LiU-FP2016: Lecture 8

Type Classes

Henrik Nilsson

University of Nottingham, UK

Haskell Overloading (1)

What is the type of (==)?

E.g. the following both work:

```
1 == 2
'a' == 'b'
```

I.e., (==) can be used to compare both numbers and characters.

Haskell Overloading (1)

What is the type of (==)?

E.g. the following both work:

```
1 == 2
'a' == 'b'
```

I.e., (==) can be used to compare both numbers and characters.

Maybe `(==) :: a -> a -> Bool`?

Haskell Overloading (1)

What is the type of (==)?

E.g. the following both work:

```
1 == 2
'a' == 'b'
```

I.e., (==) can be used to compare both numbers and characters.

Maybe `(==) :: a -> a -> Bool`?

No!!! Cannot work uniformly for arbitrary types!

Haskell Overloading (2)

A function like the identity function

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

is ***polymorphic*** precisely because it works uniformly for all types: there is no need to "inspect" the argument.

Haskell Overloading (2)

A function like the identity function

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

is ***polymorphic*** precisely because it works uniformly for all types: there is no need to "inspect" the argument.

In contrast, to compare two "things" for equality, they very much have to be inspected, and an ***appropriate method of comparison*** needs to be used.

Haskell Overloading (3)

Moreover, some types do not in general admit a decidable equality. E.g. functions (when their domain is infinite).

Haskell Overloading (3)

Moreover, some types do not in general admit a decidable equality. E.g. functions (when their domain is infinite).

Similar remarks apply to many other types. E.g.:

Haskell Overloading (3)

Moreover, some types do not in general admit a decidable equality. E.g. functions (when their domain is infinite).

Similar remarks apply to many other types. E.g.:

- We may want to be able to add numbers of any kind.

Haskell Overloading (3)

Moreover, some types do not in general admit a decidable equality. E.g. functions (when their domain is infinite).

Similar remarks apply to many other types. E.g.:

- We may want to be able to add numbers of any kind.
- But to add properly, we must understand what we are adding.

Haskell Overloading (3)

Moreover, some types do not in general admit a decidable equality. E.g. functions (when their domain is infinite).

Similar remarks apply to many other types. E.g.:

- We may want to be able to add numbers of any kind.
- But to add properly, we must understand what we are adding.
- Not every type admits addition.

Haskell Overloading (4)

Idea:

Haskell Overloading (4)

Idea:

- Introduce the notion of a ***type class***: a set of types that support certain related operations.

Haskell Overloading (4)

Idea:

- Introduce the notion of a ***type class***: a set of types that support certain related operations.
- ***Constrain*** those operations to ***only*** work for types belonging to the corresponding class.

Haskell Overloading (4)

Idea:

- Introduce the notion of a ***type class***: a set of types that support certain related operations.
- ***Constrain*** those operations to ***only*** work for types belonging to the corresponding class.
- Allow a type to be ***made an instance of*** (added to) a type class by providing ***type-specific implementations*** of the operations of the class.

The Type Class `Eq`

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

`(==)` is not a function, but a ***method*** of the ***type class*** `Eq`. It's type signature is:

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

`Eq a` is a ***class constraint***. It says that that the equality method works for any type belonging to the type class `Eq`.

Instances of `Eq` (1)

Various types can be made instances of a type class like `Eq` by providing implementations of the class methods for the type in question:

```
instance Eq Int where
    x == y = primEqInt x y

instance Eq Char where
    x == y = primEqChar x y
```

Instances of `Eq` (2)

Suppose we have a data type:

```
data Answer = Yes | No | Unknown
```

We can make `Answer` an instance of `Eq` as follows:

```
instance Eq Answer where
    Yes     == Yes     = True
    No      == No      = True
    Unknown == Unknown = True
    _       == _       = False
```

Instances of `Eq` (3)

Consider:

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

Can `Tree` be made an instance of `Eq`?

Instances of `Eq` (4)

Yes, for any type `a` that is already an instance of `Eq`:

```
instance (Eq a) => Eq (Tree a) where
    Leaf a1       == Leaf a2       = a1 == a2
    Node t1l t1r == Node t2l t2r = t1l == t2l
                                     && t1r == t2r
    _             == _             = False
```

Note that `(==)` is used at type `a` (whatever that is) when comparing `a1` and `a2`, while the use of `(==)` for comparing subtrees is a recursive call.

