EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Functional Programing

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Abstract

This is just the product of me taking notes on the lecture. Nothing official. If you find mistakes or have got any questions, please feel free to contact me. Cheers!

Contents

≫A programming language is a medium for expressing ideas (not to get a computer to perform operations) and only incidentally for machines to execute.≪

Harold Abelson and Gerald Jay Sussman

Links

Site 2014: `http://db.inf.uni-tuebingen.de/teaching/FunctionalProgrammingSS2014.html`
Site 2015: `http://db.inf.uni-tuebingen.de/teaching/FunctionalProgrammingWS2015-2016.html` Ilias: `http://goo.gl/rlqbkK`

Literature

- Bird:
  Thinking Functionally with Haskell, Cambridge University Press 2014
  `http://www.cs.ox.ac.uk/publications/books/functional/`

- Keller, Chakravarthy: "Learning Haskell", online course in development
  `http://learn.hfm.io/`

- Lipovača:
  Learn You a Haskell for Great Good
  No Starch Press 2011,
  `http://learnyouahaskell.com`

- O'Sullivan, Steward, Goerzen:
  Real World Haskell
  O'Reilly 2010
  `http://book.realworldhaskell.org`

- Haskell 2010 Report,
  `http://www.haskell.org/onlinereport/haskell2010`

1   Introduction

Computational model in Functional Programming: **reduction** (replace expression to values)
In Functional Programming, expressions are formed by applying functions to values.

1. Functions as in math: $x = y \Rightarrow f(x) = f(y)$

2. Functions are values (just like numbers, text ...)

	Functional	Imperative
program construction	function application and composition	statement sequencing
execution	reduction (expression evaluation)	state changes
semantics	lambda calculus	complex (denotational)

Example

$n \in \mathbb{N}, n \geq 2$ is a prime number *if* the set of non-trivial factors is empty:

$$n \text{ is prime} \Leftrightarrow \{ \, m \mid m \in \{2, \ldots, n-1\}, \, n \bmod m = 0\} = \emptyset$$

```haskell
-- Is n a prime number?
isPrime :: Integer -> Bool
isPrime n = factors n == []
  where
    factors :: Integer -> [Integer]
    factors n = [ m | m <- [2..n-1], mod n m == 0 ]


main :: IO ()
main = do
  let n = 43
  print (isPrime n)
```

2   Haskell Ramp-Up

(Read $\equiv$ as "denotes the same value as")

- Apply f to value e: `f` e (juxtaposition, "apply", binary operator ␣, Haskell speak: infixL 10 ␣)

- ␣ has max precedence (10): `f` e_1 `+` e_2 $\equiv$ `(f` e_1`)` `+` e_2

- ␣ associates to the left: `g` `f` `e` $\equiv$ `(g f) e` `--(g f) is a function)`

- Function composition:

  - `(g . f) e` $\equiv$ `g (f e)` `--(. is something like mathematical |∘| ''after'')`
  - Alternative "apply"-operator `$` (lowest precedence, associates to the right, infixR 0 $):
    `g $ f $ e` $\equiv$ `g $ (f $ e)` $\equiv$ `g (f e)`
  - Prefix application of binary infix operator $\otimes$: `(`$\otimes$`)` e_1 e_2 $\equiv$ e_1 $\otimes$ e_2
  - Infix application of binary function f: e_1 `` `f` `` e_2 $\equiv$ `f` e_1 e_2:

    * `1` `` `elem` `` `[`1`,`2`,`3`]` `--(`$1 \in \{1,2,3\}$`)`
    * `n` `` `mod` `` `m`
    * ...
  - User defined operators, built from symbols
    ! # $ % & * + / ¡ = ¿ ? \ˆ |~:.

2.1   Function Application

Any series of identifiers is a function call or, as we often call it, a function application.
`a` b c d
This is an application of a function a to three arguments b, c and d.
You may parenthesize function application if you need to.
`f` a b $\equiv$ `(f a b)` $\not\equiv$ `f (a, b)`
The last one is valid Haskell, but f is a function that takes a pair, `(a, b)` as an argument.

