LiU-FP2016: Lecture 1

Review of Haskell:
A lightening tour in 90 minutes

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This Lecture (1)

Review of basic Haskell features and concepts:

- Recap of much of the first few chapters of Learn You a Haskell. Your chance to:
  - ask questions
  - catch up :-)
- Introduce you to some additional features that we will use or are generally useful.
- Point out some common pitfalls

What is a Functional Language? (1)

Which functional languages are you aware of?

Surprisingly hard to give a precise definition. One reasonable if pragmatic view:

- Functional programming is a ***style*** of programming in which the basic method of computation is function application.
- A functional language is one that ***supports*** and ***encourages*** the functional style.

(Another, complementary perspective later.)

What Is a Functional Language? (2)

This "definition" covers:

- ***Pure*** functional languages: no side effects
  - (Weakly) declarative: equational reasoning valid (with care); ***referentially transparent***.
  - Examples: Haskell, Agda, Idris, Elm
- ***Mostly*** functional languages: some side effects
  - Equational reasoning valid for pure fragments.
  - Examples: ML, OCaml, Scheme, Erlang
- Arguably even covers ***multi-paradigm*** languages
  - Examples: F#, Scala, JavaScript

Example: Computing Sums (1)

Summing the integers from 1 to 10000 in Java:

```
total = 0;
for (i = 1; i <= 10000; ++i)
    total = total + 1;
```

The method of computation is to ***execute operations in sequence***, in particular ***variable assignment***.

Example: Computing Sums (2)

Summing the integers from 1 to 10000 in the functional language Haskell:

```
sum [1..10000]
```

The method of computation is ***function application***.

Of course, essentially the same program could be written in, say, Java. Does that make Java a functional language? ***Discuss!***

Example: Computing Sums (3)

Some reasons not to adopt the “functional approach” in Java:

- Syntactically awkward (even given suitable library definitions)
- Temporarily creating a list of 10000 integers just to add them seems highly objectionable; not good Java style.

But isn’t the second point a good argument against the “functional approach” in ***general***?

Example: Computing Sums (4)

Actually, no!

- ***Nothing says the entire list needs to be created at once.***
  In ***lazy*** languages, like Haskell, the list will be generated as needed, element by element.
- ***Nothing says the list needs to be created at all!***
  Compilers for functional languages, thanks to equational reasoning being valid, are often able to completely ***eliminate*** intermediate data structures.

Example: Computing Sums (5)

- Note that the Haskell code is ***modular***, while the Java code is not.
- Being overly prescriptive regarding computational details (evaluation order) often hampers modularity.

We will discuss the last point in more depth later.

Typical Functional Features (1)

Nevertheless, some typical features and characteristics of functional languages can be identified:

- Light-weight notation geared at
  - defining functions
  - expressing computation through function application.
- Functions are first-class entities.
- Recursive (and co-recursive) function and data definitions central.

Typical Functional Features (2)

- Implementation techniques aimed at executing code expressed in a functional style efficiently.

More?

This and the Following Lectures

- In this and the following lectures we will explore ***Purely Functional Programming*** in the setting of ***Haskell***.
- Some themes:
  - Lazy evaluation
  - Purely functional data structures
  - Effects purely
  - Advanced typeful programming

The GHC System (1)

- GHC supports Haskell 98, Haskell 2010, and many extensions
- GHC is currently the most advanced Haskell system available
- GHC is a compiler, but can also be used interactively: ideal for serious development as well as teaching and prototyping purposes

The GHC System (2)

On a Unix system, GHCi can be started from the prompt by simply typing the command `ghci`:

```
isis-1% ghci
   ___         ___ _
  / _ \ /\  /\/ __(_)
 / /_\// /_/ / /  | |      GHC Interactive, version 6.3, for Haskell 98.
/ /_\\/ __  / /___| |      http://www.haskell.org/ghc/
\____/\/ /_/\____/|_|      Type :? for help.

Loading package base ... linking ... done.
Prelude>
```


The GHC System (3)

The GHCi > prompt means that the GHCi system is ready to evaluate an expression.
For example:

```
> 2+3*4
14

> reverse [1,2,3]
[3,2,1]

> take 3 [1,2,3,4,5]
[1,2,3]
```


Function Application (1)

In mathematics, function application is denoted using parentheses, and multiplication is often denoted using juxtaposition or space.

```
f(a,b) + c d
```

“Apply the function `f` to `a` and `b`, and add the result to the product of `c` and `d`.”

