 | <expr2> = <value2>
4 ...
5 | otherwise = <default_value>
```

Where `<expr>` is a boolean expression. If `<expr>` matches, then `<value>` will be returned. If none is matched, the `otherwise` is returned.

For example,

```
1 fac n =
2 | n <= 1    = 1
3 | otherwise = n * fac (n-1)
```

3.3.4 Accumulators

In this example, we define an auxiliary function `aux` inside `fac` to calculate the factorial

```
1  fac n = aux n 1
2      where
3          aux n acc
4              | n <= 1      = acc
5              | otherwise = aux (n-1) (n*acc)
```

This is called *tail recursion*. This is because the final result of `aux` is the result we want, meaning that it is much more memory efficient. A good compiler could even unwind this into a non-recursive imperative approach using a loop. (For more insight, see https://www.youtube.com/watch?v=_JtPhF8MshA.)

Normal recursion (using an above definition of `fac`):

```
fac 4
= 4 * fac 3
= 4 * (3 * fac 2)
= 4 * (3 * (2 * fac 1))
= 4 * (3 * (2 * 1))
= 4 * (3 * 2)
= 4 * 6
= 24
```

Tail recursion (using the definition in this sub-section):

```
fac 4
= aux 3 4
= aux 2 12
= aux 1 24
= 24
```

3.4 Lambdas

Syntax:

$$(\backslash \langle \text{args} \rangle \rightarrow \langle \text{expr} \rangle)$$

Some examples:

- $(\backslash x \rightarrow x+1) \ 2$ returns 3.
- $(\backslash x \ y \ z \rightarrow x+y+z) \ 1 \ 2 \ 3$ returns 6.

Lambdas may be bound to names.

3.5 Higher Order Functions

Higher order functions are functions that take other functions as arguments.

For example, a function which takes another function and applies it to an argument:

```
1  app :: (a -> b) -> a -> b
2  app f x = f x
```

A synonym of such a function is the dollar (\$) operator: $(\$) :: (a \rightarrow b) \rightarrow a \rightarrow b$.

3.5.1 Useful Higher Order Functions

- `map :: (a -> b) -> [a] -> [b]` applies a function to every element on an array.

$$L' = \{f(x) : x \in L\}$$

Example: `map (\x -> x^2) [1,2,3]` returns `[1,4,9]`.

- `filter :: (a -> Bool) -> [a] -> [a]` filters the list on a predicate.

$$L' = \{x \in L : P(x)\}$$

Example: `filter (\x -> mod x 2 == 0) [1,2,3,4,5]` returns `[2,4]`.

- `fold :: (a -> b -> b) -> b -> [a] -> b` processes a list with some function to produce a single value, starting at a given value.

In Haskell, `fold` doesn't exist, but rather `foldr` and `foldl` wherein the position of the base value is different

```
1 foldr f a [] = a
2 foldr f a (x:xs) = f x (foldr f a xs)
3 -- foldr f a [x1, x2, ..., xn] = (x1 `f` (x2 `f` (... (xn `f` a))))
4
5 foldl f a = []
6 foldl f a (x:xs) = f (foldl f a xs) x
7 -- foldl f a [x1, x2, ..., xn] = (...((a `f` x1) `f` x2) `f` xn)
8
```

See code/folding.hs

Example: `foldr (+) 0 [1,2,3,4,5]` returns 15.

3.6 Currying

The principle behind currying is that given

$$f :: a \rightarrow b \rightarrow c \rightarrow d$$

We could re-write this as

$$f' :: a \rightarrow (b \rightarrow (c \rightarrow d))$$

For example, one could define a function `add` in multiple ways:

```
1 add x y = x + y
2 add x = (\y -> x + y)
3 add = (\x -> (\y -> x + y))
```

3.7 Currying

```
1 curry :: (a,b -> c) -> a -> b -> c)
2 curry f x y = f (x,y)
```

3.8 Uncurrying

```
1 uncurry :: (a -> b -> c) -> (a,b) -> c
2 uncurry f (x,y) = f x y
```

3.8.1 Partial Function Application

Using the last definition of `add`, consider the result of `add 1`. This would be a new function; `add 1 :: Int -> Int`. This is known as a *section*.

A good example would be using `map`.

$$\text{doubleList} = \text{map } (\lambda x \rightarrow x * 2)$$

3.9 Function Composition

Function composition is a way to combine functions. For this, we use the dot `(.)` operator.

$$(\cdot) \quad :: \quad (b \rightarrow c) \rightarrow (a \rightarrow b) \rightarrow (a \rightarrow c)$$

Then, `(f.g)` is equivalent to `(\x -> f (g x))`.

For example, all three definitions of `descSort` are equivalent:

