User-Defined Types

Stephen A. Edwards

Columbia University

Fall 2020
Algebraic Data Types
  Show and other derived type classes
  Records: Naming Fields

Parameterized Types: Maybe

The type keyword

The Either Type

Lists as an Algebraic Data Type
  Defining Your Own Infix Operators

Specifying and Implementing Type Classes

The Functor Type Class
Algebraic Data Types

```
data Bool = False | True
```

**Bool: Type Constructor**  **False and True: Data Constructors**

```
Prelude> data MyBool = MyFalse | MyTrue
Prelude> :t MyFalse
MyFalse :: MyBool  -- A literal
Prelude> :t MyTrue
MyTrue :: MyBool
Prelude> :t MyBool
<interactive>:1:1: error: Data constructor not in scope: MyBool
```

```
Prelude> :k MyBool
MyBool :: *  -- A concrete type (no parameters)
```
**Algebraic Types and Pattern Matching**

```haskell
data Bool = False | True
```

Type constructors may appear in type signatures; data constructors in expressions and patterns

```haskell
Prelude> :{
Prelude|   myAnd :: Bool -> Bool -> Bool
Prelude|   myAnd False _ = False
Prelude|   myAnd True  x = x
Prelude| }:

Prelude> [(a,b,myAnd a b) | a <- [False, True], b <- [False, True] ]
[(False,False,False),(False,True,False),
  (True,False,False),(True,True,True)]
```
An Algebraic Type: A Sum of Products

data Shape = Circle Float Float Float Float
| Rectangle Float Float Float Float Float

Sum = one of A or B or C...
Product = each of D and E and F...
A.k.a. tagged unions, sum-product types

Mathematically,

Shape = Circle ∪ Rectangle

Circle = Float × Float × Float

Rectangle = Float × Float × Float × Float
An Algebraic Type: A Sum of Products

data Shape = Circle Float Float Float
             | Rectangle Float Float Float Float

area :: Shape -> Float
area (Circle _ _ r) = pi * r ^ 2
area (Rectangle x1 y1 x2 y2) = (abs $ x2 - x1) * (abs $ y2 - y1)

*Main> :t Circle
Circle :: Float -> Float -> Float -> Shape

*Main> :t Rectangle
Rectangle :: Float -> Float -> Float -> Float -> Shape

*Main> :k Shape
Shape :: *

*Main> area $ Circle 10 20 10
314.15927
*Main> area $ Rectangle 10 10 20 30
200.0
Printing User-Defined Types: Deriving Show

*Main> Circle 10 20 30

<interactive>:9:1: error:
  * No instance for (Show Shape) arising from a use of 'print'
  * In a stmt of an interactive GHCi command: print it

Add deriving (Show) to make the compiler generate a default show:

data Shape = Circle Float Float Float Float
  | Rectangle Float Float Float Float
deriving Show

*Main> Circle 10 20 30
Circle 10.0 20.0 30.0
*Main> show $ Circle 10 20 30
"Circle 10.0 20.0 30.0"
Every Possible Automatic Derivation

data Bool = False | True  -- Standard Prelude definition
deriving (Eq, Ord, Enum, Read, Show, Bounded)

Prelude> True == True
True  -- Eq
Prelude> False < False
False  -- Ord
Prelude> succ False
True  -- Enum
Prelude> succ True
Prelude> read "True" :: Bool
True  -- Read
Prelude> show False
"False"  -- Show
Prelude> minBound :: Bool
False  -- Bounded
Types as Documentation

When in doubt, add another type

data Point = Point Float Float deriving Show
data Shape = Circle Point Float
  | Rectangle Point Point
deriving Show

area :: Shape -> Float
area (Circle _ r) = pi * r ^ 2
area (Rectangle (Point x1 y1) (Point x2 y2)) =
  (abs $ x2 - x1) * (abs $ y2 - y1)