Function Application (2)

In Haskell, ***function application*** is denoted using ***space***, and multiplication is denoted using `*`.

```
f a b + c*d
```

Meaning as before, but Haskell syntax.

Function Application (3)

Moreover, function application is assumed to have ***higher priority*** than all other operators. For example:

```
f a + b
```

means

```
(f a) + b
```

not

```
f (a + b)
```


What is a Type?

Deep question! But for now:

A ***type*** is a name for a collection of related values. For example, in Haskell the basic type

```
Bool
```

contains the two logical values

```
False True
```

(Haskell's type system is ***nominal*** as opposed to structural: a type is only equal to itself.)

Types in Haskell

- If evaluating an expression e would produce a value of type t, then e has type t, written

  e :: t

- Every well-formed expression has a type. It can ***usually*** be calculated automatically at compile time using a process called ***type inference*** or ***type reconstruction*** (Hindley-Milner).
- However, giving manifest type declarations for at least top-level definitions is good practice.
- Sometimes ***necessary*** to state type explicitly, e.g. polymorphic recursion.

Basic Types

Haskell has a number of ***basic types***, including:

`Bool`	Logical values
`Char`	Single characters
`Int`	Fixed-precision integers
`Integer`	Arbitrary-precision integers
`Double`	Double-precision floating point

List Types (1)

A ***list*** is sequence of values of the ***same*** type:

```
[False,True,False] :: [Bool]

['a','b','c','d']  :: [Char]
```

In general:

`[`t`]` is the type of lists with elements of type t.

List Types (2)

Haskell defines the string type to be a list of characters:

```
type String = [Char]
```

String syntax is supported. For example:

```
"abcd" = ['a','b','c','d']
```

Note that the keyword `type` just introduces a ***type synonym*** or ***type alias***. In contrast, `data` and `newtype` introduce new types.

Tuple Types

A tuple is a sequence of values of ***different*** types:

```
(False,True)        :: (Bool,Bool)

(False,'a',True) :: (Bool,Char,Bool)
```

In general:

$(t_1, t_2, \ldots, t_n)$ is the type of n-tuples whose i^{th} component has type t_i for $i \in [1 \ldots n]$.

Aside: Naming Conventions

Haskell ***enforces*** certain naming conventions. For example:

- Type constructors (like `Bool`) and value constructors (like `True`) always begin with a capital letter.
- Variables (including function names) always begin with a lowercase letter.

A somewhat similar convention applies to infix operators where constructors are distinguished by starting with a colon (`:`).

Function Types (1)

A ***function*** is a mapping from values of one type to values of another type:

```
not   :: Bool -> Bool
```

In general:

t_1 `->` t_2 is the type of functions that map values of type t_1 to values to type t_2.

Function Types (2)

If a function needs more than one argument, pass a tuple, or use ***Currying***:

```
(&&) :: Bool -> Bool -> Bool
```

This really means:

```
(&&) :: Bool -> (Bool -> Bool)
```

Idea: a function is applied to its arguments one by one. This allows ***partial application***.

Aside: Functions and Operators

- Any (infix) operator can be used as a (prefix) function by enclosing it in parentheses. E.g.:
  ```
  True && False
  ```
  is equivalent to
  ```
  (&&) True False
  ```
- Any function can be used as an operator by enclosing it in back quotes. E.g.:
  ```
  add 1 2
  ```
  is equivalent to
  ```
  1 `add` 2
  ```

Polymorphic Functions (1)

A function is called ***polymorphic*** ("of many forms") if its type contains one or more type variables.

```
length :: [a] -> Int
```

"For any type `a`, `length` takes a list of values of type `a` and returns an integer."

This is called ***Parametric Polymorphism***.

Polymorphic Functions (2)

The type signature of length is really:

```
length :: forall a . [a] -> Int
```

- It is understood that `a` is a type variable, and thus it ranges over all possible types.
- Haskell 2010 does not allow explicit `forall`s: all type variables are implicitly qualified at the outermost level.
- GHC extensions allow explicit `forall`s (e.g. `-XRankNTypes` or equivalent `LANGUAGE` pragma).

Exercise 1

Given:

```
id :: a -> a
not :: Bool -> Bool
foo :: (a -> a) -> a -> a
fie :: (forall a . a -> a) -> a -> a
```

what is the type of each of:

```
foo id  :: ?? forall a . a -> a
foo not :: ?? Bool -> Bool
fie id  :: ?? forall a . a -> a
fie not :: ?? Type error
```


Types are Central in Haskell

Some reasons:

- Expressive type system:
  - Parametric Polymorphism
  - Type classes
  - Many extensions ...
- Types say a ***lot*** about a function because Haskell is a pure language: no side effects (Referential Transparency).
  For example, a function of type `Int -> Int` can only return an integer (or fail to terminate, which admittedly is a side effect).