3 Values and Types

Any Haskell expression e has a type t (`e :: t`) that is determined at compile time. The **type assigmnent ::** is either given explicitly or inferred by the compiler.

3.1 Base Types

Type	Description	values
Int	fixed-prec. integer	0, 1, (-42)
Integer	arbitrary prec. integer	$10\hat{\ }100$
Float, Double	single/double floating point (IEEE)	0.1, 1e02
Char	Unicode character	"x", "\t", "△", "\8710"
Bool	Boolean	True, False
()	Unit	()

3.2 Type Constructors

- Build new types from existing types

- Let a, b . . . denote arbitrary types (**type variables**)

Type	Description	values
(a, b)	pairs of values of type a, b	`(1, True) :: (Int, Bool)`
$(a_1, a_2, \ldots a_n)$	n-tuples	
[a]	list of values of type a	`[True, False] :: [Bool], []::[a]`
Maybe a	optional value of type a	`Just 42 :: Maybe Int` `Nothing :: Maybe a`
Either a b	choice	`Left 'x' :: Either Char b` `Right pi :: Either a Double`
IO a	I/O actions that return a value of type a	`print 42 :: IO ()`
a -> b	functions from a to b	`isLetter :: Char -> Bool`

3.3 Currying

Currying is the technique of translating the evaluation of a function that takes multiple arguments into evaluating a sequence of functions, each with a single argument.

- *Recall*: e_1 `++` e_2 ≡ `(++)` e_1 e_2

- `(++)` e_1 e_2 ≡ `((++)` e_1`)` e_2

- Function application happens one argument at a time.

(**Currying**, Haskell B. Curry)

- Type of n-ary function is
  a_1 `->` a_2 `->` . . . a_n `->` b

- Type fun `->` associates to the right,

read above type as

```
a₁ -> (a₂ -> (... (aₙ -> b)))
```

- Enables **Partial Application**

3.4 Defining Values (and thus functions)

- = binds names to values. Names must not start with A-Z (Haskell style: camelCase)

- Define constant (0-ary function) c. Value of c is value of expression e.
  ```
  c = e
  ```

- Define n-ary function f with arguments x_i. f may occur in e.
  ```
  f x₁ x₂ ... xₙ = e
  ```

- A Haskell program is a set of bindings.

- Good style: give type assignments for top-level (global) bindings:

```
1  f :: a₁ -> a₂ -> b
2  f x₁ x₂ = e
```

3.4.1 Guards

Guards are conditional expressions (something like "switch" in Java). They are a lot more readable and more powerful than `if ... then ... else ...` .

Guards are introduced by |:

```
1  f x₁ x₂ ... xₙ
2      | q₁      = e₁
3      | q₂      = e₂
4    ...
5      | qₘ      = eₘ
6  [ | otherwise  = eₘ₊₁ ]
```

Guards (q_i) are expressions of type Bool, evaluated top to bottom.

```
1  -- Compute n!
2  fac :: Integer -> Integer
3  fac n | n <= 1    = 1
4        | otherwise = n * fac (n - 1)
5
6  main :: IO ()
7  main = print $ fac 10
```

3.4.2 Local Definitions

1. **Where bindings**: local definitions visible in the entire rhs of a definition.

```
f₁ x₁ x₂ ... xₙ | q₁ = e₁
                | q₂ = e₂
                ...
                | qₘ = eₘ
    where
         g₁ = ...
         g₂ = ...
         ...
         gₒ
```

```
-- Efficient power computation, basic idea: x^2k = (x^2)^k

power :: Double -> Integer -> Double
power x k | k == 1    = x
          | even k    = power (x * x) (halve k)
          | otherwise = x * power (x * x) (halve k)
  where
     even n  = n `mod` 2 == 0
     halve n = n `div` 2

main :: IO ()
main = print $ power 2 16
```

2. **Let expressions**: local definitions visible inside one expression.

```
let g₁ = ...
    g₂ = ...
    ...
    gₒ
in e
```