*Main> area $ Rectangle (Point 10 20) (Point 30 40)
400.0
*Main> area $ Circle (Point 0 0) 100
31415.928
moveTo :: Point -> Shape -> Shape
moveTo p (Circle _ r) = Circle p r
moveTo p@(Point x0 y0) (Rectangle (Point x1 y1) (Point x2 y2)) = Rectangle p $ Point (x0 + x2 - x1) (y0 + y2 - y1)

origin :: Point
origin = Point 0 0

originCircle :: Float -> Shape
originCircle = Circle origin -- function in "point-free style"

originRect :: Float -> Float -> Shape
originRect x y = Rectangle origin (Point x y)

Prelude> :l Shapes
[1 of 1] Compiling Shapes             ( Shapes.hs, interpreted )
Ok, one module loaded.
*Shapes> moveTo (Point 10 20) $ originCircle 5
Circle (Point 10.0 20.0) 5.0
*Shapes> moveTo (Point 10 20) $ Rectangle (Point 5 15) (Point 25 35)
Rectangle (Point 10.0 20.0) (Point 30.0 40.0)
module Shapes
(
    Point(..)  -- Export the Point constructor
,  Shape(..)  -- Export Circle and Rectangle constructors
,  area
,  moveTo
,  origin
,  originCircle
,  originRect
) where

data Point = Point Float Float deriving Show
-- etc.
Records: Naming Product Type Fields

```haskell
data Person = Person { firstName :: String,
                       lastName :: String,
                       age :: Int,
                       height :: Float,
                       phoneNumber :: String,
                       flavor :: String
               } deriving Show

hbc = Person { lastName = "Curry",
               firstName = "Haskell",
               age = 42,
               height = 6.0,
               phoneNumber = "555-1212",
               flavor = "Curry" }
```

```
*Main> :t lastName
lastName :: Person -> String
*Main> lastName hbc
"Curry"
```
Updating and Pattern-Matching Records

*Main> hbc
Person {firstName = "Haskell", lastName = "Curry", age = 42,
       height = 6.0, phoneNumber = "555-1212", flavor = "Curry"}

*Main> hbc { age = 43, flavor = "Vanilla" }
Person {firstName = "Haskell", lastName = "Curry", age = 43,
       height = 6.0, phoneNumber = "555-1212", flavor = "Vanilla"}

*Main> sae = Person "Stephen" "Edwards" 49 6.0 "555-1234" "Durian"

fullName :: Person -> String
fullName (Person { firstName = f, lastName = l }) = f ++ " " ++ l

*Main> map fullName [hbc, sae]
["Haskell Curry","Stephen Edwards"]
Record Named Field Puns In Patterns

:set -XNamedFieldPuns in GHCi or put a pragma at the beginning of the file

{-# LANGUAGE NamedFieldPuns #-}

favorite :: Person -> String
favorite (Person { firstName, flavor } ) =
    firstName ++ " loves " ++ flavor

*Main> favorite hbc
"Haskell loves Curry"

Omitting a field when constructing a record is a compile-time error unless you
:set -Wno-missing-fields, which allows uninitialized fields. Evaluating an
uninitialized field throws an exception.
Record Wildcards

:set -XRecordWildCards in GHCi or add a pragma:

{--# LANGUAGE RecordWildCards #-}

favorite :: Person -> String
favorite Person {..} = firstName ++ " loves " ++ flavor
−− like Person {firstName = firstName, lastName = lastName, .. }
sae = let lastName = "Edwards"
    firstName = "Stephen"
    age = 50
    height = 6.0
    phoneNumber = "555-2121" in
Person {flavor = "Pizza", ..} −− Picks up lastName, etc.

*Main> favorite hbc
"Haskell loves Curry"
*Main> firstName sae
"Stephen"
Parameterized Types: Maybe

A safe replacement for null pointers

```haskell
data Maybe a = Nothing | Just a
```

The `Maybe` type constructor is a function with a type parameter (`a`) that returns a type (`Maybe a`).

```haskell
Prelude> :k Maybe
Maybe :: * -> *

Prelude> Just "your luck"
Just "your luck"

Prelude> :t Just "your luck"
Just "your luck" :: Maybe [Char]

Prelude> :t Nothing
Nothing :: Maybe a

Prelude> :t Just (10 :: Int)
Just (10 :: Int) :: Maybe Int
```
Maybe In Action

Useful when a function may “fail” and you don’t want to throw an exception.