Parametricity

In fact, due to a property called ***parametricity***, it goes even further: polymorphic types give rise to ***free theorems*** (Wadler 1989). For example:

For ***any*** function `r :: forall a . [a]->[a]`, and every total function `f ::` t_1 `->` t_2 for some specific types t_1 and t_2, we have:

```
map f . r  =  r . map f
```

This holds by virtue of `r`'s polymorphic type: no need to even consider its definition!

Hoogle

Hoogle is a Haskell API search engine:

`http://www.haskell.org/hoogle/`

Allows searching by function name or by ***approximate type signature***.

For example, searching on

```
(a -> b) -> [a] -> [b]
```

turns up `map`, `fmap`, . . .

Conditional Expressions

As in most programming languages, functions can be defined using ***conditional expressions***:

```
abs :: Int -> Int
abs n = if n >= 0 then n else -n
```

Alternatively, such a function can be defined using ***guards***:

```
abs :: Int -> Int
abs n | n >= 0     = n
      | otherwise = -n
```


Pattern Matching (1)

Many functions have a particularly clear definition using ***pattern matching*** on their arguments:

```
not :: Bool -> Bool
not False = True
not True  = False
```

Pattern Matching (2)

Case expressions allow pattern matching to be performed wherever an expression is allowed, not just at the top-level of a function definition:

```
not :: Bool -> Bool
not b = case b of
            False -> True
            True  -> False
```


Aside: Layout

Haskell uses ***layout*** (indentation) to group code into blocks. For example, the following is a ***syntax error***:

```
not b = case b of
            False -> True
           True  -> False
```

Alternatively, explicit braces and semicolons can be used. It's even possible to mix and match:

```
not b = case b of {
              False -> True ;
            True -> False }
```


List Patterns (1)

Internally, every non-empty list is constructed by repeated use of an operator `(:)` called ***"cons"*** that adds an element to the start of a list, starting from `[]`, the ***empty list***.

Thus:

```
[1,2,3,4]
```

means

```
1:(2:(3:(4:[])))
```


List patterns (2)

Functions on lists can be defined using `x:xs` patterns:

```
head :: [a] -> a
head (x:_)  = x

tail :: [a] -> [a]
tail (_:xs) = xs
```

(Aside: partial. Generally, Haskell programmers strive to avoid defining or using partial functions.)

Pattern Matching and Guards

Pattern matching and guards may be combined:

```
dropWhile :: (a->Bool) -> [a] -> [a]
dropWhile _ [] = []
dropWhile p xxs@(x:xs)
    | p x       = dropWhile p xs
    | otherwise = xxs
```

(Note the as-pattern (@).)

List Comprehensions

List comprehensions, similar to standard mathematical set notation, are very useful for expressing computations on lists:

```
[ x * x | x <- [1..10], odd x ]
= [1,9,25,49,81]

[ (x,y) | x <- [1..10],
          y <- [1..10],
          even (x + y) ]
= [(1,1),(1,3),(1,5),...
   ...(10,8),(10,10)]
```


Lambda Expressions

A function can be constructed without giving it a name by using a ***lambda expression***:

```
\x -> x + 1
```

"The nameless function that takes a number `x` and returns the result `x + 1`"

Note that the ASCII character \ stands for λ (lambda).

Currying Revisited

All functions in Haskell are (nested) λ-abstractions. This explains how Currying works.

For example:

```
add x y = x+y
```

means

```
add = \x -> (\y -> x+y)
```

Thus:

```
add 7 = (\x -> (\y -> x+y)) 7
      = (\y -> 7+y)
```

Aside: Operator Sections

Another syntactic nicety in Haskell is partially applied operators or ***operator sections***. For example:

```
(+1)  =  \x -> x + 1    Add 1
(1+)  =  \x -> 1 + x    Add 1
(*2)  =  \x -> x * 2    Multiply by 2
(/2)  =  \x -> x / 2    Divide by 2
(1/)  =  \x -> 1 / x    Reciprocal
```


Recursive Definitions

- Definitions in Haskell may in general be (mutually) recursive.
- Order of definition is immaterial.

```
foo x = ... fum (x - 1) ...
fie x = ... fie (x - 1) ...
fum x = ... foo (x - 1) ...
```

- To allow inference of maximally polymorphic types, definitions are grouped into minimal recursive groups prior to type checking.