3.4.3 Lists

- Recursive definitions:

  1. `[]` is a list (nil), type `[] :: [a]`
  2. `x:xs` is a list, if `x :: a, xs :: [a]`
     (x is head, xs is tail)

- Notation: `3:(2:(1:[]))` $\equiv$ `3:2:1:[]` $\equiv$ `[3,2,1]` $\equiv$ `3:[2,1]`

- Law: $\forall$ xs :: [a] :   (xs $\neq$ [])
  `head xs : tail xs ==` xs

3.4.4   Pattern Matching

- *The* idiomatic Haskell way to define a function by cases:

```
1  f :: a₁ -> ... aₙ -> b
2  f p₁1 ... p₁k = e₁
3  f p₂1 ... p₂k = e₂
4  ...
5  f pₙ1 ... pₙk = eₖ
```

Pattern	Matches If	Bindings in e_r
constant c	$x_i == c$	
variable v	always	$v \equiv x_i$
wildcard _	always	
tuple $(p_1, \ldots p_m)$	components of x_i match patterns p	
[]	$x_i == []$	
$(p_1 : p_2)$	head x_i matches p_1, tail x_i matches p_2	

```haskell
1  -- Equivalent definitions of sum (over lists of integers)
2
3  -- (1) Conditional expression
4  sum' :: [Integer] -> Integer
5  sum' xs = if xs == [] then 0 else head xs + sum' (tail xs)
6
7  -- (2) Guards
8  sum'' :: [Integer] -> Integer
9  sum'' xs | xs == []  = 0
10          | otherwise = head xs + sum'' (tail xs)
11
12 -- (3) Pattern matching
13 sum''' :: [Integer] -> Integer
14 sum''' []     = 0
15 sum''' (x:xs) = x + sum''' xs
16
17 main :: IO ()
18 main = print $ (sum' [1..100], sum'' [1..100], sum''' [1..100])
```

```haskell
1  -- Finite prefix of a list
2  take' :: Integer -> [a] -> [a]
3  take' 0 _      = []
4  take' _ []     = []
5  take' n (x:xs) = x:take' (n-1) xs
6
7  main :: IO ()
8  main = print $ take' 20 [1,3..]
```

```haskell
1  -- Mergesort list xs, respecting ordering (<<<)
2
3  mergeSort :: (a -> a -> Bool) -> [a] -> [a]
4  mergeSort _       []  = []
5  mergeSort _       [x] = [x]
6  mergeSort (<<<) xs  = merge (<<<) (mergeSort (<<<) ls)
7                                    (mergeSort (<<<) rs)
8    where
9      (ls, rs) = splitAt (length xs `div` 2) xs
10
11     merge :: (a -> a -> Bool) -> [a] -> [a] -> [a]
12     merge (<<<) []      ys        = ys
13     merge (<<<) xs      []        = xs
14     merge (<<<) l1(x:xs) l2(y:ys)
15        | x <<< y   = x:merge (<<<) xs l2
16        | otherwise = y:merge (<<<) l1 ys
17
18 main :: IO ()
19 main = print $ mergeSort (>) [1,3..19]
```

3.5 Algebraic Data Types

(also known as **Sum-of-Product-Types**)

- *Recall*: `[]` and `(:)` are the **values constructors** for **type constructor** [a].

- Can define entirely new type T and its constructors K_i:
```haskell
1  data T a₁ a₂ ... aₙ = K₁  b₁₁  ...  b_{1_{n_1}}
2                        K₂  b₂₁  ...  b_{2_{n_2}}
3                        ...
4                        K_r  b_{r1}  ...  b_{r_{n_r}}
```
b_{ij} types mentioning the type vars $a_1 \ldots a_n$

- Defines type constructor T and r value constructors:
  $K_i \; :: \; b_{i_1} \; \text{->} \; b_{i_2} \; \text{->} \; \ldots \; b_{i_n} \; \text{->} \; T \; a_1 \; \ldots \; a_n$