Prelude> :m + Data.List
Prelude Data.List> :t uncons
uncons :: [a] -> Maybe (a, [a])
Prelude Data.List> uncons [1,2,3]
Just (1,[2,3])
Prelude Data.List> uncons []
Nothing

Prelude Data.List> :t lookup
lookup :: Eq a => a -> [(a, b)] -> Maybe b
Prelude Data.List> lookup 5 [(1,2),(5,10)]
Just 10
Prelude Data.List> lookup 6 [(1,2),(5,10)]
Nothing
Data.Map: Multiple Type Parameters

Prelude Data.Map> :k Map
Map :: * -> * -> *

Prelude Data.Map> :t empty
empty :: Map k a

Prelude Data.Map> :t singleton (1::Int) "one"
singleton (1::Int) "one" :: Map Int [Char]

Note: while you can add type class constraints to type constructors, e.g.,

```haskell
data Ord k => Map k v = ...
```

it’s bad form to do so. By convention, to reduce verbosity, only functions that actually rely on the type classes are given such constraints.
The type Keyword: Introduce an Alias

Prelude> type AssocList k v = [(k, v)]
Prelude> :k AssocList
AssocList :: * -> * -> *
Prelude> :{
Prelude| lookup :: Eq k => k -> AssocList k v -> Maybe v
Prelude| lookup _ [] = Nothing
Prelude| lookup k ((x,v):xs) | x == k = Just v
Prelude| | otherwise = lookup k xs
Prelude| :}
Prelude> :t lookup
lookup :: Eq k => k -> AssocList k v -> Maybe v
Prelude> lookup 2 [(1,"one"),(2,"two")]
Just "two"
Prelude> lookup 0 [(1,"one"),(2,"two")]
Nothing
Prelude> :t [(1,"one"),(2,"two")]
[(1,"one"),(2,"two")]: Num a => [(a, [Char])]
data Either a b = Left a | Right b
deriving (Eq, Ord, Read, Show)

Prelude> :k Either
Either :: * -> * -> *
Prelude> Right 20
Right 20
Prelude> Left "Stephen"
Left "Stephen"
Prelude> :t Right "Stephen"
Right "Stephen" :: Either a [Char]  -- Only second type inferred
Prelude> :t Left True
Left True :: Either Bool b
Prelude> :k Either Bool
Either Bool :: * -> *
Either: Often a more verbose Maybe

By convention, Left = “failure,” Right = “success”

Prelude> type AssocList k v = [(k,v)]
Prelude> :

Prelude| lookup :: String -> AssocList String a -> Either String a
Prelude| lookup k [] = Left $ "Could not find " ++ k
Prelude| lookup k ((x,v):xs) | x == k = Right v
Prelude| | otherwise = lookup k xs
Prelude| :

Prelude> lookup "Stephen" [("Douglas",42),("Don",0)]
Left "Could not find Stephen"

Prelude> lookup "Douglas" [("Douglas",42),("Don",0)]
Right 42
data List a = Cons a (List a) -- A recursive type
    | Nil
deriving (Eq, Ord, Show, Read)

*Main> :t Nil
Nil :: List a -- Nil is polymorphic
*Main> :t Cons
Cons :: a -> List a -> List a -- Cons is polymorphic
*Main> :k List
List :: * -> * -- Type constructor takes an argument
*Main> Nil
Nil
*Main> 5 `Cons` Nil
Cons 5 Nil
*Main> 4 `Cons` (5 `Cons` Nil)
Cons 4 (Cons 5 Nil)
*Main> :t 'a` `Cons` Nil
'a` `Cons` Nil :: List Char -- Proper type inferred
Lists of Our Own with User-Defined Operators

```haskell
infixr 5 :

data List a = a :: List a
  | Nil

deriving (Eq, Ord, Show, Read)
```

