Informatics 1

Functional Programming Lectures 13 and 14

Monday 10 and Tuesday 11 November 2014

Type Classes

Don Sannella

University of Edinburgh

Mock exam

Slots and rooms have now been assigned

Mon 17–Fri 21 November

Check the course web page for your assignment

You may only come to the assigned slot and room

The 2014 Informatics 1 Competition

- First prize: A bottle of champagne or equivalent in book tokens. And glory!
- Previous year entries are online:

  www.inf.ed.ac.uk/teaching/courses/inf1/fp/#competition

- Number of prizes depend on number/quality of entries.
- Sponsored by Galois (galois.com)
- Send code and image(s), list everyone who contributed.
- E-mail your entry to Karoliina Lehtinen
  `<M.K.Lehtinen@sms.ed.ac.uk>`
- *Deadline: midnight, Wednesday 19 November 2014*

Part I

Type classes

Element

```
elem :: Eq a => a -> [a] -> Bool

-- comprehension
elem x ys       =  or [ x == y | y <- ys ]

-- recursion
elem x []       =  False
elem x (y:ys)   =  x == y || elem x ys

-- higher-order
elem x ys       =  foldr (||) False (map (x ==) ys)
```

Using element

```
*Main> elem 1 [2,3,4]
False

*Main> elem 'o' "word"
True

*Main> elem (1,'o') [(0,'w'),(1,'o'),(2,'r'),(3,'d')]
True

*Main> elem "word" ["list","of","word"]
True

*Main> elem (\x -> x) [(\x -> -x), (\x -> -(-x))]
No instance for (Eq (a -> a)) arising from a use of `elem'
Possible fix: add an instance declaration for (Eq (a -> a))
```

Equality type class

```
class  Eq a  where
  (==) :: a -> a -> Bool

instance  Eq Int  where
  (==)  =  eqInt

instance  Eq Char  where
  x == y              =  ord x == ord y

instance  (Eq a, Eq b) => Eq (a,b)  where
  (u,v) == (x,y)      =  (u == x) && (v == y)

instance  Eq a => Eq [a]  where
  [] == []            =  True
  [] == y:ys          =  False
  x:xs  ==  []        =  False
  x:xs  ==  y:ys      =  (x == y) && (xs == ys)
```

Element, translation

```
data EqDict a     =  EqD (a -> a -> Bool)

eq :: EqDict a -> a -> a -> Bool
eq (EqDict f)   =  f

elem :: EqD a -> a -> [a] -> Bool

-- comprehension
elem d x ys          =  or [ eq d x y | y <- ys ]

-- recursion
elem d x []          =  False
elem d x (y:ys)      =  eq d x y || elem x ys

-- higher-order
elem d x ys          =  foldr (||) False (map (eq d x) ys)
```

Type classes, translation

```
dInt                  :: EqDict Int
dInt                  =  EqD eqInt

dChar                 :: EqDict Char
dChar                 =  EqD f
  where
  f x y               =  eq dInt (ord x) (ord y)

dPair                 :: (EqDict a, EqDict b) -> EqDict (a,b)
dPair (da,db)         =  EqD f
  where
  f (u,v) (x,y)       =  eq da u x && eq db v y

dList                 :: EqDict a -> EqDict [a]
dList d               =  EqD f
  where
  f [] []             =  True
  f [] (y:ys)         =  False
  f (x:xs) []         =  False
  f (x:xs) (y:ys)     =  eq d x y && eq (dList d) xs ys
```

Using element, translation

```
*Main> elem dInt 1 [2,3,4]
False

*Main> elem dChar 'o' "word"
True

*Main> elem (dPair dInt dChar) (1,'o') [(0,'w'),(1,'o')]
True

*Main> elem (dList dChar) "word" ["list","of","word"]
True
```

Haskell uses types to write code for you!

