

# CSE 114A: Fall 2023

## Foundations of Programming Languages

### *Type classes*

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## Roadmap

### This week: adding types

Modern language features for structuring programs

- Type classes
- Monads

2

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## 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
```

3

# Overloading Operators: Arithmetic

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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
```

4

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## Ad-Hoc Overloading

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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!

5

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## Haskell has no caste system

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No distinction between operators and functions

- All are first class citizens!

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

6

## Individual: Plus type

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Which of the following would be appropriate types for (+) ?

(A) (+) :: Integer -> Integer -> Integer

(B) (+) :: Double -> Double -> Double

(C) (+) :: a -> a -> a

(D) All of the above

(E) None of the above



<https://tiny.cc/cse116-plus-type-ind>

7

## Individual: Plus type

---

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<http://tiny.cc/cse116-plus-type-grp>

8

## Haskell has no caste system

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Integer -> Integer -> Integer is bad because?

- Then we cannot add Doubles!

9

## Haskell has no caste system

---

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

- Then we cannot add `Integer`!

10

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## 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!

11

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## Type Classes for Ad Hoc Polymorphism

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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

12

## Qualified Types

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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

13

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## Some types are Nums

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

14

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## 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
```

15

## Type Class is a Set of Operations

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

16

## The Eq Type Class

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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*.

17

## The Show Type Class

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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\",([],[],[]))"
```

18

## 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
```

19

## 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
```

20

## 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.

21

# Creating Instances

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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`

22

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# Automatic Derivation

This is silly: we *should* be able to compare and view `Unshowable` “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
```

23

---

# 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
```

24



# 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

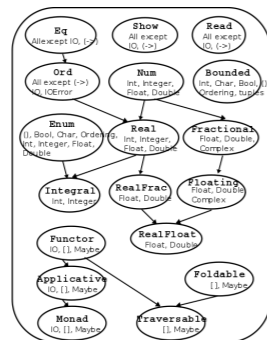
1. It has an instance of `Eq`
2. there are functions for comparing the relative order of values of that type.

# 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`.



## QUIZ

---

Recall the datatype:

```
data Showable = A' | B' | C' deriving (Eq, Show)
```

What is the result of:

```
λ> A' < B'
```

- (A) True
- (B) False
- (C) Type error
- (D) Run-time exception



<http://tiny.cc/cse116-ord-ind>

28

## QUIZ

---

Recall the datatype:

```
data Showable = A' | B' | C' deriving (Eq, Show)
```

What is the result of:

```
λ> A' < B'
```

- (A) True
- (B) False
- (C) Type error
- (D) Run-time exception



<http://tiny.cc/cse116-ord-grp>

29

## Using Typeclasses

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

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

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

30

## An API for Env

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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
```

31

## 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 = ???
```

32

## 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 = 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
```

33

## Constraint Propagation

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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!

34

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## Exercise

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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 that's 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`?*

35

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## Explicit Signatures

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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`.

36

## QUIZ

---

What does the expression `read "2"` evaluate to?

- (A) compile time error
- (B) `"2" :: String`
- (C) `2 :: Integer`
- (D) `2.0 :: Double`
- (E) run-time exception



<https://tiny.cc/cse116-read-ind>

37

## QUIZ

---

What does the expression `read "2"` evaluate to?

- (A) compile time error
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- (E) run-time exception



<https://tiny.cc/cse116-read-grp>

38

## Explicit Signatures

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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.

39

## Creating Typeclasses

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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.

40

## JSON

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*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"} ]
}
```

41

## JSON

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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.

42

# 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)
```

43

# 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")]
])
]
```

44

# 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
```

45

## Serializing Collections

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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 :(

46

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## 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 = JObject [ (k, f v) | (k, v) <- kvs ]
```

47

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## 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"}]
```

48



## 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 [ JObject [{"day",JStr "monday"}, {"loc",JStr "zanzibar"}]  
      , JObject [{"day",JStr "tuesday"}, {"loc",JStr "farmers market"}]  
      ]
```

So much for *readability*

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

49

## Typeclasses To The Rescue

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

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

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

```
instance JSON Double where  
  toJSON = JNum
```

```
instance JSON Bool where  
  toJSON = JBool
```

```
instance JSON String where  
  toJSON = JStr
```

50

## 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"
```

51

## Bootstrapping Instances

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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"]]
```

52

---

## 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")
           ]
      ]
```

53

---

## 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)]
```

...

54

## 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
```

55

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## 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)
      ]
```

56