- Compare `[] :: [a]` and `(:) :: a -> [a] -> [a]`

- **Sum Type** ($n=0$, $n_i = 0$)

```haskell
1   -- Demonstrate algebraic data types: sum type
2
3   data Weekday = Mon | Tue | Wed | Thu | Fri | Sat | Sun
4     deriving (Eq, Show, Ord, Enum, Bounded)
5
6   -- Is this day on a weekend?
7   weekend :: Weekday -> Bool
8   weekend Sat = True
9   weekend Sun = True
10  weekend _   = False
11
12
13  -- The classic rock/paper/scissor game
14
15  data Move = Rock | Paper | Scissor
16    deriving (Eq)
17
18  data Outcome = Lose | Tie | Win
19    deriving (Show)
20
21  -- Outcome of a game round (us vs. them)
22  outcome :: Move -> Move -> Outcome
23  outcome Rock    Scissor = Win
24  outcome Paper   Rock    = Win
25  outcome Scissor Paper   = Win
26  outcome us      them
27    | us == them = Tie
28    | otherwise  = Lose
29
30
31  main :: IO ()
32  main = do
33    print $ Mon == Sun
34    print $ Thu < Sat
35    print [Mon .. Fri]
36    print (minBound :: Weekday)
37    print $ outcome Rock Rock
```

- Add `deriving (c, c, ... c)` to data declaration to define canonical operations:

c	operations
Eq	equality (==, /=)
Show	printing (show)
Ord	ordering ($<$, $<=$, max)
Enum	enumeration
Bounded	minBound, maxBound

- **Product Types** (r=1)

```haskell
-- Demonstrate algebraic data types: product type

data Sequence a = S Int [a]
  deriving (Eq, Show)


fromList :: [a] -> Sequence a
fromList xs = S (length xs) xs

(+++) :: Sequence a -> Sequence a -> Sequence a
S lx xs +++ S ly ys = S (lx + ly) (xs ++ ys)

len :: Sequence a -> Int
len (S lx _) = lx


main :: IO ()
main = do
  print $ fromList [0..9]
  print $ len (fromList ['a'..'m'] +++ fromList ['n'..'z'])
```

- **Sum-of-Product-Types**

```haskell
data Maybe a = Just a | Nothing
data Either a b = Left a | Right b
data List a = Nil | Cons a (List a)
```

```haskell
1  -- Our own formulation of cons lists
2  data List a = Nil
3              | Cons a (List a)
4    deriving (Show)
5
6  -- Haskell's builtin type [a] and List a are isomorphic:
7  --        toList . fromList = id
8  --   and  fromList . toList = id
9  toList :: [a] -> List a
10 toList []     = Nil
11 toList (x:xs) = Cons x (toList xs)
12
13 fromList :: List a -> [a]
14 fromList Nil        = []
15 fromList (Cons x xs) = x:fromList xs
16
17 -- The family of well-known list functions (combinators) can be
18 -- reformulated for List a
19 mapList :: (a -> b) -> List a -> List b
20 mapList f Nil        = Nil
21 mapList f (Cons x xs) = Cons (f x) (mapList f xs)
22
23 filterList :: (a -> Bool) -> List a -> List a
24 filterList p Nil                    = Nil
25 filterList p (Cons x xs) | p x       = Cons x (filterList p xs)
26                          | otherwise = filterList p xs
27
28 liftList :: ([a] -> [b]) -> List a -> List b
29 liftList f = toList . f . fromList
30
31 mapList' :: (a -> b) -> List a -> List b
32 mapList' f = liftList (map f)
33
34 filterList' :: (a -> Bool) -> List a -> List a
35 filterList' p = liftList (filter p)
36
37 main :: IO ()
38 main = print $ fromList $ filterList' (> 3) $ mapList' (+1) $ toList
   ↪  [1..5]
```

```
1  -- Use the isomorphism between [a] and List a
2  -- to save work when defining functions over List a:
3  --
4  --                  fromList
5  --       List a ------------→ [a]
6  --          |                  |
7  --        g |                  | f
8  --          ↓                  ↓
9  --       List b ←------------ [b]
```

```
1  -- Abstract syntax tree for arithmetic expressions of literals
2  data Exp a = Lit a
3             | Add (Exp a) (Exp a)
4             | Sub (Exp a) (Exp a)
5             | Mul (Exp a) (Exp a)
6    deriving (Show)
7
8  ex1 :: Exp Integer
9  ex1 = Add (Mul (Lit 5) (Lit 8)) (Lit 2)
10
11
12 evaluate :: Num a => Exp a -> a
13 evaluate (Lit n)     = n
14 evaluate (Add e1 e2) = evaluate e1 + evaluate e2
15 evaluate (Mul e1 e2) = evaluate e1 * evaluate e2
16 evaluate (Sub e1 e2) = evaluate e1 - evaluate e2
17
18
19 main :: IO ()
20 main = print $ evaluate ex1
```

