CSE 114A: Fall 2021

Foundations of Programming Languages

Type classes

Owen Arden

UC Santa Cruz

Based on course materials developed by Nadia Polikarpova and Ranjit Jhala

Roadmap

This week: adding types

Modern language features for structuring programs

- Type classes
- Monads

Overloading Operators: Arithmetic

The `+` operator works for a bunch of different types.

For `Integer`:

```
λ> 2 + 3
5
```

for `Double` precision floats:

```
λ> 2.9 + 3.5
6.4
```

Overloading Operators: Arithmetic

Similarly we can *compare* different types of values

```
λ> 2 == 3
False

λ>  [2.9, 3.5] == [2.9, 3.5]
True

λ> ("cat", 10) < ("cat", 2)
False

λ> ("cat", 10) < ("cat", 20)
True
```

Ad-Hoc Overloading

Seems unremarkable?

Languages since the dawn of time have supported “operator overloading”

- To support this kind of **ad-hoc polymorphism**
- Ad-hoc: “created or done for a particular purpose as necessary.”

You really **need** to *add* and *compare* values of *multiple* types!

Haskell has no caste system

No distinction between operators and functions

- All are first class citizens!

But then, what type do we give to *functions* like + and == ?

Haskell has no caste system

`Integer -> Integer -> Integer` is bad because?

- Then we cannot add `Double`s!

Haskell has no caste system

`Double -> Double -> Double` is bad because?

- Then we cannot add Integer!

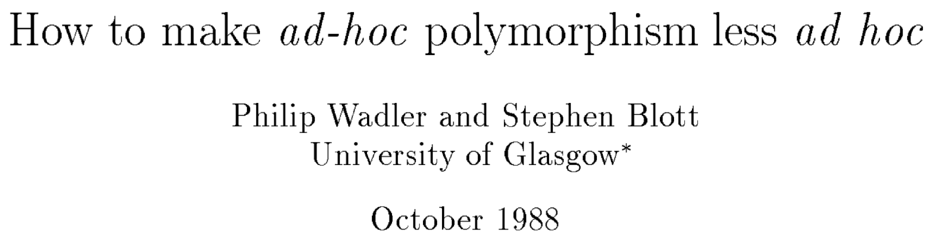
Haskell has no caste system

`a -> a -> a` is bad because?

- That doesn’t make sense, e.g. to add two `Bool` or two `[Int]` or two functions!

Type Classes for Ad Hoc Polymorphism

Haskell solves this problem with an *insanely slick* mechanism called typeclasses, introduced by Wadler and Blott


How to make *ad-hoc* polymorphism less *ad hoc*

Philip Wadler and Stephen Blott
University of Glasgow*

October 1988

Qualified Types

To see the right type, lets ask:

```
λ> :type (+)
(+) :: (Num a) => a -> a -> a
```

We call the above a **qualified type**. Read it as `+`

- takes in two `a` values and returns an `a` value

for any type `a` that

- *is a* `Num` or
- *implements* the `Num` interface or
- *is an instance of* a `Num`.

The name `Num` can be thought of as

a *predicate* or *constraint* over types

Some types are Nums

- Examples include Integer, Double etc
- Any such values of those types can be passed to +.

Other types are not Nums

Examples include `Char`, `String`, functions etc,

- Values of those types *cannot* be passed to `+`.

```
λ> True + False

<interactive>:15:6:
    No instance for (Num Bool) arising from a
use of ‘+’
    In the expression: True + False
    In an equation for ‘it’: it = True + False
```

Type Class is a Set of Operations

A ***typeclass*** is a collection of operations (functions) that must exist for the underlying type.

The Eq Type Class

The simplest typeclass is perhaps, Eq

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

A type a is *an instance of* Eq if there are two functions

- == and /=

That determine if two a values are respectively *equal* or *unequal*.