Local Definitions

Haskell provides two ways to introduce local definitions:

- `let`-expressions
- `where`-clauses

```
f x = h x + c          g x = let
  where                        h x = x * x
    h x = x * x                c = 100
    c = 100                  in
                               h x + c
```

Again, the definitions can be (mutually) recursive.

Data Declarations (1)

A new type can be declared by specifying its set of values using a ***data declaration***. For example, `Bool` is in principle defined as:

```
data Bool = False | True
```

Data Declarations (2)

What happens is:

- A new type `Bool` is introduced
- ***Constructors*** (functions to build values of the type) are introduced:

  ```
  False :: Bool
  True :: Bool
  ```

  (In this case, just constants.)
- Because constructor functions are bijective, and thus in particular injective, pattern matching can be used to take values of defined types apart.

Data Declarations (3)

Values of new types can be used in the same ways as those of built in types. E.g., given:

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

we can define:

```
answers :: [Answer]
answers = [Yes,No,Unknown]

flip :: Answer -> Answer
flip Yes     = No
flip No      = Yes
flip Unknown = Unknown
```


Recursive Types (1)

New types can be declared in terms of themselves. That is, types can be (mutually) ***recursive***:

```
data Nat = Zero | Succ Nat
```

`Nat` is a new type with constructors

- `Zero :: Nat`
- `Succ :: Nat -> Nat`

Effectively, we get both a new way to form terms and typing rules for these new terms.

Recursive Types (2)

A value of type `Nat` is either `Zero`, or of the form `Succ n` where `n :: Nat`. That is, Nat contains the following infinite sequence of values:

```
Zero

Succ Zero

Succ (Succ Zero)
```

Recursion and Recursive Types

Using recursion, it is easy to define functions that convert between values of type `Nat` and `Int`:

```
nat2int :: Nat -> Int
nat2int Zero     = 0
nat2int (Succ n) = 1 + nat2int n

int2nat :: Int -> Nat
int2nat 0          = Zero
int2nat n | n >= 1 = Succ (int2nat (n - 1))
```


Parameterized Types

Types can also be parameterized on other types:

```
data List a = Nil | Cons a (List a)

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

Resulting constructors:

```
Nil  :: List a
Cons :: a -> List a -> List a
Leaf :: a -> Tree a
Node :: Tree a -> Tree a -> Tree a
```


Overloading (1)

Haskell supports a form of ***overloading***: using the same name to refer to different definitions depending on the involved types. For example:

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

This means `==` is defined for any type `a` belonging to the ***type class*** `Eq`.

This style of overloading is also known as ***ad hoc polymorphism***.

Overloading (2)

In particular, `Bool` and `Char` both belong to `Eq`, so the following two expressions are well-typed:

```
True == False
'a' == 'b'
```

Behind the scenes, the equality test is dispatched to the appropriate function for `Bool` and `Eq` respectively.

A powerful (and unusual) aspect of Haskell's approach to overloading is that overloading on the result type is possible. E.g.:

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

Overloading (3)

We will discuss type classes in more depth later. However, it is useful to know that Haskell allow class instances for new types to be ***derived*** for a handful of built in classes, notably `Eq`, `Ord`, and `Show`:

```
data Nat = Zero
         | Succ Nat
         deriving (Eq, Ord, Show)
```

Now `show (Succ (Succ Zero))` yields `"Succ (Succ Zero)"`.

Modules in Haskell (1)

- A Haskell program consists of a set of ***modules***.
- A module contains definitions:
  - functions
  - types
  - type classes
- The top module is called `Main`:

```
module Main where

main = putStrLn "Hello World!"
```


Modules in Haskell (2)

By default, only entities defined within a module are in scope. But a module can ***import*** other modules, bringing their definitions into scope:

```
module A where
f1 x = x + x
f2 x = x + 3
f3 x = 7

module B where
import A
g x = f1 x * f2 x + f3 x
```


The Prelude

There is one special module called the ***Prelude***. It is ***imported implicitly*** into every module and contains standard definitions, e.g.:

- Basic types (`Int`, `Bool`, tuples, `[]`, `Maybe`, `...`)
- Basic arithmetic operations (`+`, `*`, `...`)
- Basic tuple and list operations (`fst`, `snd`, `head`, `tail`, `take`, `map`, `filter`, `length`, `zip`, `unzip`, `...`)

(It is possible to explicitly exclude (parts of) the Prelude if necessary.)

Qualified Names (1)

The ***fully qualified name*** of an entity `x` defined in module `M` is `M.x`.