4   Type Classes

A **type class** C defines a family of type signatures (”methods”) which all **instances** of C must implement.

```
1  class C a where
2      f₁ :: t₁
3      ...
4      fₙ :: tₙ
```

The t_i <u>must</u> mention a.
For any f_i the class may provide default implementations.
We have f_i :: C a => t_i
(read ”if a is instance C then f_i has type t_i”).
C a is called **class constraint**.

Example:

```
1  class Eq a where
2      (==) :: a -> a -> Bool
3      (/=) :: a -> a -> Bool
4      x == y = not (x /= y)
5      x /= y = not (x == y)
```

(These are default implementations. To redefine one of them is sufficient.)

4.1   Class Inheritance

- Defining class (c_1 a, c_2 a, ...) => C a where ...   makes type class C a subclass of the C_i.

- C a => t implies C_1 a, C_2 a ... .

4.2   Class Instances

If type t implements the methods of class C, t becomes an **instance of** C:

```
1  instance C t where
2      f₁ = <def of f₁>
3      ...
4      fₙ = <def of fₙ>
```

(All defs of f_i may be provided, minimal complete definition <u>must</u> be provided.)   Class constraint C t is satisfied from now on.

Example:

```
1  instance Eq Bool where
2      x == y = x && y || (not x && not y)
```

An instance definition for type constructor t may formulate class constraints for its argument types a, b, ...: instance (C_1 a, C_2 a, ...) => C t where

```haskell
import Data.Maybe
import Data.Tuple
-- The classic rock/paper/scissor game
data Outcome = Lose | Tie | Win

instance Eq Outcome where
  Lose == Lose = True
  Tie  == Tie  = True
  Win  == Win  = True
  _    == _    = False

instance Enum Outcome where
  fromEnum Lose = 0
  fromEnum Tie  = 1
  fromEnum Win  = 2

  toEnum 0 = Lose
  toEnum 1 = Tie
  toEnum 2 = Win

instance Show Outcome where
  show Lose = "Lose"
  show Tie  = "Tie"
  show Win  = "Win"

instance Ord Outcome where
  Lose <= Lose = True
  Lose <= Tie  = True
  Lose <= Win  = True
  Tie  <= Tie  = True
  Tie  <= Win  = True
  Win  <= Win  = True
  _    <= _    = False

instance Bounded Outcome where
  minBound = Lose
  maxBound = Win
---------------------------------------------------------------
data Move = Rock | Paper | Scissor

instance Eq Move where
  Rock    == Rock    = True
```

```haskell
  Paper   == Paper   = True
  Scissor == Scissor = True
  _       == _       = False

-- Lookup table defining a consistent mapping between Move and Int
table :: [(Move, Int)]
table = [(Rock, 0), (Paper, 1), (Scissor, 2)]

instance Enum Move where
  fromEnum o = fromJust $ lookup o table
  toEnum n   = fromJust $ lookup n $ map swap table

instance Show Move where
  show Rock    = "Rock"
  show Paper   = "Paper"
  show Scissor = "Scissor"

instance Ord Move where
  Rock    <= Rock    = True
  Rock    <= Paper   = True
  Rock    <= Scissor = True
  Paper   <= Paper   = True
  Paper   <= Scissor = True
  Scissor <= Scissor = True
  _       <= _       = False

instance Bounded Move where
  minBound = Rock
  maxBound = Scissor
---------------------------------------------------------------
outcome :: Move -> Move -> Outcome
outcome Rock    Scissor = Win
outcome Paper   Rock    = Win
outcome Scissor Paper   = Win
outcome us      them
  | us == them = Tie
  | otherwise  = Lose

main :: IO ()
main = print $ outcome Paper Paper
```