```
1 descSort = reverse . sort
2 descSort = (\x -> reverse (sort x))
3 descSort = reverse (sort x)
```

4 Types

Every expression in Haskell has a type. Types are inferred, even when given explicitly.

Types always begin with an UPPERCASE letter.

The cardinality of a type is how many *states* the data type could hold. Polymorphic types have no cardinality.

4.1 Variable Types

```
var :: type
```

4.1.1 Lists

To define a list of a `type`, one would write `[type]`. This may be nested.

4.2 Function Types

```
func :: type1 -> ... -> typeN -> ret_type
```

Where the function `func` takes n arguments of types `type1`, ..., `typeN` and returns `ret_type`.

4.2.1 Type Variables

Type variables may be used where any type would be permissible and must be lowercase. For example,

```
id :: a -> a
id x = x
```

This is called “parametric polymorphism”.

4.3 Type Aliasing

This doesn’t define a new datatype, but rather an alias for another type.

```
type Pos = type
```

A common example is using a tuple e.g. `type Pos = (Int, Int)`. The type name need not be stated in pattern matching.

4.4 Type Classes

Type classes may be used to restrict the types a polymorphic function may take. This is useful if we would like to use features in a polymorphic function that may only be available to certain types. For a type to be a member of a type class, it must implement all of the required methods.

To impose a constraint on variable `a` in a function `f`: `f :: (<TypeClass> a, ...) =>`
This is called “ad-hoc polymorphism”.

4.4.1 Definition

A type class definition begins with

```
class <Name> <var> where
```

Below is a list of function declarations. For a type to be a member of `<Name>`, it must implement all of these functions.

4.4.2 Implementation

To define a new type which belongs to a type class: `instance <TypeClass> <TypeName> where`
Where below this is a list of function definitions.

4.4.3 Common Type Classes

Common type classes include:

- **Eq** – types which may be compared i.e. `(==)` is defined;
- **Num** – numeric types, gives us access to standard mathematical operations i.e. `(+)`, `(-)`, `(*)`, `abs`, ... are defined;
- **Ord** – types which may be ordered, imposes a total ordering i.e. `(<)`, `(>)`, `(<=)` are defined;
- **Read** – types which may be converted from a string i.e. `read` is defined;
- **Show** – types which may be converted to a string i.e. `show` is defined;
- **Integral** – types which are integer-like i.e. `div`, ... is defined;
- **Floating** – types which are float-like i.e. `(/)`, ... is defined;
- **Enum** – types which may be enumerated i.e. `succ`, `pred`, ... are defined;

N.B. for information on complex type classes, see Type Class section

4.4.4 Instances

Instances allow us to write functions which make use of type classes. Syntax:

instance (<constraints>) => <typeClass> <value> **where** followed by a list of function definitions.

4.4.5 Derivation

The **deriving** keyword can be used to automatically generate implementations for the given type class(es).

Syntax: **data** <Name> = ...**deriving** (<Class1>, ...)

Example: **data** Shape = Circle Int | Rect Int Int **deriving** Show. Then, **print** (Circle 5) → Circle 5.

4.5 Defining Datatypes

The **data** keyword is used to define a new datatype; unlike the above, these are entirely custom. This may be done using the data keyword:

```
data Name = Constructor1 [<args>] | ...
```

where <args> are the *types* of each argument, not literals.

Constructors are either plain values, or functions which take args and return the datatype.

Data constructors can include polymorphism by including type variables after <Name> e.g. **data** Maybe a = Nothing | Just a.

4.5.1 Examples

- `rock-paper-scissors.hs` – A basic example revolving around Rock-Paper-Scissors;
- `expr.hs` – A program to build and evaluate expressions;
- `tree.hs` – A representation of a tree structure;
- `nat-num.hs` – A definition of natural numbers using the successor function;

4.6 Records

Records allow data to be stored with an associated name.

Syntax:

```
data <Name> = <Name> { <field> :: <type>, ... }
```

This will automatically generate functions `<field> :: <Name> -> <type>` to extract said properties. This has the side-effect that field names must be globally unique.

4.6.1 Multiple Constructors

Note that records may also have multiple constructors,

```
data Point = D2 { x :: Int, y :: Int } | D3 { x :: Int, y :: Int, z :: Int }
```

Duplicate field names in this context is OK.

This will generate functions `x`, `y` and `z` all with the signature `x/y/z :: Point -> Int`. Both `x` and `y` will work on either `D2` or `D3`, but applying `z` to `D2` will throw an exception.

For an example, see `code/vector.hs`.

5 Useful Types

This section will list some common, useful types which should be known.

5.1 Maybe

The `Maybe` type is incredibly useful, as it can be used to represent the *absence* of a value. This is useful when our function is passed invalid data, for example.

If it defined as: `data Maybe a = Nothing | Just a`

Functions Found inside `Data.Maybe`.

- `isJust :: Maybe a -> Bool` – returns if the passed `Maybe` is a `Just` value;
- `fromMaybe :: a -> Maybe a -> a` – returns the `Just` value if a value is present, else returns the default value;
- `fromJust :: Maybe a -> a` – returns the `Just` value, or throws an exception if recieved `Nothing`;
- `catMaybes :: [Maybe a] -> [a]` – returns a list containing all the `Just` values.
- `mapMaybe :: (a -> Maybe b) -> [a] -> [b]` – maps a function over a list of `Maybes`, discarding any `Nothings`;
- `maybe :: b -> (a -> b) -> Maybe a -> b` – takes a `maybe`. If `Just`, applies a function and returns. Else, returns a default;

5.2 Either

The `Either` type can be used to represent a union of types – a value which is either one type, or another. It is defined as `data Either a b = Left a | Right b`

Functions Found inside `Data.Either`.

- `lefts :: [Either a b] -> [a]` – returns an array of left-hand side values;
- `rights :: [Either a b] -> [b]` – returns an array of right-hand side values;
- `isLeft :: Either a b -> Bool` – returns whether the provided value is a left-hand side value;
- `isRight :: Either a b -> Bool` – returns whether the provided value is a right-hand side value;
- `fromLeft :: a -> Either a b -> a` – returns the left-hand side value if a `Left` is provided, else returns a default;
- `fromRight :: n -> Either a b -> n` – returns the right-hand side value if a `Right` is provided, else returns a default;
- `either :: (a -> c) -> (b -> c) -> Either a b -> c` – processes the left- or right-hand value in the `Either` as per the given functions;
- `partitionEithers :: [Either a b] -> ([a], [b])` – traverses the list, placing and `Left` values in one list and any `Right` values in another;

Use – Error Handling `Either` can be used in place of `Maybe` for error handling. `Left` can represent a correct input/output with `Right` holding the incorrect value.

6 Collections

Haskell has two collections: lists, and tuples.

6.1 Lists

A *mutable* collection of elements of the *same type*. Every elements has an ordinal.

A list of type `type` has the given type signature

```
name :: [type]
```

6.1.1 Construction

A list may be created by the following constructor:

- Using square brackets: $[x_1, x_2, \dots, x_n]$
- Using the prepend operator: $x_1 : x_2 : \dots : x_n : []$. With the syntax of `x:list`, it prepends `x` to the list `list`.

6.1.2 Pre-defined functions

Many pre-defined functions for lists are defined in the `Data.List` module.

General Functions These functions work on a list of any type, namely `[a]`.

- `head <list>`. This function returns the head (x_1) of the list. Example: `head [1,2,3]` returns `1`.
- `tail <list>`. This function returns the tail of the list. Example: `tail [1,2,3]` returns `[2,3]`.
- `length <list>`. This function returns the length of the list. Example: `length [1,2,3]` returns `3`.
- `init <list>`. This function returns the list without the last element. Example: `init [1,2,3]` returns `[1,2]`.
- `null <list>`. This function returns whether the list is empty. Example: `null [1,2,3]` returns `False`.
- `take <n> <list>`. This function returns a list of the first n elements of the list. Example: `take 2 [1,2,3,4,5]` returns `[1,2]`.
- `drop <n> <list>`. This function returns a list excluding the first n elements of the list. Example: `drop 2 [1,2,3,4,5]` returns `[3,4,5]`.
- `<list1> ++ <list2>`. This function “append” returns a concatenation of both lists. Example: `[1,2] ++ [3,4]` returns `[1,2,3,4]`.

Boolean Functions These functions are of the type `fn :: [Bool] -> Bool`

- `and <list>`. This functions returns `True` if every elements in `<list>` is `True`.
- `or <list>`. This functions returns `True` if at least one element in `<list>` is `True`.

6.1.3 List Comprehension

List comprehension can be used to transform one or more lists according to a predicate. Syntax:

```
[ <gen> | <elem> <- <list>, ..., <guard>, ...]
```

Where

- `<elem> <- <list>` is called a *generator* – it binds each value from `<list>` to `<elem>` in turn so that they may be used. There may be multiple generators, in which case they will be worked through left-to-right.
- `<guard>` is a statement which returns a `Bool`. If false, the current bound value(s) will not be output.

Examples:

- `[2*x | x <- [1,2,3]]` generates `[2,4,6]`
- `[x^2 | x <- [1,2,3], x > 1]` generates `[4,9]`
- `[(x,y) | x <- [1,2,3], y <- ['a','b']]` generates
`[(1,'a'), (1,'b'), (2,'a'), (2,'b'), (3,'a'), (3,'b')]`

6.1.4 Ranges

Generate ranges (arithmetic sequences) in Haskell using the ellipse ..:

```
[<start>, [<step>] .. [<end>]]
```

Where

- `step` is optional, and default to 1 e.g. `[1..5] = [1,2,3,4,5]`, `[1,3..5] = [1,3,5]`
- `<end>` may be omitted to generate an infinite list e.g. `[1 ..] = [1,2,3,...]`.

6.2 Tuples

An *immutable* collection of elements of *different types*.

A tuple has the signature

```
(x,y,...) :: (typex, typey, ...)
```

7 Kinds

The types of *types* and *type constructors* are called *kinds*.

A kind signature is denoted by `:: ..`. The number of *kinds* correspond to the number of type parameters a type constructor takes.

- Types which take no type parameters are of kind `*` (“*type*”).
 - `Bool :: *`
 - `String :: *`
 - `Maybe :: * -> *`
- When we apply a type parameter, one of the parameters is consumed in the kind
 - `Maybe Int :: *`

8 Modules

In Haskell, each file is a module. Hence, each file (other than the entry file) must begin with a module declaration:

```
module filename [(n1, n2, ...)] where
```

By default, every symbol is exported. If `(n1, n2, ...)` is included, only symbols `n1`, `n2` etc. are exported.

8.1 Importing

To import a module, use an import statement:

```
import module [(n1, n2, ...)]
```

By default, every symbol exported by module is imported. If `(n1, n2, ...)` is included, only symbols `n1`, `n2` etc. are imported.

To import `Animals.hs` one would write `import Animals`. To import `Farm/Tractor.hs` one would write `import Farm.Tractor`.

Once imported, symbols may be used freely. For example, if the function `double` is imported, to reference it we would write `double`. However, if two different definitions for `double` are imported, we must use its full name e.g. `Module.double`.

8.1.1 Qualified Imports

Syntax:

```
import qualified module [(...)]
```

This forces the module name to precede any symbols imported. In the example above, `Module.double` **must** be used.

8.1.2 Aliased Imports

Syntax:

```
import module [(...)] as alias
```

Using the above example, now, instead of writing `Module.double` one would now write `Alias.double`.

8.1.3 Hiding Imports

The `hiding` keyword can be used to omit imports. E.g. `import Prelude hiding (map)` would import every function from `Prelude` but omit `map`.

8.2 Importing Datatypes

Let's say `data DataType = A | B | C` is defined inside module `Module`.

- To import every constructor, we'd write `import Module (DataType (...))`
- To import only constructor `A`, we'd write `import Module (DataType(A))`
- To import constructors `A` and `B`, we'd write `import Module (DataType(A,B))`

9 Type Classes

This section covers more complex type classes. For basics, see `Types -> Type Classes`.

9.1 Semigroups

A type is a Semigroup if there exists some function which, when two values from the group are combined, that value is also in the Semigroup.

```
1 class Semigroup a where
2   (<>) :: a -> a -> a
3
4 infixr 6 <>
```

This diamond operator must be **associative**:

```
1 x <> (y <> z) == (x <> y) <> z
```

9.2 Monoid

A Monoid is an extension of a Semigroup, adding an identity element.