Haskell symbols are  ! # $ % & * + . / < = > ? @ \ ^ | - ~

A (user-defined) operator is a symbol followed by zero or more symbols or :

A (user-defined) constructor is a : followed by one or more symbols or :

```
*Main> (1 :: 2 :: 3 :: Nil) :: List Int
1 :: (2 :: (3 :: Nil))

*Main> :t (::)
(::) :: a -> List a -> List a
```
Fixity of Standard Prelude Operators

infixr 9 , , !!  -- Highest precedence
infixr 8 ^, ^^, **  -- Right-associative
infixl 7 *, /, `quot`, `rem`, `div`, `mod`
infixl 6 +, -, -  -- Left-associative
infixr 5 :, ++  -- : is the only builtin
infix 4 ==, /=, <, <=, >=, >, `elem`  -- Non-associative
infixr 3 &&
infixr 2 ||
infixl 1 >>, >>=
infixr 1 =<<
infixr 0 $, $!, `seq`  -- Lowest precedence

*Main> (1::Int) == 2 == 3
<interactive>:9:1: error:
  Precedence parsing error
  cannot mix '==' [infix 4] and '==' [infix 4] in the
  same infix expression
The List Concatenation Operator

```
infixr 5 ++.  -- Define operator precedence & associativity
(++.) :: List a -> List a -> List a
Nil ++. ys = ys
(x :: xs) ++. ys = x :: (xs ++. ys)
```

```
*Main> (1 :: 2 :: 3 :: Nil ++. 4 :: 5:: Nil) :: List Int
1 :: (2 :: (3 :: (4 :: (5 :: Nil))))
```

The only thing special about lists in Haskell is the [,] syntax

```
*Main> :k List
List :: * -> *
*Main> :k []
[] :: * -> *
```

Our `List` type constructor has the same kind as the built-in list constructor `[]`
data Tree a = Node a (Tree a) (Tree a)  -- Unbalanced binary tree
  | Nil
  deriving (Eq, Show, Read)

singleton :: a -> Tree a
singleton x = Node x Nil Nil

insert :: Ord a => a -> Tree a -> Tree a
insert x Nil = singleton x
insert x n@(Node a left right) = case compare x a of
  LT  -> Node a (insert x left) right
  GT  -> Node a left (insert x right)
  EQ  -> n

fromList :: Ord a => [a] -> Tree a
fromList = foldr insert Nil

toList :: Tree a -> [a]
toList Nil = []
toList (Node a l r) = toList l ++ [a] ++ toList r
member :: Ord a => a -> Tree a -> Bool
member _ Nil = False
member x (Node a left right) = case compare x a of
  LT -> member x left
  GT -> member x right
  EQ -> True

*Main> t = fromList ([8,6,4,1,7,3,5] :: [Int])
*Main> t
Node 5 (Node 3 (Node 1 Nil Nil) (Node 4 Nil Nil))
  (Node 7 (Node 6 Nil Nil) (Node 8 Nil Nil))
*Main> toList t
[1,3,4,5,6,7,8]  
*Main> 1 `member` t
True
*Main> 42 `member` t
False
Specifying and Implementing Type Classes

class Eq a where -- Standard Prelude definition of Eq
    (==), (/=) :: a -> a -> Bool -- The class: names & signatures
    x /= y = not (x == y) -- Default implementations
    x == y = not (x /= y)

data TrafficLight = Red | Yellow | Green

instance Eq TrafficLight where
    Red  == Red   = True  -- Suffices to only supply
    Green == Green = True -- an implementation of ==
    Yellow == Yellow = True
    _      == _     = False -- "deriving Eq" would have been easier