4.2.1 Deriving Class Instances

Automatically make user-defined data types (`data ...`) instances of classes $C_i \in$ { Eq, Ord, Enum, Bounded, Show, Read }:

```
1  data T a₁ a₁ ... aₙ = ...
2                      | ...
3      deriving (C₁, C₂, ...)
```

```
1  -- Use deriving the obtain the standard interpretation for the type
   ↪ classes
2  -- Eq, Ord, Enum, Bounded, Show, Read
3  -- The classic rock/paper/scissor game
4
5  data Outcome = Lose | Tie | Win
6     deriving (Eq, Ord, Enum, Bounded, Show, Read)
7
8  data Move = Rock | Paper | Scissor
9     deriving (Eq, Enum, Read)   -- Ord, Show defined below;
10                                -- Bounded makes no sense
11 instance Show Move where
12    show Rock    = "rock"
13    show Paper   = "paper"
14    show Scissor = "scissor"
15
16 instance Ord Move where         -- NB: non-conventional,
17    Rock    <= Rock    = True    -- encodes game rules
18    Rock    <= Paper   = True
19    Paper   <= Paper   = True
20    Paper   <= Scissor = True
21    Scissor <= Scissor = True
22    Scissor <= Rock    = True
23    _       <= _       = False
24
25 outcome :: Move -> Move -> Outcome
26 outcome m1 m2 | m1 == m2  = Tie
27               | m1 <  m2  = Lose
28               | otherwise = Win
29
30 main :: IO ()
31 main = do
32    print $ outcome Paper Scissor
33    print $ [Rock, Paper, Scissor]
34    print $ (read "Scissor" :: Move)
```

5   Domain-Specific Languages

a.k.a. **DSLs**

- "small" languages designed to easily and directly express the concepts/idioms of a specific domain. <u>Not</u> Turing-complete in general.

- Examples:

Domain	DSLs
OS automation	shell scripts, OSX Automater
Typesetting	LaTeX
Queries	SQL
Game Scripting	Unreal Script, Lua
Parsing	Yacc, Bison, ANTLR

- Functional Languages make good hosts for **embedded DSLs**:

  - algebraic data types (e.g. to model ASTs)

  - higher-order functions (abstraction, control constructs)

  - lightweight syntax (layout / whitespace, non-alphabetic ids)

Example: An embedded DSL for integer sets:

```
type IntegerSet =
    -- constructors:
    empty :: IntegerSet
    insert :: Integer -> IntegerSet -> IntegerSet
    delete :: Integer -> IntegerSet -> IntegerSet
    -- observer:
    member :: Integer -> IntegerSet -> Bool

member 3 (insert 1 (delete 3 (insert 2 (insert 3 empty))))
    ≡ False
```

