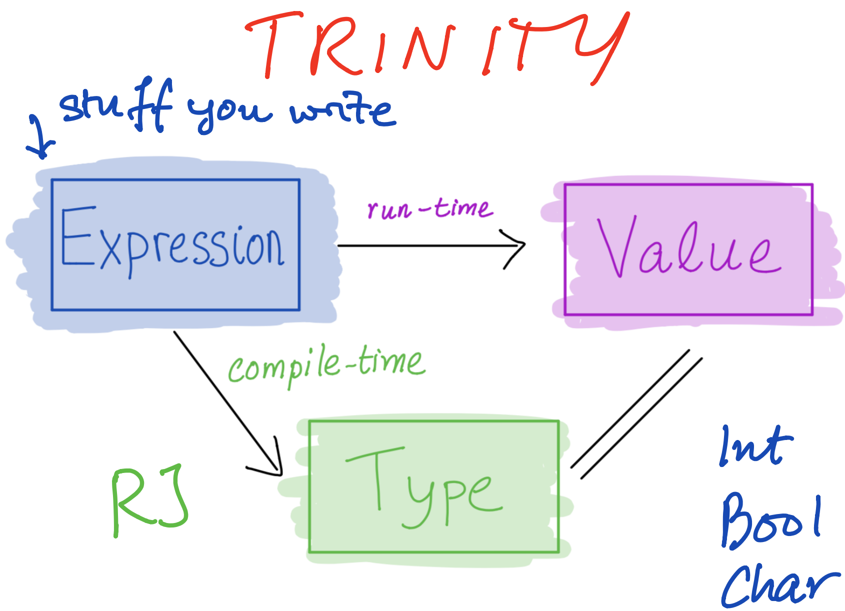
Types



In *Haskell* every expression either

- **ill-typed** and *rejected at compile time* or
- **has a type** and can be *evaluated* to obtain _ **a value** of the same type.

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

- **like** in Java
- **unlike** λ-calculus or Python …

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

Microsoft TS   FB Flow   'FB' Hack

mypy

Lisp Racket   Python, JS, Ruby, PHP

Why are types good?   2000-2010

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

make junk values not representable

Type annotations

You can annotate your bindings with their types using `::`, like so:

```haskell
-- | This is a Boolean:
haskellIsAwesome :: Bool
haskellIsAwesome = True

-- | This is a string
message :: String
message = if haskellIsAwesome
            then "I love CSE 130"
            else "I'm dropping CSE 130"

-- | This is a word-size integer
rating :: Int
rating = if haskellIsAwesome then 10 else 0

-- | This is an arbitrary precision integer
bigNumber :: Integer
bigNumber = factorial 100
```

If you omit annotations, GHC will infer them for you

- Inspect types in GHCi using `:t`
- You should annotate all top-level bindings anyway! (Why?)

Function Types

Functions have **arrow types**:

- `\x -> e` has type `A -> B`
- if `e` has type `B` assuming `x` has type `A`

For example:

```
> :t (\x -> if x then `a` else `b`)  -- ???
```

Always annotate your function bindings

First understand *what the function does*

- Before you think about *how to do it*

```
sum :: Int -> Int
sum 0 = 0
sum n = n + sum (n - 1)
```

*When you have *multiple arguments*

For example

```
add3 :: Int -> (Int -> (Int -> Int))
add3 x y z = x + y + z
```

why? because the above is the same as:

```
add3 :: Int -> (Int -> (Int -> Int))
add3 = \x -> (\y -> (\z -> x + y + z))
```

however, as with the lambdas, the `->` **associates to the right** so we will just write:

```
add3 :: Int -> Int -> Int -> Int
add3 x y z = x + y + z
```

(+) = \x y -> 'call x86 inst to add x,y'

$(t_1 \to (t_2 \to (t_3 \to T)))$

Int → Bool

List T

Lists

A list is

- either an *empty list*

  ```
  [] -- pronounced "nil"
  ```

- or a *head element* attached to a *tail list*

  ```
  x:xs -- pronounced "x cons xs"
  ```

Examples:

```haskell
[]                -- A list with zero elements

1 : []            -- A list with one element: 1

(:) 1 []          -- As above: for any infix op, `x op y` is same as `(op) x y`

1:(2:(3:(4:[])))  -- A list with four elements: 1, 2, 3, 4

1:2:3:4:[]        -- Same thing (: is right associative)

[1,2,3,4]         -- Same thing (syntactic sugar)
```

