00-lambda due on $\boxed{\text{1/21 FRI}}$

Haskell Crash Course Part I

From the Lambda Calculus to Haskell

01-haskell due on $\boxed{\text{1/29}}$

What is Haskell?

A **typed**, **lazy**, **purely functional** programming language

Haskell = λ-calculus ++

- better syntax
- types
- built-in features
  - booleans, numbers, characters
  - records (tuples)
  - lists
  - recursion
  - ...

Programming in Haskell

Computation by Calculation

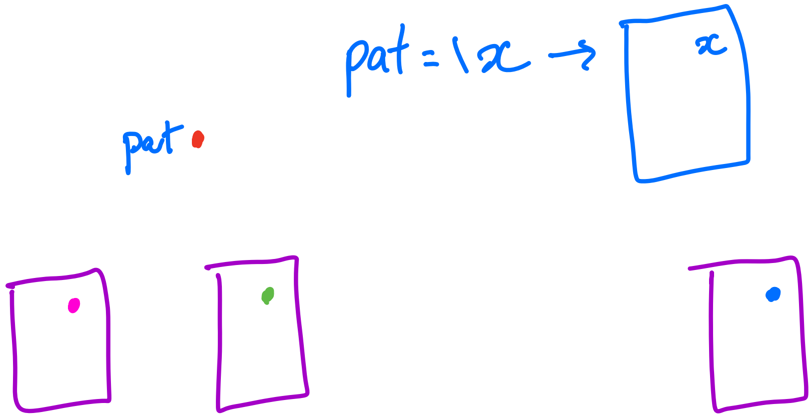
Substituting equals by equals

Computation via Substituting Equals by Equals

```
    (1 + 3) * (4 + 5)
                              -- subst 1 + 3 = 4
==>        4 * (4 + 5)
                              -- subst 4 + 5 = 9
==>        4 * 9
                              -- subst 4 * 9 = 36
==>        36
```

Computation via Substituting Equals by Equals

Equality-Substitution enables **Abstraction** via **Pattern Recognition**



Abstraction via Pattern Recognition

pat = \x y z -> x * (y+z)

Repeated Expressions

```
x      y      z
31 * (42 + 56)
pat 70 12 95 = 70 * (12 + 95)
pat 90 68 12 = 90 * (68 + 12)
```

Recognize Pattern as λ-function

```
pat = \x y z -> x  * ( y + z )
```

Equivalent Haskell Definition

```
pat   x y z =  x  * ( y + z )
```

Function Call is Pattern Instance

```
pat 31 42 56 =*> 31 * (42 + 56) =*> 31 * 98  =*> 3038
pat 70 12 95 =*> 70 * (12 + 95) =*> 70 * 107 =*> 7490
pat 90 68 12 =*> 90 * (68 + 12) =*> 90 * 80  =*> 7200
```

Key Idea: Computation is *substitute* equals by equals.

Programming in Haskell

Substitute Equals by Equals

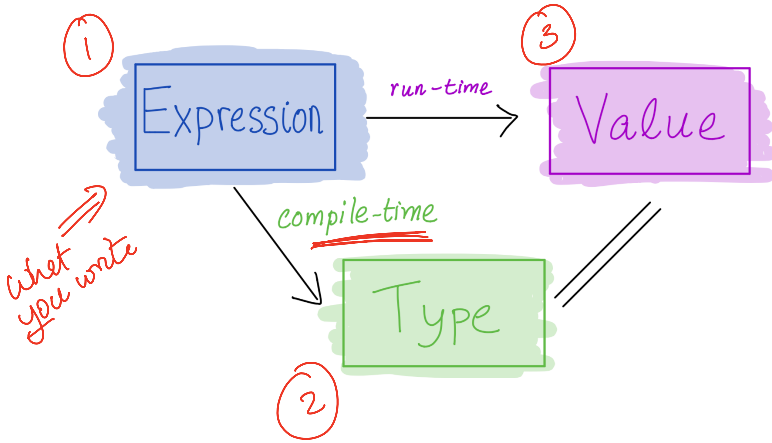
Thats it! (*Do not* think of registers, stacks, frames etc.)

CSE 30

CSE 131

Elements of Haskell

HOLY TRINITY



- Core program element is an **expression**
- Every *valid* expression has a **type** (determined at compile-time)
- Every *valid* expression reduces to a *value* (computed at run-time)

Ill-typed* expressions are rejected at *compile-time* before execution

- *like* in Java
- *not like* λ-calculus or ~~Python~~ … (mypy)

```
weirdo = 1 0     -- rejected by GHC
```

Why are types good?