(1) DSL as library of functions, implementation details exposed.

```haskell
1   import Data.List (nub)
2   -- A library of functions on integer sets,
3   -- implementation fully exposed
4
5   type IntegerSet = [Integer] -- unsorted, duplicates allowed
6
7   empty :: IntegerSet
8   empty = []
9
10  insert :: Integer -> IntegerSet -> IntegerSet
11  insert x xs = x:xs
12
13  delete :: Integer -> IntegerSet -> IntegerSet
14  delete x xs = filter (/= x) xs
15
16  (∈) :: Integer -> IntegerSet -> Bool
17  x ∈ xs = elem x xs
18
19  -----------------------------------------------------------------------
20
21  -- "Extending" the library, accessing the exposed
22  -- implementation.  Now we're doomed to stick the
23  -- list-based representation...
24
25  (⊆) :: IntegerSet -> IntegerSet -> Bool
26  xs ⊆ ys = all (\x -> x ∈ ys) xs
27
28  card :: IntegerSet -> Int
29  card xs = length (nub xs)
30
31  -----------------------------------------------------------------------
32
33  s1, s2 :: IntegerSet
34  s1 = insert 1 (insert 2 (insert 3 empty))
35  s2 = foldr insert empty [1..10]
36
37  prog :: Bool
38  prog = s1 ⊆ s2
39
40  main :: IO ()
41  main = print $ prog
```

5.1 Modules

- Group of related definitions (values, types) in a single file
  (named "M.hs" / "M.lhs"):

```haskell
module M where
    type Predicate a = a -> Bool
    id :: a -> a
    id x = x
```

- Hierarchy: module A.B.C.M in file A/B/C/M.hs

- Access definitions in other module M: `import M`

- Explicit export lists hide all other definitions:

```
1  module M (id) where
2      ...
3      -- type Predicate a not exported
```

- **Abstract data types**:
  export algebraic data types, but <u>not</u> its constructors:

```
1  module M (Rose, leaf) where
2      data Rose a = Node a [Rose a]
3      leaf :: a -> Rose a [Rose a]
4      leaf x = Node x []
```

  - Export constructors:

```
1  module M (Rose(Node), leaf) where
2      ...
3  -- or export all constructors:
4  module M (Rose(..), leaf) where
```

  - Instance definitions (including deriving) are exported with their type.

- Qualified imports to partition name space:

```
1  import qualified M
2      ...
3      -- use M.foobar syntax
4      t :: M.Rose Char
5      t = M.leaf 'x'
```

- Partially import module:

```
1  -- only import nub and reverse
2  import Data.List (nub, reverse)
3
4  -- import whole module but without otherwise
5  import Prelude hiding (otherwise)
6  otherwise :: Bool
7  otherwise = False -- harhar
```

- Pass imported modules to importer of own module:

```
1  module M (..., module Data.List, ...) where
2      import Data.List (nub)
```

```
1  import qualified M
2      M.nub
```

```haskell
module SetLanguageShallowCard (IntegerSet,
                               empty,
                               insert,
                               delete,
                               member,
                               card) where

data IntegerSet = IS (Integer -> Bool) Int -- characteristic function +
  ↪ cardinality

-- constructors
empty :: IntegerSet
empty = IS (\_ -> False)
           0
-- empty = IS (const False) 0
{-
insert :: IntegerSet -> Integer -> IntegerSet
insert xs@(IS f c) x = IS (\y -> x == y || f y)
                          (if member xs x then c else c + 1)
-}
delete :: IntegerSet -> Integer -> IntegerSet
delete xs@(IS f c) x = IS (\y -> y /= x && f y)
                          (if member xs x then c - 1 else c)

-- observer
member :: IntegerSet -> Integer -> Bool
member (IS f _) x = f x
-- member (IS f _) = f

card :: IntegerSet -> Int
card (IS _ c) = c
```

```haskell
1   --import SetLanguage
2   import SetLanguageShallow
3   --import SetLanguageShallowCard
4
5   -- impossible
6   -- (SetLanguage/SetLanguageShallow do not export
7   --  data constructor IS)
8   {-
9
10  union :: IntegerSet -> IntegerSet -> IntegerSet
11  union (IS xs) (IS ys) = IS (xs ++ ys)
12
13  union :: IntegerSet -> IntegerSet -> IntegerSet
14  union (IS f) (IS g) = IS (\y -> f y || g y)
15
16  -}
17
18  set12 :: IntegerSet
19  set12 = (((empty `insert` 3) `insert` 2) `delete` 3) `insert` 1
20
21  main :: IO ()
22  main = print $ set12 `member` 3
```

(2) DSL as library of functions, abstract data type (module).