*Main> Red == Red
True

-- Uses TrafficLight definition of ==

*Main> Red /= Yellow
True

-- Relies on default implementation
Implementing Show

```
instance Show TrafficLight where
  show Red    = "Red Light"
  show Green  = "Green Light"
  show Yellow = "Yellow Light"
```

```
*Main> show Yellow
"Yellow Light"
*Main> [Red, Yellow, Green]
[Red Light,Yellow Light,Green Light]  -- GHCi uses show

*Main> :k Maybe
Maybe :: ∗ → ∗  -- A polymorphic type constructor
*Main> :k Eq
Eq :: ∗ → Constraint  -- Like a polymorphic type constructor
*Main> :k Eq TrafficLight
Eq TrafficLight :: Constraint  -- Give it a type to make it happy
```
The MINIMAL Pragma: Controlling Compiler Warnings

```hs
infix 4 ==., /=.

class MyEq a where
  {−# MINIMAL (==.) | (=/.) #−}
  (==.), (/=.) :: a -> a -> Bool
  x /=. y = not (x ==. y)
  x ==. y = not (x /=. y)

instance MyEq Int where

instance MyEq Integer where
  x ==. y = (x `compare` y) == EQ
```

The MINIMAL pragma tells the compiler what to check for. Operators are , (and) and | (or). Parentheses are allowed.

Prelude> :load myeq
[1 of 1] Compiling Main

myeq.hs:9:10: warning:
  [-Wmissing-methods]
  * No explicit implementation for either '==.' or '/=.'
  * In the instance declaration for 'MyEq Int'

9 | instance MyEq Int where
   | ^^^^^^^^^^^
Eq (Maybe t)

data Maybe t = Just t | Nothing

instance Eq t => Eq (Maybe t) where
    Just x == Just y = x == y  -- This comparison requires Eq t
    Nothing == Nothing = True
    _ == _ = False

The Standard Prelude includes this by just deriving Eq
class Eq a where
    (==) :: a -> a -> Bool
    (/=) :: a -> a -> Bool

instance [safe] Eq TrafficLight
instance (Eq a, Eq b) => Eq (Either a b)
instance Eq a => Eq (Maybe a)
instance Eq a => Eq [a]
instance Eq Ordering
instance Eq Int
instance Eq Float
instance Eq Double
instance Eq Char
instance Eq Bool
instance (Eq a, Eq b) => Eq (a, b)
instance (Eq a, Eq b, Eq c) => Eq (a, b, c)
instance (Eq a, Eq b, Eq c, Eq d) => Eq (a, b, c, d)
ToBool: Treat Other Things as Booleans

class ToBool a where
  toBool :: a -> Bool

instance ToBool Bool where
  toBool = id -- Identity function

instance ToBool Int where
  toBool 0 = False -- C-like semantics
  toBool _ = True

instance ToBool [a] where
  toBool [] = False -- JavaScript, python semantics
  toBool _ = True

instance ToBool (Maybe a) where
  toBool (Just _) = True
  toBool Nothing = False
Now We Can toBool Bools, Ints, Lists, and Maybes

```
> :t toBool
toBool :: ToBool a => a -> Bool

> toBool True
True

> toBool (1 :: Int)
True

> toBool "dumb"
True

> toBool []
False

> toBool [False]
True

> toBool $ Just False
True

> toBool Nothing
False
```
The Functor Type Class: Should be “Mappable”†

```haskell
class Functor f where
  fmap :: (a -> b) -> f a -> f b
  (<$) :: b -> f a -> f b
m <$> b = fmap (_ -> b)
```

If \( f :: a \to b \),

\[
bs = \text{fmap } f \text{ as}
\]

applies \( f \) to every \( a \) in \( \text{as} \) to give \( bs \); \( bs = \text{as} \ <$ x \) replaces every \( a \) in \( \text{as} \) with \( x \).

Here, \( f \) is a type constructor that takes an argument, like Maybe or List.