- Helps with program *design*

- Types are *contracts* (ignore ill-typed inputs!)
- Catches errors *early*
- Allows compiler *to generate code*
- Enables compiler *optimizations*

The Haskell Eco-System

- **Batch compiler:** `ghc` Compile and run large programs
- **Interactive Shell** `ghci` Shell to interactively run small programs online (https://repl.it/languages/haskell)
- **Build Tool** `stack` Build tool to manage libraries etc.

Interactive Shell: `ghci`

```
$ stack ghci

:load file.hs
:type expression
:info variable
```

A Haskell Source File

A sequence of **top-level definitions** `x1` , `x2` , ...

- Each has *type* `type_1` , `type_2` , ...
- Each defined by *expression* `expr_1` , `expr_2` , ...

```
x_1 :: type_1
x_1 = expr_1

x_2 :: type_2
x_2 = expr_2

.
.
.
```

Basic Types

```haskell
ex1 :: Int
ex1 = 31 * (42 + 56)   -- this is a comment

ex2 :: Double
ex2 = 3 * (4.2 + 5.6)  -- arithmetic operators "overloaded"

ex3 :: Char
ex3 = 'a'              -- 'a', 'b', 'c', etc. built-in `Char` values

ex4 :: Bool
ex4 = True             -- True, False are builtin Bool values

ex5 :: Bool
ex5 = False
```

QUIZ: Basic Operations

$$ENV \vdash e_3 : T$$

$$\frac{ENV \vdash e_1 : Bool \qquad ENV \vdash e_2 : T}{ENV \vdash \text{if } e_1 \text{ then } e_2 \text{ else } e_3 : T}$$

```
ex6 :: Int
ex6 = 4 + 5

ex7 :: Int
ex7 = 4 * 5

ex8 :: Bool
ex8 = 5 > 4

quiz :: ???
quiz = if ex8 then ex6 else ex7
```

?

bool int int

What is the *type* of `quiz` ?

A. `Int`

B. `Bool`

C. Error!

QUIZ: Basic Operations

```
ex6 :: Int
ex6 = 4 + 5      => 9

ex7 :: Int
ex7 = 4 * 5

ex8 :: Bool
ex8 = 5 > 4      =>  TRUE

quiz :: ???
quiz = if ex8 then ex6 else ex7
          TRUE
```

What is the *value* of `quiz`?

A. `9`

B. `20`

C. Other!

$\backslash x \rightarrow e$

In $\rightarrow$ Out

Function Types

In Haskell, a **function is a value** that has a type

```
A -> B
```

A function that

- takes *input* of type `A`
- returns *output* of type `B`

For example

```
isPos :: Int -> Bool
isPos = \n -> (x > 0)
```

Int Bool

Define **function-expressions** using `\` like in λ-calculus!

But Haskell also allows us to put the parameter on the *left*

```
isPos :: Int -> Bool
isPos n = (x > 0)
```

(Meaning is **identical** to above definition with `\n -> ...`)

isPos 12

Multiple Argument Functions

A function that

- takes three *inputs* `A1`, `A2` and `A3`
- returns one *output* `B` has the type

```
A1 -> A2 -> A3 -> B
```

out

For example

```
pat :: Int -> Int -> Int -> Int
pat = \x y z -> x * (y + z)
```

which we can write with the params on the *left* as

```
pat :: Int -> Int -> Int -> Int
pat x y z = x * (y + z)
```

QUIZ

What is the type of `quiz` ?

```
quiz :: ???
quiz x y = (x + y) > 0
```

A. `Int -> Int`

B. `Int -> Bool`

C. `Int -> Int -> Int`

D. `Int -> Int -> Bool`

E. `(Int, Int) -> Bool` ?

$$\texttt{quiz} = \backslash \underset{\text{Int}}{x} \to \boxed{\backslash \underset{\text{Int}}{y} \to \overbrace{\overbrace{(\underset{\text{Int}}{x}+\underset{\text{Int}}{y})}^{\text{Int}} > 0}^{\text{Bool}}}$$

$$\text{Int} \to (\text{Int} \to \text{Bool})$$

Function Calls

A function call is *exactly* like in the λ-calculus

```
e1 e2
```

fun arg.

where `e1` is a function and `e2` is the argument. For example

```
>>> isPos 12
True

>>> isPos (0 - 5)
False
```

Multiple Argument Calls

With multiple arguments, just pass them in one by one, e.g.

```
(((e e1) e2) e3)
```

For example

```
>>> pat 31 42 56
3038
```

EXERCISE

Write a function `myMax` that returns the *maximum* of two inputs

```
myMax :: Int -> Int -> Int
myMax = ???
```

When you are done you should see the following behavior:

```
>>> myMax 10 20
20

>>> myMax 100 5
100
```

EXERCISE

Write a function `sumTo` such that `sumTo n` evaluates to `0 + 1 + 2 + ... + n`

```
sumTo :: Int -> Int
sumTo n = ???
```

$0 + 1 + 2 + \dots + n$

When you are done you should see the following behavior:

```
>>> sumTo 3
6
>>> sumTo 4
10
>>> sumTo 5
15
```

$= 0+1+2+3 = 6$

$= 0+1+2+3+4 = 10$

$= 0+1+2+3+4+5 = 15$

How to Return Multiple Outputs?

