

Datatypes and functions

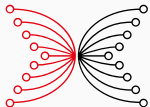
Haskell and Cryptocurrencies

Dr. Andres Löh, Well-Typed LLP

Dr. Lars Brünjes, IOHK

Dr. Polina Vinogradova, IOHK

2019-01-11



INPUT | OUTPUT

Goals

- Introduce `Bool`, `Maybe`, `[a]`, binary trees, and one or two other types.
- Introduce the *standard design pattern* (*catamorphism*) by example for all these types.

Bool

Booleans

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

Booleans

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

Constructors:

```
False :: Bool  
True  :: Bool
```

Booleans

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

Constructors:

```
False :: Bool  
True  :: Bool
```

Functions on Booleans:

```
fun :: Bool -> ...  
fun False = ...  
fun True  = ...
```

Allowed patterns are:

- Saturated constructor applications to other patterns.
- Variables (match anything).
- Underscore / wildcard pattern (matches anything).
- Literals (numbers, characters, strings, lists).

Exhaustive patterns and overlap

- Patterns are matched in order.
- In particular, catch-all cases must come last.
- Best practice: split programming problems by expanding variables into all possible constructors for the type of the variable.
- For non-overlapping cases, the order does not matter.

Step-by-step function definition

```
not :: Bool -> Bool  
not = _
```

Start with the type signature. Use **typed holes**.

Type of hole: `Bool -> Bool`.

Step-by-step function definition

```
not :: Bool -> Bool  
not x = _
```

Introduce function arguments.

Type of hole: `Bool`.

Available locally: `x :: Bool`.

Step-by-step function definition

```
not :: Bool -> Bool
not False = _
not True  = _
```

Split cases (if you cannot solve directly).

Type of holes: `Bool` and `Bool`.

Step-by-step function definition

```
not :: Bool -> Bool  
not False = True  
not True  = False
```

Solve. Easy in this case.

Step-by-step function definition

```
not :: Bool -> Bool  
not False = True  
not True  = False
```

Reflect. Everything looks good.

Disjunction (or)

```
(||) :: Bool -> Bool -> Bool  
(||) = _
```

Start with the type signature.

Type of hole: `Bool -> Bool -> Bool`.

Disjunction (or)

```
(||) :: Bool -> Bool -> Bool  
(||) x y = _
```

Introduce function arguments.

Type of hole: `Bool`.

Available locally: `x :: Bool` and `y :: Bool`.

Disjunction (or)

```
(||) :: Bool -> Bool -> Bool  
x || y = _
```

(If preferred, we can use infix notation.)

Type of hole: `Bool`.

Available locally: `x :: Bool` and `y :: Bool`.

Disjunction (or)

```
(||) :: Bool -> Bool -> Bool  
False || y = _  
True  || y = _
```

Split on a suitable argument (let's take the first).

Type of holes: `Bool` and `Bool`.

Available locally: `y :: Bool` (in each case).

Disjunction (or)

```
(||) :: Bool -> Bool -> Bool  
False || y = y  
True  || y = True
```

We actually can solve at this point.

Disjunction (or)

```
(||) :: Bool -> Bool -> Bool  
False || y = y  
True  || y = True
```

Reflect. Everything looks good.

Different options

```
(||) :: Bool -> Bool -> Bool  
False || y = y  
True  || y = True
```

```
(||) :: Bool -> Bool -> Bool  
False || False = False  
False || True  = True  
True  || False = True  
True  || True  = True
```

Different options

```
(||) :: Bool -> Bool -> Bool  
False || y = y  
True  || y = True
```

```
(||) :: Bool -> Bool -> Bool  
False || False = False  
False || True  = True  
True  || False = True  
True  || True  = True
```

```
loop :: a  
loop = loop
```

What about `True || loop`?