The Show Type Class

The typeclass `Show` requires that instances be convertible to `String` (which can then be printed out)

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

Indeed, we can test this on different (built-in) types

```
λ> show 2
"2"


λ> show 3.14
"3.14"


λ> show (1, "two", ([],[],[]))
"(1,\"two\",([],[],[]))"
```

Type Class is a Set of Operations

When we type an expression into ghci, it computes the value and then calls `show` on the result. Thus, if we create a *new* type by

```
data Unshowable = A | B | C
```

and then create values of the type,

```
λ> let x = A
λ> :type x
x :: Unshowable
```

Type Class is a Set of Operations

but then we **cannot view** them

```
λ> x
<interactive>:1:0:
    No instance for (Show Unshowable)
      arising from a use of `print' at <interactive>:1:0
    Possible fix: add an instance declaration for (Show
Unshowable)
    In a stmt of a 'do' expression: print it
```

Type Class is a Set of Operations

and we **cannot compare** them!

```
λ> x == x
<interactive>:1:0:
    No instance for (Eq Unshowable)
      arising from a use of `==' at <interactive>:1:0-5
    Possible fix: add an instance declaration for (Eq
Unshowable)
    In the expression: x == x
    In the definition of `it': it = x == x
```

Again, the previously incomprehensible type error message should make sense to you.

Creating Instances

Tell Haskell how to show or compare values of type `Unshowable`

By **creating instances** of `Eq` and `Show` for that type:

```
instance Eq Unshowable where
  (==) A A = True               -- True if both inputs are A
  (==) B B = True               -- ...or B
  (==) C C = True               -- .. or C
  (==) _ _ = False              -- otherwise

  (/=) x y = not (x == y)       -- Test if `x == y` and negate
result!
```

EXERCISE Lets *create* an `instance` for `Show Unshowable`

Automatic Derivation

This is silly: we *should* be able to compare and view `Unshowble` “automatically”!

Haskell lets us *automatically derive* functions for some classes in the standard library.

To do so, we simply dress up the data type definition with

```
data Showable = A' | B' | C'
  deriving (Eq, Show) -- tells Haskell to automatically
generate instances
```

Automatic Derivation

```
data Showable = A' | B' | C'
  deriving (Eq, Show) -- tells Haskell to automatically
generate instances
```

Now we have

```
λ> let x' = A'
λ> :type x'
x' :: Showable
λ> x’
A'
λ> x' == x'
True
λ> x' == B'
False
```

Standard Typeclass Hierarchy

Let us now peruse the definition of the Num typeclass.

```
λ> :info Num
class Num a where
  (+) :: a -> a -> a
  (*) :: a -> a -> a
  (-) :: a -> a -> a
  negate :: a -> a
  abs :: a -> a
  signum :: a -> a
  fromInteger :: Integer -> a
```

A type a *is an instance of* (i.e. *implements*) Num if there are functions for adding, multiplying, subtracting, negating etc values of that type.

The Ord Typeclass

Another typeclass you've used already is the one for Ordering values:

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

For example:

```
λ> 2 < 3
True

λ> "cat" < "dog"
True
```

A type a *is an instance of* (i.e. *implements*) Ord if

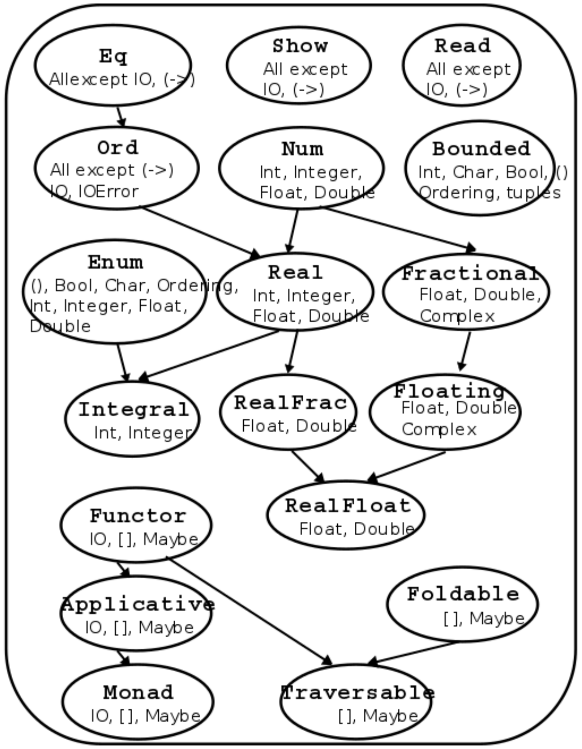
1. It has an instance of Eq
2. there are functions for comparing the relative order of values of that type.