Part II

Eq, Ord, Show

Eq, Ord, Show

```
class Eq a where
  (==) :: a -> a -> Bool
  (/=) :: a -> a -> Bool

  -- minimum definition: (==)
  x /= y  =  not (x == y)

class (Eq a) => Ord a where
  (<)  :: a -> a -> Bool
  (<=) :: a -> a -> Bool
  (>)  :: a -> a -> Bool
  (>=) :: a -> a -> Bool

  -- minimum definition: (<=)
  x < y   =  x <= y && x /= y
  x > y   =  y < x
  x >= y  =  y <= x

class  Show a  where
  show  :: a -> String
```

Part III

Booleans, Tuples, Lists

Instances for booleans

```
instance Eq Bool where
  False == False  =  True
  False == True   =  False
  True  == False  =  False
  True  == True   =  True

instance Ord Bool where
  False <= False  =  True
  False <= True   =  True
  True  <= False  =  False
  True  <= True   =  True

instance Show Bool where
  show False      =  "False"
  show True       =  "True"
```

Instances for pairs

```
instance (Eq a, Eq b) => Eq (a,b) where
  (x,y) == (x',y')  =  x == x' && y == y'

instance (Ord a, Ord b) => Ord (a,b) where
  (x,y) <= (x',y')  =  x < x' || (x == x' && y <= y')

instance (Show a, Show b) => Show (a,b) where
  show (x,y)  =  "(" ++ show x ++ "," ++ show y ++ ")"
```

Instances for lists

```
instance Eq a => Eq [a] where
  []     ==  []     =  True
  []     ==  y:ys   =  False
  x:xs   ==  []     =  False
  x:xs   ==  y:ys   =  x == y && xs == ys

instance Ord a => Ord [a] where
  []     <=  ys     =  True
  x:xs   <=  []     =  False
  x:xs   <=  y:ys   =  x < y || (x == y && xs <= ys)

instance Show a => Show [a] where
  show []        =  "[]"
  show (x:xs)    =  "[" ++ showSep x xs ++ "]"
    where
    showSep x []       =  show x
    showSep x (y:ys)   =  show x ++ "," ++ showSep y ys
```

Deriving clauses

```
data Bool = False | True
       deriving (Eq, Ord, Show)

data Pair a b = MkPair a b
       deriving (Eq, Ord, Show)

data List a = Nil | Cons a (List a)
       deriving (Eq, Ord, Show)
```

Haskell uses types to write code for you!

Part IV

Sets, revisited

Sets, revisited

```
instance Ord a => Eq (Set a) where
  s == t   =   s `equal` t
```

Note that this differs from the derived instance!

Part V

Numbers

Numerical classes

```
class (Eq a, Show a) => Num a where
  (+),(-),(*)    ::  a -> a -> a
  negate         ::  a -> a
  fromInteger    ::  Integer -> a
  -- minimum definition: (+),(-),(*),fromInteger
  negate x       =   fromInteger 0 - x

class (Num a) => Fractional a where
  (/)            ::  a -> a -> a
  recip          ::  a -> a
  fromRational   ::  Rational -> a
  -- minimum definition: (/), fromRational
  recip x        =   1/x

class (Num a, Ord a) => Real a where
  toRational     :: a -> Rational

class (Real a, Enum a) => Integral a where
  div, mod       :: a -> a -> a
  toInteger      :: a -> Integer
```

A built-in numerical type

```
instance Num Float where
  (+)           =  builtInAddFloat
  (-)           =  builtInSubtractFloat
  (*)           =  builtInMultiplyFloat
  negate        =  builtInNegateFloat
  fromInteger   =  builtInFromIntegerFloat

instance Fractional Float where
  (/)           =  builtInDivideFloat
  fromRational  =  builtInFromRationalFloat
```

Natural.hs (1)

```
module Natural(Nat) where
import Test.QuickCheck

data Nat = MkNat Integer

invariant :: Nat -> Bool
invariant (MkNat x)  =  x >= 0

instance Eq Nat where
  MkNat x == MkNat y  =  x == y

instance Ord Nat where
  MkNat x <= MkNat y  =  x <= y

instance Show Nat where
  show (MkNat x)  =  show x
```

Natural.hs (2)

```
instance Num Nat where
  MkNat x + MkNat y    =  MkNat (x + y)
  MkNat x - MkNat y
          | x >= y     =  MkNat (x - y)
          | otherwise  =  error (show (x-y) ++ " is negative")
  MkNat x * MkNat y    =  MkNat (x * y)
  fromInteger x
          | x >= 0     =  MkNat x
          | otherwise  =  error (show x ++ " is negative")
  negate               =  undefined
```