Undefined / run-time crashes

Haskell does not prevent looping or crashing:

```
undefined :: a  
error :: String -> a
```

Undefined / run-time crashes

Haskell does not prevent looping or crashing:

```
undefined :: a  
error :: String -> a
```

First (library) version:

```
GHCi> GHCi > True || undefined  
True
```

Second (fully expanded) version:

```
GHCi> GHCi > True || undefined  
*** Exception: Prelude.undefined
```

Undefined / run-time crashes

Haskell does not prevent looping or crashing:

```
undefined :: a  
error :: String -> a
```

First (library) version:

```
GHCi> GHCi > True || undefined  
True
```

Second (fully expanded) version:

```
GHCi> GHCi > True || undefined  
*** Exception: Prelude.undefined
```

Also relevant for possibly infinite or just very large terms.

If-then-else

```
ifthenelse :: Bool -> a -> a -> a  
ifthenelse False t e = e  
ifthenelse True  t e = t
```

Works as expected: only one branch is evaluated.

Syntax for if-then-else

```
ifthenelse :: Bool -> a -> a -> a  
ifthenelse c t e = if c then t else e
```

Guards

```
ifthenelse :: Bool -> a -> a -> a  
ifthenelse c t e  
  | c           = t  
  | otherwise = e
```

Guards

```
ifthenelse :: Bool -> a -> a -> a  
ifthenelse c t e  
  | c           = t  
  | otherwise = e
```

- Guards are tried one by one.
- Conditions all of type `Bool`.
- First guard that evaluates to `True` is chosen.

Guards

```
ifthenelse :: Bool -> a -> a -> a
ifthenelse c t e
  | c           = t
  | otherwise = e
```

- Guards are tried one by one.
- Conditions all of type `Bool`.
- First guard that evaluates to `True` is chosen.

```
otherwise :: Bool
otherwise = True
```

Maybe

Optional values

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

Optional values

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

Constructors:

```
Nothing :: Maybe a  
Just     :: a -> Maybe a
```


Optional values

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

Constructors:

```
Nothing :: Maybe a  
Just     :: a -> Maybe a
```

Functions on `Maybe`:

```
fun :: Maybe a -> ...  
fun Nothing = ...  
fun (Just x) = ...
```

Using a default Value

```
fromMaybe :: a -> Maybe a -> a  
fromMaybe def Nothing = def  
fromMaybe _   (Just x) = x
```

Using a default Value

```
fromMaybe :: a -> Maybe a -> a  
fromMaybe def Nothing = def  
fromMaybe _   (Just x) = x
```

```
GHCi> fromMaybe 3 Nothing  
3  
GHCi> fromMaybe 3 (Just 5)  
5
```

Chaining optional values

```
orElse :: Maybe a -> Maybe a -> Maybe a  
orElse Nothing y = y  
orElse (Just x) _ = Just x
```

Chaining optional values

```
orElse :: Maybe a -> Maybe a -> Maybe a  
orElse Nothing y = y  
orElse (Just x) _ = Just x
```

```
GHCi> Nothing `orElse` Just 5  
Just 5  
GHCi> Just 3 `orElse` Just 5  
Just 3  
GHCi> Just 3 `orElse` Nothing  
Just 3  
GHCi> Nothing `orElse` Nothing  
Nothing
```

Modifying an optional value

```
mapMaybe :: (a -> b) -> Maybe a -> Maybe b  
mapMaybe f Nothing  = Nothing  
mapMaybe f (Just x) = Just (f x)
```

Modifying an optional value

```
mapMaybe :: (a -> b) -> Maybe a -> Maybe b
mapMaybe f Nothing  = Nothing
mapMaybe f (Just x) = Just (f x)
```

```
GHCi> mapMaybe (+ 1) Nothing
Nothing
GHCi> mapMaybe (+ 1) (Just 5)
Just 6
GHCi> mapMaybe not (Just True)
Just False
```

Adding two optional values

```
addMaybes :: Maybe Int -> Maybe Int -> Maybe Int
addMaybes (Just x) (Just y) = Just (x + y)
addMaybes _      _      = Nothing
```


Adding two optional values

```
addMaybes :: Maybe Int -> Maybe Int -> Maybe Int
addMaybes (Just x) (Just y) = Just (x + y)
addMaybes _         _       = Nothing
```

```
liftMaybe ::
  (a -> b -> c)
  -> Maybe a -> Maybe b -> Maybe c
liftMaybe f (Just x) (Just y) = Just (f x y)
liftMaybe _ _ _ = Nothing
```