```
1 class Semigroup a => Monoid a where
2   mempty :: a
3
4   -- Optional functions
5   mappend :: a -> a -> a
6   mappend = (<>)
7
8   mconcat :: [a] -> a
9   mconcat = foldr mappend mempty
```

mempty must be an identity element for the Semigroup. Therefore, it must obey:

```
1 x <> mempty == x
2 mempty <> x == x
```

9.2.1 Multiple Monoids

A type may have multiple Monoid implementations (i.e. multiple viable operators exist which satisfy Monoidal conditions).

For example, take numerical types:

```
1 newtype Sum n = Sum { getSum :: n }
2 instance Num a => Semigroup (Sum a) where
3   (<>) = (+)
4 instance Num a => Monoid (Sum a) where
5   mempty = 0
6
7
8 newtype Product n = Product { getProduct :: n }
9 instance Num a => Semigroup (Product a) where
10  (<>) = (*)
11 instance Num a => Monoid (Product a) where
12  mempty = 1
```

9.2.2 Foldable

A Foldable datatype is one which may be reduced to a single value i.e. folded in on itself.

```
1 class Foldable t where
2   foldr :: (a -> b -> b) -> b -> t a -> b
```

9.3 Functors

A Functor is a type class which may have an operation mapped over it.

```
1 class Functor f where
2   fmap :: (a -> b) -> f a -> f b -- Infix symbol is <$>
3
4   -- The following functions are optional
5   (<$) :: a -> f b -> f a
6   (<$) = fmap . const
```

A Functor instance must obey the following laws:

- The mapping must preserve the structure of the arguments.
- **Identity:**

```
1 fmap id == id
```

- **Distributive over Composition:**

```
1 fmap (f . g) == fmap f . fmap g
```

9.3.1 Fmap

fmap allows a function to be mapped over a structure without the internal structure of the Functor changing.

Example:

```
1 data Tree a = Leaf a | Node (Tree a) a (Tree a)
2
3 instance Functor Tree where
4   fmap f (Leaf a) = Leaf (f a)
5   fmap f (Node a b c) = Node (fmap f a) (f b) (fmap f c)
```

9.4 Applicatives

Applicatives are Functors with more and better functionality, with <*> essentially *injecting* a value into a wrapped function, and pure allowing easy construction of an applicative.

```
1 class Functor f => Applicative f where
2   pure :: a -> f a
3   (<*>) :: f (a -> b) -> f a -> f b
4
5   -- Optional functions
6   (<*>) :: f a -> f b -> f b
7   a *> b = b
8   (<*) :: f a -> f b -> f a
9   a <* b = a
```

An Applicative must obey the following laws:

- **Identity:**

```
1 pure id <*> v == v
```

- **Homomorphism:**

```
1 pure f <*> pure x == pure (f x)
```

- **Interchange:**

```
1 u * pure y == pure (\$ y) <*> u
```

- **Composition:**

```
1 pure (.) <*> u <*> v <*> w == u <*> (v <*> w)
```

9.5 Monads

A Monad allows the transformation of a value into a Monad via a function.

```
1 class Applicative m => Monad m where
2   (>>=) :: m a -> (a -> m b) -> m b -- "Bind"
3
4   -- Optional functions
5   (>>) :: m a -> m b -> m b -- "Then"
6   a >> b = a >>= \x -> b
7
8   return :: a -> m a
9   return = pure
```

Any implementation must abide by these laws:

- **Left identity:**

```
1 return a >= h == h a
```

- **Right identity:**

```
1 m >= return == m
```

- **Associativity:**

```
1 (m >>= g) >>= h == m >>= (\x -> g x >>= h)
```

9.5.1 Bind

```
(>>=) :: Monad m => m a -> (a -> m b) -> m b
```

This function takes a monad and a function which takes a raw value and returns a new monad, and returns another new monad.

When implemented, then, we may vary the action taken depending on the value of the provided monad, such as returning a default value – this is what `(>>=)` does with `Maybe`, as shown below:

Example:

```
1 add :: Num a => Maybe a -> Maybe a -> Maybe a
2 add mx my = mx >>= (\x -> my >>= (\y -> Just (x + y)))
3
4 -- Then addition works as expected
5 add (Just 1) (Just 2) -- => Just 3
6 -- And if either one of the arguments is Nothing, it returns Nothing
7 add Nothing (Just ?) -- => Nothing
```

9.5.2 Then

```
(>>) :: Monad m => m a -> m b -> m a
```

This function discards the second monad given to it. `m >> n` is equivalent to `m >>= _ -> n`. “Then” can be thought of wanting to carry out an action but not caring what the result is.

9.5.3 Return

```
return :: Monad m => a -> m a
```

Return wraps a monad around a raw value.

Using the example from the Bind section, we could substitute the explicit `Just` with the more general `return`. Now, this would theoretically work with any appropriately-defined monad.