FST (Pair apple banana)

=> apple

SND ( )

=> banana.

Tuples

A type for packing `n` different kinds of values into a single "struct"

```
(T1,..., Tn)
```

For example

$$\frac{ENV \vdash e_1 :: T_1 \qquad ENV \vdash e_2 :: T_2}{ENV \vdash \underline{(e_1, e_2)} :: (T_1, T_2)}$$

```
tup1 :: ???
tup1 = ('a', 5)

tup2 :: (Char, Double, Int)
tup2 = ('a', 5.2, 7)
```

QUIZ

What is the type `???` of `tup3`?

```
tup3 :: ???
tup3 = ((7, 5.2), True)
```

(Int, Double)

(?, Bool)

A. `(Int, Bool)`

B. `(Int, Double, Bool)`

C. `(Int, (Double, Bool))`

? **D.** `((Int, Double), Bool)`

? **E.** `(Tuple, Bool)`

Extracting Values from Tuples

We can **create** a tuple of three values `e1`, `e2`, and `e3` ...

```
tup = (e1, e2, e3)
```

... but how to **extract** the values from this tuple?

Pattern Matching via **`case-of`** expressions

```
fst3 :: (t1, t2, t3) -> t1
fst3 t = case t of
           (x1, x2, x3) -> x1

snd3 :: (t1, t2, t3) -> t2
snd3 t = case t of
           (x1, x2, x3) -> x2

thd3 :: (t1, t2, t3) -> t3
thd3 t = case t of
           (x1, x2, x3) -> x3
```

QUIZ

What is the value of `quiz` defined as

```haskell
tup2 :: (Char, Double, Int)
tup2 = ('a', 5.2, 7)

snd3 :: (t1, t2, t3) -> t2
snd3 t = case t of
           (x1, x2, x3) -> x2

quiz = snd3 tup2
```

A. `'a'`

B. `5.2`

C. `7`

D. `('a', 5.2)`

E. `(5.2, 7)`

Lists

Unbounded Sequence of values of type `T`

$\boxed{[T]}$

$[\quad]$

For example

```
chars :: [Char]
chars = ['a', 'b', 'c']

ints :: [Int]
ints = [1, 3, 5, 7]

pairs :: [(Int, Bool)]
pairs = [(1,True), (2,False)]
```

$$\frac{ENV \vdash e_1 :: T \quad \ldots \quad ENV \vdash e_n :: T}{ENV \vdash [e_1, e_2, \ldots, e_n] :: [T]}$$

QUIZ

What is the type of `things` defined as

[Int]

```
things :: ???
things = [ [1], [2, 3], [4, 5, 6] ]
```

[Int] [Int]

A. `[Int]`

B. `([Int], [Int], [Int])`

C. `[(Int, Int, Int)]`

D. `[[Int]]`

[[Int]]

E. `List`

List's Values Must Have The SAME Type!

The type `[T]` denotes an unbounded sequence of values of type `T`

Suppose you have a list

```
oops = [1, 2, 'c']
```

There is no `T` that we can use

- As last element is not `Int`
- First two elements are not `Char`!

Result: Mysterious Type Error!

Constructing Lists

There are two ways to construct lists

"Nil"
"Cons"

```
[]      -- creates an empty list
h:t     -- creates a list with "head" 'h' and "tail" t
```

For example

```
>>> 3 : []
[3]

>>> 2 : (3 : [])
[2, 3]

>>> 1 : (2 : (3 : []))
[1, 2, 3]
```

Cons Operator `:` is Right Associative

`x1 : x2 : x3 : x4 : t` means `x1 : (x2 : (x3 : (x4 : t)))`

So we can just avoid the parentheses.