Standard Typeclass Hierarchy

In other words in addition to the "arithmetic" operations, we can compare two `Num` values and we can view them (as a `String`.)

Haskell comes equipped with a rich set of built-in classes.

In the picture, there is an edge from `Eq` to `Ord` because for something to be an `Ord` it must also be an `Eq`.



Using Typeclasses

Typeclasses integrate with the rest of Haskell’s type system.

Lets build a small library for *Environments* mapping keys k to values v

```haskell
data Env k v
  = Def  v                -- default value `v`
                          --   to be used for "missing" keys
  | Bind k v (Env k v)    -- bind key `k` to the value `v`
  deriving (Show)
```

An API for Env

Lets write a small API for `Env`

```
-- >>> let env0 = add "cat" 10.0 (add "dog" 20.0 (Def 0))

-- >>> get "cat" env0
-- 10

-- >>> get "dog" env0
-- 20

-- >>> get "horse" env0
-- 0
```

An API for Env

Ok, lets implement!

```
-- | 'add key val env' returns a new env that additionally
maps `key` to `val`
add :: k -> v -> Env k v -> Env k v
add key val env = ???

-- | 'get key env' returns the value of `key` and the
"default" if no value is found
get :: k -> Env k v -> v
get key env = ???
```

An API for Env

Ok, lets implement!

```haskell
-- | 'add key val env' returns a new env that additionally
maps `key` to `val`
add :: k -> v -> Env k v -> Env k v
add key val env = Bind key val env

-- | 'get key env' returns the value of `key` and the
"default" if no value is found
get :: k -> Env k v -> v
get key (Def val) = val
get key (Bind key' val env) | key == key' = val
get key (Bind key' val env) | otherwise = get key env
```

Constraint Propagation

Lets *delete* the types of `add` and `get` and see what Haskell says their types are!

```
λ> :type get
get :: (Eq k) => k -> v -> Env k v -> Env k v
```

Haskell tells us that we can use any `k` value as a *key* as long as the value is an instance of the `Eq` typeclass.

How, did GHC figure this out?

- If you look at the code for `get` you'll see that we check if two keys *are equal*!

Exercise

Write an optimized version of

- `add` that ensures the keys are in *increasing* order,
- `get` that gives up and returns the "default" the moment we see a key thats larger than the one we're looking for.

(How) do you need to change the type of `Env`?

(How) do you need to change the types of `get` and `add`?

Explicit Signatures

While Haskell is pretty good about inferring types in general, there are cases when the use of type classes requires explicit annotations (which change the behavior of the code.)

For example, `Read` is a built-in typeclass, where any instance a of `Read` has a function

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

which can parse a string and turn it into an `a`.

That is, `Read` is the *opposite* of `Show`.

Explicit Signatures

Haskell is confused!

- Doesn't know *what type* to convert the string to!
- Doesn't know *which* of the `read` functions to run!

Did we want an `Int` or a `Double` or maybe something else altogether?

Thus, here an **explicit type annotation** is needed to tell Haskell what to convert the string to:

```
λ> (read "2") :: Int
2
λ> (read "2") :: Float
2.0
```

Note the different results due to the different types.

Creating Typeclasses

Typeclasses are useful for *many* different things.

We will see some of those over the next few lectures.