```
1 add mx my = mx >>= (\x -> my >>= (\y -> return (x + y)))
```

9.5.4 Fail

```
fail :: Monad m => String -> m a
```

Fail is intended to be called when something goes wrong. The default implementation is to call `error` (i.e. error out of the program), but it may be implemented so that certain errors may be handled and return an appropriate monad as a response.

9.5.5 “do” Syntax

Chaining together applications of `(>>=)`, `(>>)` and lambda functions can get tedious; that’s where the syntactic sugar “do” expression comes in.

The “statements” inside of `do` are executed in order, and if one “statement” fails this will be propagated through.

- Bind

```
1 m >>= \x -> ...
2 -- Becomes
3 do
4     x <- m
5     ...
6
```

- Then

```
1 m >> ...
2 -- Becomes
3 do
4     m
5     ...
6
```

Example:

```
1 -- Re-writing the above definition of 'add'
2 add mx my = do
3     x <- mx
4     y <- my
5     return $ x + y
```

9.5.6 Kleisli-Composition

This operator, denoted `>=>`, acts as a Monad composition operator. It is defined in `Control.Monad` as so

```
1 infixr 1 >=>
2 (>=>) :: Monad m => (a -> m b) -> (b -> m c) -> a -> m c
3 f >=> g = \x -> f x >>= g
```

10 I/O

I/O produces an issue with Haskell as I/O functions aren't *pure*.

10.1 The IO Type

All I/O functions in Haskell have the following type: `IO <value>`.

This special type holds a given I/O action. When the `IO` value is used, the stored action will be carried out, and `IO <value>` is returned.

For example, in GHCi

```
> hi = putStrLn "Hello, World!"
```

```
> hw
```

```
Hello, World!
```

Notice how nothing was outputted until the `IO` value was used. Note that `hw` may be used multiple times.

10.2 Input

- `getLine :: IO String` – retrieves a line of input from STDIN;
- `readLn :: Read a => IO a` – retrieves a line of input from STDIN, reading it as specified by `a`;

10.3 Output

- `putStr :: String -> IO ()` – puts the given string to STDOUT;
- `putStrLn :: String -> IO ()` – puts the given string to STDOUT on a new line;
- `print :: Show a => a -> IO ()` – essentially the same as `putStrLn . show`;

10.4 Extracting <value>

`IO` is a *monad*, and should be extracted as such.

```
1 greet :: IO ()
2 greet = do
3   putStrLn "What is your name?"
4   name <- getLine
5   putStrLn $ "Hello, " ++ name ++ "!"
```

You can only extract values from `IO` inside of another `IO` action.

For a more complex example, see `code/IO.hs`.

10.5 Environment

The following functions are defined in `System.Environment`.

10.5.1 Command-Line Arguments

Command-line arguments are arguments passed to the executable e.g. `./prog.exe arg1 arg2 ...`

These can be accessed via `getArgs :: IO [String]`

Note, the program name “`prog.exe`” is omitted; this can be accessed via `getProgName :: IO String`

10.5.2 Environment Variables

The function `getEnvironment :: IO [(String, String)]` gets a list of all environment variables in name-value pairs.

To get only one variable, the function `lookupEnv :: String -> IO (Maybe String)` returns the value of an environment variable.

The function `withArgs :: [String] -> IO a -> IO a` loads sets the environment variables inside an IO action.

10.5.3 Error Handling

Defined in `System.Exit`

- `exitWith :: ExitCode -> IO a` exits the program with the provided exit code (`ExitCode = ExitSuccess | ExitFailure Int`);
- `exitSuccess :: IO a` exits the program with exit code of success;
- `exitFailure :: IO a` exits the program with exit code of failure (1);
- `die :: String -> IO a` prints the given message, then exits the program with exit code of failure (1);