Pairs

```
data (a, b) = (a, b)  -- special syntax
```

Pairs

```
data (a, b) = (a, b)  -- special syntax
```

Constructor:

```
(, ) :: a -> b -> (a, b)
```

Pairs

```
data (a, b) = (a, b)  -- special syntax
```

Constructor:

```
(, ) :: a -> b -> (a, b)
```

Functions on pairs:

```
fun :: (a, b) -> ...
```

```
fun (a, b) = ...
```

Extracting components

```
fst :: (a, b) -> a  
fst (a, b) = a
```

```
snd :: (a, b) -> b  
snd (a, b) = b
```

Swapping components

```
swap :: (a, b) -> (b, a)  
swap (a, b) = (b, a)
```

Currying and uncurrying

```
curry :: ((a, b) -> c) -> a -> b -> c  
curry f a b = f (a, b)
```


Currying and uncurrying

```
curry :: ((a, b) -> c) -> a -> b -> c  
curry f a b = f (a, b)
```

```
uncurry :: (a -> b -> c) -> (a, b) -> c  
uncurry f (a, b) = f a b
```

Lists

Lists

```
data [a] = [] | a : [a]  -- special syntax
```

Lists

```
data [a] = [] | a : [a]  -- special syntax
```

Constructors:

```
[]  :: [a]  
(:) :: a -> [a] -> [a]
```

Lists

```
data [a] = [] | a : [a]  -- special syntax
```

Constructors:

```
[]  :: [a]  
(:) :: a -> [a] -> [a]
```

Functions on lists:

```
fun :: [a] -> ...  
fun []      = ...  
fun (x : xs) = ... fun xs ...
```

Recursion in types and functions are connected!

Length of a list

```
length :: [a] -> Int  
length []      = 0  
length (x : xs) = 1 + length xs
```

Finding an element in a list

```
elem :: Eq a => a -> [a] -> Bool  
elem x []          = False  
elem x (y : ys) = x == y || elem x ys
```

Appending two lists

```
(++) :: [a] -> [a] -> [a]  
[]      ++ ys = ys  
(x : xs) ++ ys = x : (xs ++ ys)
```


Reversing a list

```
reverse :: [a] -> [a]
reverse []      = []
reverse (x : xs) = reverse xs ++ [x]
```

Filtering a list

```
filter :: (a -> Bool) -> [a] -> [a]
filter p []      = []
filter p (x : xs)
  | p x          = x : filter p xs
  | otherwise    =      filter p xs
```

Simple look-up tables

Modelling a look-up table

```
type Table k v = [(k, v)]
```

Modelling a look-up table

```
type Table k v = [(k, v)]
```

Interface:

```
empty   :: Table k v  
insert  :: k -> v -> Table k v -> Table k v  
delete  :: Eq k => k -> Table k v -> Table k v  
lookup  :: Eq k => k -> Table k v -> Maybe v
```

Note: functional data structures are *persistent*!

An empty table

```
empty :: Table k v  
empty = []
```

Inserting a new key-value pair

```
insert :: k -> v -> Table k v -> Table k v  
insert k v t = (k, v) : t
```

Deleting a key

```
delete :: Eq k => k -> Table k v -> Table k v
delete k []      = []
delete k ((k', v) : t)
  | k == k'      = delete k t
  | otherwise    = (k', v) : delete k t
```


Deleting a key

```
delete :: Eq k => k -> Table k v -> Table k v
delete k []      = []
delete k ((k', v) : t)
  | k == k'      = delete k t
  | otherwise    = (k', v) : delete k t
```

```
delete :: Eq k => k -> Table k v -> Table k v
delete k = filter (\(k', _) -> not (k == k'))
```

Finding a value for a given key

```
lookup :: Eq k => k -> Table k v -> Maybe v
lookup k []      = Nothing
lookup k ((k', v) : xs)
  | k == k'      = Just v
  | otherwise    = lookup k xs
```

A new datatype for tables

```
newtype Table k v = Table [(k, v)]
```

Constructor:

```
Table :: [(k, v)] -> Table k v
```

Functions on tables:

```
fun :: Table k v -> ...  
fun (Table table) = ...
```

newtype :

- restricted to one constructor with one argument,
- otherwise like **data**,
- guaranteed to have the same representation as the wrapped type.

data :

- arbitrary number of constructors and argument,
- introduces an additional indirection.