Lets conclude today's class with a quick example that provides a small taste.

JSON

JavaScript Object Notation or JSON is a simple format for transferring data around. Here is an example:

```
{ "name"    : “Elliot Alderson"
, "age"     : 28
, "likes"   : ["coffee", "hacking"]
, "hates"   : [ “e-corp" ]
, "lunches" : [ {"day" : "monday",    "loc" : “cafe iveta"}
              , {"day" : "tuesday",   "loc" : “cruzn gourmet"}
              , {"day" : "wednesday", "loc" : "perk"}
              , {"day" : "thursday",  "loc" : “burger."}
              , {"day" : "friday",    "loc" : “ray’s truck"} ]
}
```

JSON

In brief, each JSON object is either

- a *base* value like a string, a number or a boolean,
- an (ordered) *array* of objects, or
- a set of *string-object* pairs.

A JSON Datatype

We can represent (a subset of) JSON values with the Haskell datatype

```
data JVal
  = JStr  String
  | JNum  Double
  | JBool Bool
  | JObj  [(String, JVal)]
  | JArr  [JVal]
  deriving (Eq, Ord, Show)
```

A JSON Datatype

Thus, the above JSON value would be represented by the `JVal`

```
JObj [("name", JStr "Elliot Alderson")
     ,("age",  JNum 28)
     ,("likes",   JArr [ JStr "coffee", JStr "hacking"])
     ,("hates",   JArr [ JStr "e-corp" ])
     ,("lunches", JArr [ JObj [("day",  JStr "monday")
                              ,("loc",  JStr "cafe iveta")]
                       , JObj [("day",  JStr "tuesday")
                              ,("loc",  JStr "cruzn gourmet")]
                       , JObj [("day",  JStr "wednesday")
                              ,("loc",  JStr "perk")]
                       , JObj [("day",  JStr "thursday")
                              ,("loc",  JStr "burger.")]
                       , JObj [("day",  JStr "friday")
                              ,("loc",  JStr "ray's truck")]
                       ])
     ]
```

Serializing Haskell Values to JSON

Let’s write a small library to *serialize* Haskell values as JSON.

We could write a bunch of functions like

```
doubleToJSON :: Double -> JVal
doubleToJSON = JNum

stringToJSON :: String -> JVal
stringToJSON = JStr

boolToJSON   :: Bool -> JVal
boolToJSON   = JBool
```

Serializing Collections

But what about collections, namely *lists* of things?

```
doublesToJSON    :: [Double] -> JVal
doublesToJSON xs = JArr (map doubleToJSON xs)

boolsToJSON      :: [Bool] -> JVal
boolsToJSON xs   = JArr (map boolToJSON xs)

stringsToJSON    :: [String] -> JVal
stringsToJSON xs = JArr (map stringToJSON xs)
```

This is **getting rather tedious**

- We are rewriting the same code :(

Serializing Collections (with HOFs)

You could abstract by making the *individual-element-converter* a parameter

```
xsToJSON :: (a -> JVal) -> [a] -> JVal
xsToJSON f xs = JArr (map f xs)

xysToJSON :: (a -> JVal) -> [(String, a)] -> JVal
xysToJSON f kvs = JObj [ (k, f v) | (k, v) <- kvs ]
```

Serializing Collections (with HOFs)

But this is *still rather tedious** as you have to pass in the individual data converter (yuck)

```
λ> doubleToJSON 4
JNum 4.0

λ> xsToJSON stringToJSON ["coffee", "hacking"]
JArr [JStr "coffee",JStr "hacking"]

λ> xysToJSON stringToJSON [("day", "monday"), ("loc",
“cafe iveta")]
JObj [("day",JStr "monday"),("loc",JStr “cafe iveta”)]
```

Serializing Collections (with HOFs)