Syntactic Sugar

Haskell lets you write `[x1, x2, x3, x4]` instead of `x1 : x2 : x3 : x4 : []`

Functions Producing Lists

Lets write a function `copy3` that

- takes an input `x` and
- returns a list with *three* copies of `x`

```
copy3 :: ???
copy3 x = ???
```

When you are done, you should see the following

```
>>> copy3 5
[5, 5, 5]

>>> copy3 "cat"
["cat", "cat", "cat"]
```

Lets write some Functions

A Recipe (https://www.htdp.org/)

Step 1: Write some tests

Step 2: Write the type

Step 3: Write the code

PRACTICE: Clone

Write a function `clone` such that `clone n x` returns a list with `n` copies of `x`.

1. Tests

When you are done you should see the following behavior

```
>>> clone 0 "cat"
[]

>>> clone 1 "cat"
["cat"]

>>> clone 2 "cat"
["cat", "cat"]

>>> clone 3 "cat"
["cat", "cat", "cat"]

>>> clone 3 100
[100, 100, 100]
```

2. Types

```
clone :: ???
```

3. Code

```
clone n x = ???
```

How does `clone` execute?

(Substituting equals-by-equals!)

```
clone 3 100
  =*> ???
```

EXERCISE: Range

lo

Write a function `range` such that `range i j` returns the list of values `[i, i+1, ..., j]`

hi

```
range :: ???
range i j = ???
```

1. Tests

```
>>> range 4 3
[]

>>> range 3 3
[3]

>>> range 2 3
[2, 3]

>>> range 1 3
[1, 2, 3]

>>> range 0 3
[0, 1, 2, 3]
```

2. Type

```
range :: ???
```

3. Code

```
range = ???
```

Functions Consuming Lists

So far: how to *produce* lists.

Next how to *consume* lists!

EXERCISE

Lets write a function `firstElem` such that `firstElem xs` returns the *first* element `xs` if it is a non-empty list, and `0` otherwise.

HINT: How to *extract* values from a list?

1. Tests

When you are done you should see the following behavior:

```
>>> firstElem []
0

>>> firstElem [10, 20, 30]
10

>>> firstElem [5, 6, 7, 8]
5
```

2. Type

```
firstElem :: ???
```

3. Code

```
firstElem = ???
```

QUIZ

Suppose we have the following `mystery` function

```
mystery :: [a] -> Int
mystery l = case l of
              []     -> 0
              (x:xs) -> 1 + mystery xs
```

What does `mystery [10, 20, 30]` evaluate to?

A. `10`

B. `20`

C. `30`

D. `3`

E. `0`

EXERCISE: Summing a List

Write a function `sumList` such that `sumList [x1, ..., xn]` returns `x1 + ... + xn`

1. Tests

When you are done you should get the following behavior:

```
>>> sumList []
0

>>> sumlist [3]
3

>>> sumlist [2, 3]
5

>>> sumlist [1, 2, 3]
6
```

2. Type

```
sumList :: [Int] -> Int
```

3. Code

```
sumList = ???
```

Functions on lists: `take`

Let's write a function to `take` first `n` elements of a list `xs` .

1. Tests

````
-- >>> ???
````

2. Type

````
take :: ???## Some useful library functions

```haskell
-- | Length of the list
length :: [t] -> Int

-- | Append two lists
(++) :: [t] -> [t] -> [t]

-- | Are two lists equal?
(==) :: [t] -> [t] -> Bool
````

You can search for library functions on Hoogle (https://www.haskell.org/hoogle/)!
````

~~~
**3. Code**

```haskell
take = ???
~~~

Some useful library functions

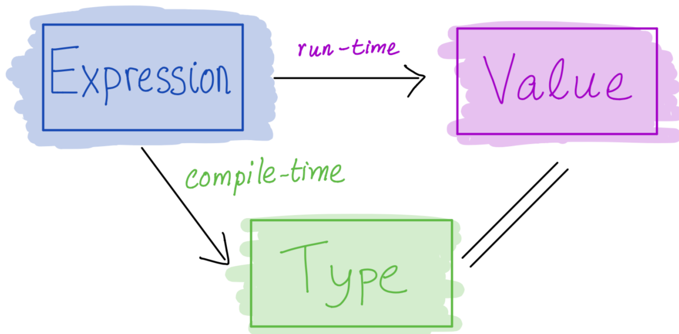
```haskell
-- | Length of the list
length :: [t] -> Int

-- | Append two lists
(++) :: [t] -> [t] -> [t]

-- | Are two lists equal?
(==) :: [t] -> [t] -> Bool
```

You can search for library functions on Hoogle (https://www.haskell.org/hoogle/)!

Recap



- Core program element is an **expression**
- Every *valid* expression has a **type** (determined at compile-time)
- Every *valid* expression reduces to a *value* (computed at run-time)

Execution

- Basic values & operators
- Execution / Function Calls just *substitute equals by equals*
- Pack data into *tuples* & *lists*
- Unpack data via *pattern-matching*