Derived Instances (1)

Instance declarations are often obvious and mechanical. Thus, for certain ***built-in*** classes (notably `Eq`, `Ord`, `Show`), Haskell provides a way to ***automatically derive*** instances, as long as

- the data type is sufficiently simple
- we are happy with the standard definitions

Thus, we can do:

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

Derived Instances (2)

GHC provides some additional possibilities. With the extension `-XGeneralizedNewtypeDeriving`, a new type defined using `newtype` can “inherit” any of the instances of the representation type:

```
newtype Time = Time Int deriving Num
```

Derived Instances (2)

GHC provides some additional possibilities. With the extension `-XGeneralizedNewtypeDeriving`, a new type defined using `newtype` can "inherit" any of the instances of the representation type:

```
newtype Time = Time Int deriving Num
```

With the extension `-XStandaloneDeriving`, instances can be derived separately from a type definition (even in a separate module):

```
deriving instance Eq Time
deriving instance Eq a => Eq (Tree a)
```

Class Hierarchy

Type classes form a hierarchy. E.g.:

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

`Eq` is a superclass of `Ord`; i.e., any type in `Ord` must also be in `Eq`.

Haskell vs. OO Overloading (1)

A method, or overloaded function, may thus be understood as a family of functions where the right one is chosen depending on the types.

A bit like OO languages like Java. But the underlying mechanism is quite different and much more general. Consider `read`:

```
read :: (Read a) => String -> a
```

Note: overloaded on the ***result*** type! A method that converts from a string to ***any*** other type in class `Read`!

Haskell vs. OO Overloading (2)

```
> let xs = [1,2,3] :: [Int]
> let ys = [1,2,3] :: [Double]
> xs
[1,2,3]
> ys
[1.0,2.0,3.0]
> (read "42" : xs)
[42,1,2,3]
> (read "42" : ys)
[42.0,1.0,2.0,3.0]
> read "'a'" :: Char
'a'
```

Implementation (1)

The class constraints represent extra implicit arguments that are filled in by the compiler. These arguments are (roughly) the functions to use.

Thus, internally `(==)` is a ***higher order function*** with ***three*** arguments:

```
(==) eqF x y = eqF x y
```

Implementation (2)

An expression like

```
1 == 2
```

is essentially translated into

```
(==) primEqInt 1 2
```

Implementation (3)

So one way of understanding a type like

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

is that `Eq a` corresponds to an extra implicit argument.

The implicit argument corresponds to a so called directory, or tuple/record of functions, one for each method of the type class in question.

Some Basic Haskell Classes (1)

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

class (Eq a) => Ord a where
    compare              :: a -> a -> Ordering
    (<), (<=), (>=), (>) :: a -> a -> Bool
    max, min             :: a -> a -> a

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

Some Basic Haskell Classes (2)

```
class (Eq a, Show a) => Num a where
    (+), (-), (*) :: a -> a -> a
    negate        :: a -> a
    abs, signum   :: a -> a
    fromInteger   :: Integer -> a
```

Some Basic Haskell Classes (2)

```
class (Eq a, Show a) => Num a where
    (+), (-), (*) :: a -> a -> a
    negate        :: a -> a
    abs, signum   :: a -> a
    fromInteger   :: Integer -> a
```

Quiz: What is the type of a numeric literal like 42? What about 42.0? Why?

Some Basic Haskell Classes (2)

```
class (Eq a, Show a) => Num a where
    (+), (-), (*) :: a -> a -> a
    negate        :: a -> a
    abs, signum   :: a -> a
    fromInteger   :: Integer -> a
```

Quiz: What is the type of a numeric literal like 42? What about 42.0? Why?

Haskell's numeric literals are overloaded. E.g. `42` is expanded into `fromInteger 42`.

A Typing Conundrum (1)

Overloaded (numeric) literals can lead to some surprises.

What is the type of the following list? Is it even well-typed???

```
[1, [2,3]]
```

A Typing Conundrum (1)

Overloaded (numeric) literals can lead to some surprises.

What is the type of the following list? Is it even well-typed???

```
[1, [2,3]]
```

Surprisingly, it is well-typed:

```
> :type [1, [2,3]]
[1, [2,3]] :: (Num [t], Num t) => [[t]]
```

Why?

A Typing Conundrum (2)

The list is expanded into:

```
[ fromInteger 1,
  [fromInteger 2, fromInteger 3] ]
```

Thus, if there were some type `t` for which `[t]` were an instance of `Num`, the `1` would be an overloaded literal of that type, matching the type of the second element of the list.

A Typing Conundrum (2)

The list is expanded into:

```
[ fromInteger 1,
  [fromInteger 2, fromInteger 3] ]
```

Thus, if there were some type `t` for which `[t]` were an instance of `Num`, the `1` would be an overloaded literal of that type, matching the type of the second element of the list.