```
g x = A.f1 x * A.f2 x + f3 x
```

Note! Different from function composition!!! Always write function composition with spaces:

```
f . g
```

The module ***name space*** is ***hierarchical***, with names of the form $M_1 . M_2 . \ldots . M_n$. This allows related modules to be grouped together.

Qualified Names (2)

Fully qualified names can be used to resolve name clashes. Consider:

```
module A where          module C where
f x = 2 * x             import A
                        import B
module B where
f x = 3 * x             g x = A.f x + B.f x
```

Two ***different functions*** with the ***same unqualified name*** `f` in scope in `C`. Need to write `A.f` or `B.f` to disambiguate.

Import Variations

Another way to resolve name clashes is to be more precise about imports:

`import A (f1,f2)`	Only `f1` and `f2`
`import A hiding (f1,f2)`	Everything but `f1` and `f2`
`import qualified A`	All names from `A` imported fully qualified only.

Can be combined in all possible ways; e.g.:

```
import qualified A hiding (f1, f2)
```


Export Lists

It is also possible to be precise about what is ***exported***:

```
module A (f1, f2) where
...
```

Various abbreviations possible; e.g.:

- A type constructor along with all its value constructors
- Everything imported from a specific module

Labelled Fields (1)

Suppose we need to represent data about people:

- Name
- Age
- Phone number
- Post code

One possibility: use a tuple:

```
type Person = (String, Int, String, String)
henrik = ("Henrik", 25, "8466506", "NG92YZ")
```


Labelled Fields (2)

Problems? Well, the type does not say much about the purpose of the fields! Easy to make mistakes; e.g.:

```
getPhoneNumber :: Person -> String
getPhoneNumber (_, _, _, pn) = pn
```

or

```
henrik = ("Henrik", 25, "NG92YZ", "8466506")
```


Labelled Fields (3)

Can we do better? Yes, we can introduce a new type with ***named fields***:

```
data Person = Person {
                  name     :: String,
                  age      :: Int,
                  phone    :: String,
                  postcode :: String
              }
            deriving (Eq, Show)
```


Labelled Fields (4)

Labelled fields are just “syntactic sugar”: the defined type really is this:

```
data Person = Person String Int String String
```

and can be used as normal.

However, additionally, the field names can be used to facilitate:

- Construction
- Update
- Selection
- Pattern matching

Construction

We can construct data without having to remember the field order:

```
henrik = Person {
             age = 25,
             name = "Henrik",
             postcode = "NG92YZ",
             phone = "8466506"
         }
```


Update (1)

Fields can be "updated", creating new values from old:

```
> henrik { phone = "1234567" }
Person {name = "Henrik", age = 25,
phone = "1234567",
postcode = "NG92YZ"}
```

Note: This is a ***functional*** "update"! The old value is left intact.

Update (2)

How does "update" work?

```
henrik { phone = "1234567" }
```

gets translated to something like this:

```
f (Person a1 a2 _ a4) =
    Person a1 a2 "1234567" a4

f henrik
```


Selection

We automatically get a ***selector function*** for each field:

```
name     :: Person -> String
age      :: Person -> Int
phone    :: Person -> String
postcode :: Person -> String
```

For example:

```
> name henrik
"Henrik"
> phone henrik
"8466506"
```

Pattern matching

Field names can be used in pattern matching, allowing us to forget about the field order and pick *only* fields of interest.

```
phoneAge (Person {phone = p, age = a}) =
    p ++ ": " ++ show a
```

This facilitates adding new fields to a type as most of the pattern matching code usually can be left unchanged.

Multiple Value Constructors (1)

```
data Being = Person {
                 name     :: String,
                 age      :: Int,
                 phone    :: String,
                 postcode :: String
             }
           | Alien {
                 name      :: String,
                 age       :: Int,
                 homeworld :: String
             }
           deriving (Eq, Show)
```


Multiple Value Constructors (2)

It is OK to have the same field labels for different constructors as long as their types agree.

Distinct Field Labels for Distinct Types

It is *not* possible to have the same field names for *different* types! The following does not work:

```
data X = MkX { field1 :: Int }

data Y = MkY { field1 :: Int, field2 :: Int }
```

One work-around: use a prefix convention:

```
data X = MkX { xField1 :: Int }

data Y = MkY { yField1 :: Int, yField2:: Int}
```

Advantages of Labelled Fields

- Makes intent clearer.
- Allows construction and pattern matching without having to remember the field order.
- Provides a convenient update notation.
- Allows to focus on specific fields of interest when pattern matching.
- Addition or removal of fields only affects function definitions where these fields really are used.

Reading

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