Terminology: constructors and values

`[]` and `(:)` are called the *list* **constructors**

We've seen constructors before:

- `True` and `False` are `Bool` constructors
- `0`, `1`, `2` are ... well, you can think of them as `Int` constructors

- The `Int` constructors don’t take any parameters, we just called them *values*

In general, a **value** is a constructor applied to **other values**

- examples above are *list* values

The Type of a List

A list has type `[Thing]` if each of its elements has type `Thing`

Examples:

```haskell
intList :: [Int]
intList = [1,2,3,4]

boolList :: [Bool]
boolList = [True, False, True]

strList :: [String]
strList = ["nom", "nom", "burp"]
```

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

Functions on lists: range

1. Tests lo hi

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

2. Type

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

3. Code

```
range = ???
```

Syntactic Sugar for Ranges

There's also syntactic sugar for this!

```
[1..7]     -- [1,2,3,4,5,6,7]
[1,3..7]   -- [1,3,5,7]
```

Functions on lists: length

1. Tests

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

2. Type

```
len :: ???
```

3. Code

```
len = ???
```

Pattern matching on lists

```
-- | Length of the list
len :: [Int] -> Int
len []     = 0
len (_:xs) = 1 + len xs
```

~~A pattern is either a *variable* (incl. `_`) or a *value*~~

A pattern is

- either a *variable* (incl. `_`)
- or a *constructor* applied to other *patterns*

Pattern matching attempts to match *values* against *patterns* and, if desired, *bind* variables to successful matches.

Functions on lists: `take`

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

1. Tests

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

2. Type

```
take :: ???
```

3. Code

```
take = ???
```

QUIZ

Which of the following is **not** a pattern?

A. `(1:xs)`

B. `(_:_:_)`

C. `[x]`

D. `[1+2,x,y]`

E. all of the above

Strings are Lists-of-Chars

For example

```
λ> let x = ['h', 'e', 'l', 'l', 'o']
λ> x
"hello"

λ> let y = "hello"

λ> x == y
True

λ> :t x
x :: [Char]

λ> :t y
y :: [Char]
```

shout Shout SHOUT

How can we convert a string to upper-case, e.g.

```
ghci> shout "like this"
"LIKE THIS"

shout :: String -> String
shout s = ???
```

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/)!

Tuples

```haskell
myPair :: (String, Int)  -- pair of String and Int
myPair = ("apple", 3)
```

`(,)` is the *pair constructor*

Field access

Using `fst` and `snd`

```
ghci> fst ("apple", 22)
"apple"

ghci> snd ("apple", 22)
22
```

Tuples to pass parameters

```
add2 :: (Int, Int) -> Int
add2 p = fst p + snd p
```

but watch out, `add2` expects a tuple.

```haskell
exAdd2_BAD = add2 10 20      -- type error

exAdd2_OK  = add2 (10, 20)   -- OK!
```

Tuples and Pattern Matching

It is often clearer to use *patterns* for tuples, e.g.

```haskell
add2 :: (Int, Int) -> Int
add2 p = let (x, y) = p in
           x + y
```

or equivalently,

```haskell
add2 :: (Int, Int) -> Int
add2 p    = x + y
  where
   (x, y) = p
```

or, best, use the pattern in the parameter,

```haskell
add2 :: (Int, Int) -> Int
add2 (x, y) = x + y
```

You can use pattern matching not only in equations, but also in λ-bindings and **`let`**-bindings!

QUIZ: Pattern matching with pairs

Is this pattern matching correct? What does this function do?

```
quiz :: String -> [(String, Int)] -> Int
quiz _ []     = 0
quiz x ((k,v) : ps)
  | x == k    = v
  | otherwise = quiz x ps
```

What is `quiz "dog" [ ("cat", 10), ("dog", 20), ("cat", 30)]` ?

A. Type error!

B. `0`

C. `10`

D. `20`

Generalized Tuples

Can we implement triples like in λ-calculus?