This gets more hideous when you have richer objects like

```
lunches = [ [("day", "monday"),    ("loc", "zanzibar")]
          , [("day", "tuesday"),   ("loc", "farmers market")]
          ]
```

because we have to go through gymnastics like

```
λ> xsToJSON (xysToJSON stringToJSON) lunches
JArr [ JObj [("day",JStr "monday")   ,("loc",JStr "zanzibar")]
     , JObj [("day",JStr "tuesday")  ,("loc",JStr "farmers market")]
     ]
```

So much for *readability*

Is it too much to ask for a magical `toJSON` that *just works?*

Typeclasses To The Rescue

Lets *define* a typeclass that describes types `a` that can be converted to JSON.

```haskell
class JSON a where
  toJSON :: a -> JVal
```

Now, just make all the above instances of `JSON` like so

```haskell
instance JSON Double where
  toJSON = JNum

instance JSON Bool where
  toJSON = JBool

instance JSON String where
  toJSON = JStr
```

Typeclasses To The Rescue

This lets us uniformly write

```
λ> toJSON 4
JNum 4.0

λ> toJSON True
JBool True

λ> toJSON “hacking"
JStr "hacking"
```

Bootstrapping Instances

The real fun begins when we get Haskell to automatically bootstrap the above functions to work for lists and key-value lists!

```
instance JSON a => JSON [a] where
  toJSON xs = JArr [toJSON x | x <- xs]
```

The above says, if `a` is an instance of `JSON`, that is, if you can convert `a` to `JVal` then here's a generic recipe to convert lists of `a` values!

```
λ> toJSON [True, False, True]
JArr [JBool True, JBool False, JBool True]
λ> toJSON ["cat", "dog", "Mouse"]
JArr [JStr "cat", JStr "dog", JStr "Mouse"]
```

or even lists-of-lists!

```
λ> toJSON [["cat", "dog"], ["mouse", "rabbit"]]
JArr [JArr [JStr "cat",JStr "dog"],JArr [JStr "mouse",JStr "rabbit"]]
```

Bootstrapping Instances

We can pull the same trick with key-value lists

```
instance (JSON a) => JSON [(String, a)] where
  toJSON kvs = JObj [ (k, toJSON v) | (k, v) <- kvs ]
```

after which, we are all set!

```
λ> toJSON lunches
JArr [ JObj [ ("day",JStr "monday"), ("loc",JStr “cafe iveta”)]
     , JObj [("day",JStr "tuesday"), ("loc",JStr “cruzn gourmet")]
     ]
```

Bootstrapping Instances

It is also useful to bootstrap the serialization for tuples (up to some fixed size) so we can easily write "non-uniform" JSON objects where keys are bound to values with different shapes.

```
instance (JSON a, JSON b) => JSON ((String, a), (String, b)) where
  toJSON ((k1, v1), (k2, v2)) =
    JObj [(k1, toJSON v1), (k2, toJSON v2)]

instance (JSON a, JSON b, JSON c) => JSON ((String, a), (String, b),
(String, c)) where
  toJSON ((k1, v1), (k2, v2), (k3, v3)) =
    JObj [(k1, toJSON v1), (k2, toJSON v2), (k3, toJSON v3)]
```

…

Bootstrapping Instances

Now, we can simply write

```
hs = (("name"    , "Elliot Alderson")
     ,("age"     , 28)
     ,("likes"   , ["coffee", "hacking"])
     ,("hates"   , ["e-corp"])
     ,("lunches", lunches)
     )
```

which is a Haskell value that describes our running JSON example, and can convert it directly like so

```
js2 = toJSON hs
```

Serializing Environments

To wrap everything up, lets write a routine to serialize our `Env`

```
instance JSON (Env k v) where
  toJSON env = ???
```

and presto! our serializer *just works*

```
λ> env0
Bind "cat" 10.0 (Bind "dog" 20.0 (Def 0))

λ> toJSON env0
JObj [ ("cat", JNum 10.0)
     , ("dog", JNum 20.0)
     , ("def", JNum 0.0)
     ]
```