Natural.hs (3)

```
prop_plus :: Integer -> Integer -> Property
prop_plus m n  =
  (m >= 0) && (n >= 0) ==> (m+n >= 0)

prop_times :: Integer -> Integer -> Property
prop_times m n  =
  (m >= 0) && (n >= 0) ==> (m*n >= 0)

prop_minus :: Integer -> Integer -> Property
prop_minus m n  =
  (m >= 0) && (n >= 0) && (m >= n) ==> (m-n >= 0)
```

NaturalTest.hs

```
module NaturalTest where
import Natural

m, n :: Nat
m  =  fromInteger 2
n  =  fromInteger 3
```

Test run

```
ghci NaturalTest
Ok, modules loaded: NaturalTest, Natural.
*NaturalTest> m
2
*NaturalTest> n
3
*NaturalTest> m+n
5
*NaturalTest> n-m
1
*NaturalTest> m-n
*** Exception: -1 is negative
*NaturalTest> m*n
6
*NaturalTest> fromInteger (-5) :: Nat
*** Exception: -5 is negative
*NaturalTest> MkNat (-5)
Not in scope: data constructor `MkNat'
```

Hiding—the secret of abstraction

```
module Natural(Nat) where ...

> ghci NaturalTest
*NaturalTest> let m = fromInteger 2
*NaturalTest> let s = fromInteger (-5)
*** Exception: -5 is negative
*NaturalTest> let s = MkNat (-5)
Not in scope: data constructor ‘MkNat’
```

vs.

```
module NaturalUnabs(Nat(MkNat)) where ...

> ghci NaturalUnabs
*NaturalUnabs> let p = MkNat (-5)   -- breaks invariant
*NaturalUnabs> invariant p
False
```

Part VI

Seasons

Seasons

```
data Season = Winter | Spring | Summer | Fall

next :: Season -> Season
next Winter  =  Spring
next Spring  =  Summer
next Summer  =  Fall
next Fall    =  Winter

warm :: Season -> Bool
warm Winter  =  False
warm Spring  =  True
warm Summer  =  True
warm Fall    =  True
```

Eq, Ord

```
instance Eq Seasons where
  Winter == Winter  =  True
  Spring == Spring  =  True
  Summer == Summer  =  True
  Fall   == Fall    =  True
  _      == _       =  False

instance Ord Seasons where
  Spring <= Winter  =  False
  Summer <= Winter  =  False
  Summer <= Spring  =  False
  Fall   <= Winter  =  False
  Fall   <= Spring  =  False
  Fall   <= Summer  =  False
  _      <= _       =  True

instance Show Seasons where
  show Winter  =  "Winter"
  show Spring  =  "Spring"
  show Summer  =  "Summer"
  show Fall    =  "Fall"
```

Class Enum

```
class  Enum a  where
  toEnum            :: Int -> a
  fromEnum          :: a -> Int
  succ, pred        :: a -> a
  enumFrom          :: a -> [a]               -- [x..]
  enumFromTo        :: a -> a -> [a]          -- [x..y]
  enumFromThen      :: a -> a -> [a]          -- [x,y..]
  enumFromThenTo    :: a -> a -> a -> [a]     -- [x,y..z]

  -- minimum definition: toEnum, fromEnum
  succ x            =  toEnum (fromEnum x + 1)
  pred x            =  toEnum (fromEnum x - 1)
  enumFrom x
    =  map toEnum [fromEnum x ..]
  enumFromTo x y
    =  map toEnum [fromEnum x .. fromEnum y]
  enumFromThen x y
    =  map toEnum [fromEnum x, fromEnum y ..]
  enumFromThenTo x y z
    =  map toEnum [fromEnum x, fromEnum y .. fromEnum z]
```

Syntactic sugar

```
-- [x..]      =  enumFrom x
-- [x..y]     =  enumFromTo x y
-- [x,y..]    =  enumFromThen x y
-- [x,y..z]   =  enumFromThenTo x y z
```