Sure! but Haskell has native support for n-tuples:

```haskell
myPair   :: (String, Int)
myPair   = ("apple", 3)

myTriple :: (Bool, Int, [Int])
myTriple = (True, 1, [1,2,3])

my4tuple :: (Float, Float, Float, Float)
my4tuple = (pi, sin pi, cos pi, sqrt 2)
```

The "Empty" Tuple

It also makes sense to have an 0-ary tuple:

```haskell
myUnit :: ()
myUnit = ()
```

often used like `void` in other languages.

List comprehensions

A convenient way to construct lists!

QUIZ

What is the result of evaluating:

```
quiz = [ 10 * i | i <- [0,1,2,3,4,5]]
```

A. Infinite loop **B.** `[]` **C.** `[0, 10, 20, 30, 40, 50]` **D.** `150` **E.** Type error

Comprehensions and Ranges

Recall you can *enumerate* ranges as

```
ghci> [0..5]
[0,1,2,3,4,5]
```

So, we can write the above more simply

```
quiz = [ 10 * i | i <- [0..5] ]
```

QUIZ: Composing Comprehensions

What is the result of evaluating

```
quiz = [(i,j) | i <- [0, 1]      -- a first selection
              , j <- [0, 1] ]    -- a second selection
```

A. Type error **B.** `[]` **C.** `[0,1]` **D.** `[(0,0), (1,1)]` **E.** `[(0,0), (0,1, (1,0), (1,1)]`

QUIZ: Composing Comprehensions

What is the result of evaluating

```
quiz = [(i,j) | i <- [0, 1]
              , j <- [0, 1]
              , i == j      ]    -- condition!
```

A. Type error **B.** `[]` **C.** `[0,1]` **D.** `[(0,0), (1,1)]` **E.** `[(0,0), (0,1, (1,0), (1,1)]`

shout revisited

How can we convert a string to upper-case, e.g.

```
ghci> shout "like this"
"LIKE THIS"
```

Use comprehensions to write a *non-recursive" `shout` ?

```
shout :: String -> String
shout s = ???
```

QuickSort in Haskell

Step 1: Write some tests

```
-- >>> sort []
-- ???

-- >>> sort [10]
-- ???

-- >>> sort [12, 1, 10]
-- ???
```

Step 2: Write the type

```
sort :: ???
```

Step 3: Write the code

```
sort []     = ???
sort (x:xs) = ???

sort :: [Int] -> [Int]
sort []     = []
sort (x:xs) = sort ls ++ [x] ++ sort rs
  where
    ls      = [ l | l <- xs, l <= x ]
    rs      = [ r | r <- xs, x <  r ]
```

Haskell is purely functional

Functional = functions are *first-class values*

Pure = a program is an expression that evaluates to a value

- no side effects!
- unlike in Python, Java, etc:

```
public int f(int x) {
  calls++;                         // side effect: global variable update!
  System.out.println("calling f"); // side effect: writing to screen!
  launchMissile();                 // side effect: can't bring back home!
  return x * 2;
}
```

- in Haskell, a function of type `Int -> Int` Computes a *single integer output* from a *single integer input* Does **nothing else**

Referential transparency: The same expression always evaluates to the same value

Why is this good?

- easier to reason about (remember `x++` vs `++x` in C++?)
- enables compiler optimizations
- especially great for parallelization (`e1 + e2` : we can always compute `e1` and `e2` in parallel!)

QUIZ

The function `head` returns the first element of a list.

What is the result of:

```haskell
goBabyGo :: Int -> [Int]
goBabyGo n = n : goBabyGo (n + 1)

quiz :: Int
quiz = head (goBabyGo 0)
```

A. Loops forever **B.** Type error **C.** `0` **D.** `1`

Haskell is Lazy

An expression is evaluated only when its result is needed!

```
ghci> take 2 (goBabyGo 1)
[1,2]
```

Why?

```
        take 2 (goBabyGo 1)
=>      take 2 (1 : goBabyGo 2)
=>      take 2 (1 : 2 : goBabyGo 3)
=> 1:   take 1 (    2 : goBabyGo 3)
=> 1:2: take 0 (        goBabyGo 3)
=> 1:2: []
```

Why is this good?

- can implement cool stuff like infinite lists: `[1..]`

  ```
  -- first n pairs of co-primes:
  take n [(i,j) | i <- [1..],
                  j <- [1..i],
                  gcd i j == 1]
  ```

- encourages simple, general solutions

- but has its problems too :(

That's all folks!