Normally there are no such instances, so what almost certainly is a mistake will be caught. But the error message is rather confusing.

Application: Automatic Differentiation

- ***Automatic Differentiation***: method for augmenting code so that derivative(s) computed along with main result.
- Purely algebraic method: arbitrary code can be handled
- Exact results
- But no separate, self-contained representation of the derivative.

Automatic Differentiation: Key Idea

Consider a code fragment:

```
z1 = x + y
z2 = x * z1
```

Suppose the derivatives of `x` and `y` w.r.t. common variable is available in the variables `x'` and `y'`.

Then code can be augmented to compute derivatives of `z1` and `z2`:

```
z1  = x + y
z1' = x' + y'
z2  = x * z1
z2' = x' * z1 + x * z1'
```

Approaches

- Source-to-source translation
- Overloading of arithmetic operators and mathematical functions

The following variation is due to Jerzy Karczmarczuk. Infinite list of derivatives allows derivatives of ***arbitrary*** order to be computed.

Functional Automatic Differentiation (1)

Introduce a new numeric type `C`: value of a continuously differentiable function at a point along with ***all*** derivatives at that point:

```
data C = C Double C

valC (C a _)  = a
derC (C _ x') = x'
```

Functional Automatic Differentiation (2)

Constants and the variable of differentiation:

```
zeroC :: C
zeroC = C 0.0 zeroC

constC :: Double -> C
constC a = C a zeroC

dVarC :: Double -> C
dVarC a = C a (constC 1.0)
```

Functional Automatic Differentiation (3)

Part of numerical instance:

```
instance Num C where
    (C a x') + (C b y') =
        C (a + b) (x' + y')

    (C a x') - (C b y') =
        C (a - b) (x' - y')

    x@(C a x') * y@(C b y') =
        C (a * b) (x' * y + x * y')

    fromInteger n =
        constC (fromInteger n)
```

Functional Automatic Differentiation (4)

Computation of $y = 3t^2 + 7$ at $t = 2$:

```
t = dVarC 2
y = 3 * t * t + 7
```

`valC y`	$\Rightarrow$	19.0
`valC (derC y)`	$\Rightarrow$	12.0
`valC (derC (derC y))`	$\Rightarrow$	6.0
`valC (derC (derC (derC y)))`	$\Rightarrow$	0.0

Functor (1)

A Functor is a notion that originated in a branch of mathematics called Category Theory.

However, for our purposes, we can think of functors as type constructors T (of arity 1) for which a function map can be defined:

$$map :: (a \to b) \to T a \to T b$$

that satisfies the following laws:

$$\begin{array}{rcl} map\ id & = & id \\ map (f \circ g) & = & map\ f \circ map\ g \end{array}$$

Functor (2)

Common examples of functors include (but are certainly not limited to) ***container types*** like lists:

```
mapList :: (a -> b) -> [a] -> [b]
mapList _ [] = []
mapList f (x:xs) = f x : mapList f xs
```

and trees:

```
mapTree :: (a -> b) -> Tree a
              -> Tree b
```

Functor (3)

Another important example is Haskell's option type `Maybe`:

```
data Maybe a = Nothing | Just a

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

Functor (4)

Of course, the notion of a functor with a type class in Haskell:

```
class Functor f where
    fmap :: (a -> b) -> f a -> f b
```

Instances are provided for `[]`, `Maybe`, and many other types in Haskell's standard prelude.

Functor (4)

Of course, the notion of a functor with a type class in Haskell:

```
class Functor f where
    fmap :: (a -> b) -> f a -> f b
```

Instances are provided for `[]`, `Maybe`, and many other types in Haskell's standard prelude.

However, Haskell's type system is not powerful enough to enforce the functor laws.

Functor (4)

Of course, the notion of a functor with a type class in Haskell:

```
class Functor f where
    fmap :: (a -> b) -> f a -> f b
```

Instances are provided for `[]`, `Maybe`, and many other types in Haskell's standard prelude.

However, Haskell's type system is not powerful enough to enforce the functor laws.

In general: the responsibility for ensuring that an instance respects any laws associated with a type class rests squarely with the programmer.

Functor (5)

Note that the type of `fmap` can be read:

```
(a -> b) -> (f a -> f b)
```

That is, we can see `fmap` as promoting a function to work in a different context.

Reading

- Jerzy Karczmarczuk. Functional differentiation of computer programs. *Higher-Order and Symbolic Computation*, 14(1):35–57, March 2001.