Making tables abstract

- Functions on tables have to be adapted to (un)wrap the `Table` constructor applications.
- The `Table` constructor can then be hidden from the module exports.
- Pattern matching and accessing the internal representation becomes unavailable outside of the defining module, only the interface defined by the functions remains.

Transactions

Modelling a transaction

```
data Transaction =  
    Transaction Amount Account Account  
    deriving (Eq, Show)  
  
type Amount  = Int  
type Account = String
```

Modelling a transaction

```
data Transaction =  
    Transaction Amount Account Account  
    deriving (Eq, Show)  
  
type Amount    = Int  
type Account   = String
```

Constructor (same name as type):

```
Transaction ::  
    Amount -> Account -> Account -> Transaction
```

Functions on transactions:

```
fun :: Transaction -> ...  
fun (Transaction amount from to) = ...
```


Accessing components

```
trAmount :: Transaction -> Amount
trAmount (Transaction a _ _) = a
trFrom   :: Transaction -> Account
trFrom   (Transaction _ f _) = f
trTo     :: Transaction -> Account
trTo     (Transaction _ _ t) = t
```

Record syntax

```
data Transaction =  
  Transaction  
    { trAmount :: Amount  
    , trFrom   :: Account  
    , trTo     :: Account  
    }  
deriving (Eq, Show)
```

- Constructor can still be used with positional arguments.
- Provides selector functions for free.
- Also provides record construction and update syntax, and record patterns.

Updating an account table with a transaction

```
type Accounts = Table Account Amount
processTransaction ::
  Transaction -> Accounts -> Accounts
processTransaction (Transaction amount f t) as =
  let
    fOld = fromMaybe 0 (lookup f as)
    tOld = fromMaybe 0 (lookup t as)
  in
    insert f (fOld - amount)
      (insert t (tOld + amount) as)
```

(It would be better to define a dedicated `update` on tables.)

Binary trees

Binary trees

```
data Tree a = Leaf a | Node (Tree a) (Tree a)
```

Constructors:

```
Leaf :: a -> Tree a
```

```
Node :: Tree a -> Tree a -> Tree a
```

Functions on trees:

```
fun :: Tree a -> ...
```

```
fun (Leaf x) = ...
```

```
fun (Node l r) = ... fun l ... fun r ...
```

Functions usually recurse twice!

Flattening a tree into a list

```
flatten :: Tree a -> [a]
flatten (Leaf x)    = [x]
flatten (Node l r) = flatten l ++ flatten r
```

Computing the height of a tree

```
height :: Tree a -> Int
height (Leaf x)    = 0
height (Node l r) = 1 + max (height l) (height r)
```

Expressions

Abstract syntax trees of an expression language

```
data Expr =  
    Lit Int  
  | Add Expr Expr  
  | Neg Expr  
  | IfZero Expr Expr Expr
```

Constructors:

```
Lit    :: Int -> Expr  
Add    :: Expr -> Expr -> Expr  
Neg    :: Expr  
IfZero :: Expr -> Expr -> Expr -> Expr
```

Functions on expressions

```
fun :: Expr -> ...  
fun (Lit n)           = ...  
fun (Add e1 e2)       = ... fun e1 ... fun e2  
fun (Neg e)           = ... fun e ...  
fun (IfZero e1 e2 e3) =  
    ... fun e1 ... fun e2 ... fun e3 ...
```

Evaluating an expression

```
eval :: Expr -> Int
eval (Lit n)           = n
eval (Add e1 e2)       = eval e1 + eval e2
eval (Neg e)           = - (eval e)
eval (IfZero e1 e2 e3) =
    if eval e1 == 0 then eval e2 else eval e3
```