Prelude> :k Functor
Functor :: (* -> *) -> Constraint

† “Functor” is from Category Theory

```haskell
class Functor (f :: * -> *) where
  fmap :: (a -> b) -> f a -> f b
  (<$) :: a -> f b -> f a
  {--# MINIMAL fmap #--}

instance Functor (Either a)
instance Functor []
instance Functor Maybe
instance Functor IO
instance Functor ((->) r)
instance Functor ((,,) a)

-- Many others; these are
-- just the Prelude’s
```
Functor Instances for \(* \rightarrow *\) Kinds

```
data [] a = [] | a : [a]            -- The List type: not legal syntax

instance Functor [] where
  fmap = map                         -- The canonical example

data Maybe t = Nothing | Just t    -- Prelude definition

instance Functor Maybe where
  fmap _ Nothing = Nothing          -- No object a here
  fmap f (Just a) = Just (f a)      -- Apply f to the object in Just a

data Tree a = Node a (Tree a) (Tree a) | Nil  -- Our binary tree

instance Functor Tree where
  fmap f Nil = Nil
  fmap f (Node a lt rt) = Node (f a) (fmap f lt) (fmap f rt)
```
Functor Either a

data Either a b = Left a | Right b

instance Either does not type check because Either :: * -> * -> *

The Prelude definition of fmap only modifies Right

instance Functor (Either a) where
    fmap _ (Left x) = Left x
    fmap f (Right y) = Right (f y)

This works because Either a :: * -> * has the right kind
Kinds: The Types of Types

Prelude> :k Int
Int :: *             -- A concrete type

Prelude> :k [Int]
[Int] :: *           -- A specific type of list: also concrete

Prelude> :k []
[] :: * -> *        -- The list type constructor takes a parameter

Prelude> :k Maybe
Maybe :: * -> *     -- Maybe also takes a type as a parameter

Prelude> :k Maybe Int
Maybe Int :: *       -- Specifying the parameter makes it concrete

Prelude> :k Either
Either :: * -> * -> * -- Either takes two type parameters

Prelude> :k Either String
Either String :: * -> * -- Partially applying Either is OK

Prelude> :k (,)
(,) :: * -> * -> *    -- The pair (tuple) constructor takes two
Crazy Kinds

Prelude> class Tofu t where tofu :: j a -> t a j

Type class Tofu expects a single type argument t

j must take an argument a and produce a concrete type, so j :: * -> *
t must take arguments a and j, so t :: * -> (* -> *) -> *

Prelude> :k Tofu
Tofu :: (* -> (* -> *) -> *) -> Constraint

Let’s invent a type constructor of kind * -> (* -> *) -> *. It has to take two type arguments; the second needs to be a function of one argument

data What a b = What (b a) deriving Show

Prelude> :k What
What :: * -> (* -> *) -> *      -- Success
What?

```haskell
data What a b = What (b a) deriving Show
```

```haskell
Prelude> :t What "Hello"
What "Hello" :: What Char []
Prelude> :t What (Just "Ever")
What (Just "Ever") :: What [Char] Maybe
```

*What* holds any type that is a “parameterized container,” what *Tofu* wants:

```haskell
Prelude> :k What
What :: * -> (* -> *) -> *
Prelude> :k Tofu
Tofu :: (* -> (* -> *) -> *) -> Constraint
Prelude> instance Tofu What where tofu x = What x
Prelude> tofu (Just 'a') :: What Char Maybe
What (Just 'a')
Prelude> tofu "Hello" :: What Char []
What "Hello"
```
Prelude> data Barry t k a = Barry a (t k)
Prelude> :k Barry
Barry :: (* -> *) -> * -> * -> *  -- Bizarre kind, by design
Prelude> :t Barry (5::Int) "Hello"
Barry (5::Int) "Hello" :: Barry [] Char Int

A *Barry* is two objects: any type and one built from a type constructor

Prelude> :k Functor
Functor :: (* -> *) -> Constraint  -- Takes a one-arg constructor

*instance* Functor (Barry t k) *where*  -- Partially applying Barry
   fmap f (Barry x y) = Barry (f x) y  -- Applying f to first object

Prelude> fmap (+1) (Barry 5 "Hello")
Barry 6 "Hello"  -- It works!
Prelude> fmap show (Barry 42 "Hello")
Barry "42" "Hello"
Prelude> :t fmap show (Barry 42 "Hello")
fmap show (Barry 42 "Hello") :: Barry [] Char String