Enumerating Int

```
instance Enum Int where
  toEnum  x           =  x
  fromEnum x          =  x
  succ x              =  x+1
  pred x              =  x-1
  enumFrom x          =  iterate (+1) x
  enumFromTo x y      =  takeWhile (<= y) (iterate (+1) x)
  enumFromThen x y    =  iterate (+(y-x)) x
  enumFromThenTo x y z
                      =  takeWhile (<= z) (iterate (+(y-x)) x)

iterate :: (a -> a) -> a -> [a]
iterate f x  =  x : iterate f (f x)

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

Enumerating Seasons

```
instance Enum Seasons where

  fromEnum Winter  =  0
  fromEnum Spring  =  1
  fromEnum Summer  =  2
  fromEnum Fall    =  3

  toEnum 0  =  Winter
  toEnum 1  =  Spring
  toEnum 2  =  Summer
  toEnum 3  =  Fall
```

Deriving Seasons

```
data Season = Winter | Spring | Summer | Fall
              deriving (Eq, Ord, Show, Enum)
```

Haskell uses types to write code for you!

Seasons, revisited

```
next :: Season -> Season
next x  =  toEnum ((fromEnum x + 1) `mod` 4)

warm :: Season -> Bool
warm x  =  x `elem` [Spring .. Fall]

-- [Spring .. Fall] = [Spring, Summer, Fall]
```

Part VII

Shape

Shape

```
type  Radius  =  Float
type  Width   =  Float
type  Height  =  Float

data  Shape  =  Circle Radius
             |  Rect Width Height

area :: Shape -> Float
area (Circle r)  =  pi * r^2
area (Rect w h)  =  w * h
```

Eq, Ord, Show

```
instance  Eq Shape  where
  Circle r == Circle r'    =  r == r'
  Rect w h == Rect w' h'   =  w == w' && h == h'
  _        == _            =  False

instance  Ord Shape  where
  Circle r <= Circle r'    =  r < r'
  Circle r <= Rect w' h'   =  True
  Rect w h <= Rect w' h'   =  w < w' || (w == w' && h <= h')
  _        <= _            =  False

instance  Show Shape  where
  show (Circle r)     =  "Circle " ++ showN r
  show (Radius w h)   =  "Radius " ++ showN w ++ " " ++ showN h

showN :: (Num a) => a -> String
showN x | x >= 0      =  show x
        | otherwise   =  "(" ++ show x ++ ")"
```

Deriving Shapes

```haskell
data  Shape  =  Circle Radius
             |  Rect Width Height
             deriving (Eq, Ord, Show)
```

Haskell uses types to write code for you!

Part VIII

Expressions

Expression Trees

```
data  Exp  =  Lit Int
            | Exp :+: Exp
            | Exp :*: Exp

eval :: Exp -> Int
eval (Lit n)     =  n
eval (e :+: f)   =  eval e + eval f
eval (e :*: f)   =  eval e * eval f

*Main> eval (Lit 2 :+: (Lit 3 :*: Lit 3))
11
*Main> eval ((Lit 2 :+: Lit 3) :*: Lit 3)
15
```

Eq, Ord, Show

```
instance  Eq Exp  where
  Lit n     ==  Lit n'      =  n == n'
  e :+: f   ==  e' :+: f'   =  e == e' && f == f'
  e :*: f   ==  e' :*: f'   =  e == e' && f == f'
  _         ==  _           =  False

instance  Ord Exp  where
  Lit n     <=  Lit n'      =  n < n'
  Lit n     <=  e' :+: f'   =  True
  Lit n     <=  e' :*: f'   =  True
  e :+: f   <=  e' :+: f'   =  e < e' || (e == e' && f <= f')
  e :+: f   <=  e' :*: f'   =  True
  e :*: f   <=  e' :*: f'   =  e < e' || (e == e' && f <= f')
  _         <=  _           =  False

instance  Show Exp  where
  show (Lit n)     =  "Lit " ++ showN n
  show (e :+: f)   =  "(" ++ show e ++ ":+:" ++ show f ++ ")"
  show (e :*: f)   =  "(" ++ show e ++ ":*:" ++ show f ++ ")"
```

Deriving Expressions

```
data  Exp  =  Lit Int
           | Exp :+: Exp
           | Exp :*: Exp
           deriving (Eq, Ord, Show)
```

Haskell uses types to write code for you!