- **Shallow DSL embedding**:
  Semantics of DSL operations directly expressed in terms of host language value (e.g. list or characteristic function)

  - constructors (empty, insert, delete) perform the work, harder to add
  - observers (member) trivial

- **Deep DSL embedding**:
  DSL operations build an abstract syntax tree (AST) that represents applications and arguments

  - constructors merely build the AST, very easy to add
  - observers interpret (traverse) the AST and perform the work

```haskell
module SetLanguageDeepCard (IntegerSet(Empty, Insert, Delete),
                            member,
                            card) where

-- constructors

data IntegerSet =
    Empty
  | Insert IntegerSet Integer
  | Delete IntegerSet Integer
  deriving (Show)

-- TODO: build a suitable Show instance for IntegerSet

-- observers

member :: IntegerSet -> Integer -> Bool
member Empty        _ = False
member (Insert xs x) y = x == y || member xs y
member (Delete xs x) y = x /= y && member xs y

card :: IntegerSet -> Int
card Empty                     = 0
card (Insert xs x) | member xs x = card xs
                   | otherwise   = card xs + 1
card (Delete xs x) | member xs x = card xs - 1
                   | otherwise   = card xs
```

```haskell
import SetLanguageDeepCard

set12 :: IntegerSet
set12 = (((Empty `Insert` 3) `Insert` 2) `Delete` 3) `Insert` 1

main :: IO ()
main = do
  print $ set12
  print $ set12 `member` 3
  print $ card set12
```

```haskell
module ExprDeepNum (Expr(..),
                    eval) where

-- constructors

data Expr =
    Val Integer
  | Add Expr Expr
  | Mul Expr Expr
  | Sub Expr Expr
  deriving (Show)

instance Num Expr where
  fromInteger n = Val n
  e1 + e2 = Add e1 e2
  e1 - e2 = Sub e1 e2
  e1 * e2 = Mul e1 e2

  abs e = undefined
  signum e = undefined


-- observer

eval :: Expr -> Integer
eval (Val n) = n
eval (Add e1 e2) = eval e1 + eval e2
eval (Mul e1 e2) = eval e1 * eval e2
eval (Sub e1 e2) = eval e1 - eval e2
```

```
1  import ExprDeepNum
2
3  -- e1 = 8 * 7 - 14
4  e1 :: Expr
5  e1 = Sub (Mul (Val 8) (Val 7)) (Val 14)
6
7  e2 :: Expr
8  e2 = 8 * 7 - 14
9
10 main :: IO ()
11 main = do
12   print $ eval e1
13   print $ negate e2
14   print $ eval e2
```

5.2   Generalized Algebraic Data Types (GADTs)

Idea:

- Encode the type of a DSL expression (here: Integer or Bool) in its **Haskell representation type**.

- Use Haskell's type checker to ensure at compile time that only well-typed DSL expressions are built.

Language extensions:
```
\{-\# LANGUAGE GADTs \#-\}
```

- Define new parameterized type T, its constructors k_i and their type signatures:
```
1  data T a₁ a₂ ... aₙ where
2      k₁ :: b₁₁ -> ... -> b₁n₁ -> T t₁₁ t₁ₙ
3      ...
4      k_r :: b_r1 -> ... -> b_rn_r -> T t_r1 t_rn
```

```haskell
{-# LANGUAGE GADTs #-}

module ExprDeepGADTTyped (Expr(..),
                          eval) where

-- Expr a: an expression that, if evaluated, will yield a value of type
↪   a

data Expr a where
  ValI   :: Integer                         -> Expr Integer
  ValB   :: Bool                            -> Expr Bool
  Add    :: Expr Integer -> Expr Integer  -> Expr Integer
  And    :: Expr Bool -> Expr Bool        -> Expr Bool
  EqZero :: Expr Integer                    -> Expr Bool
  If     :: Expr Bool -> Expr a -> Expr a -> Expr a


instance Show (Expr a) where
  show (ValI n)     = show n
  show (ValB b)     = show b
  show (Add e1 e2)  = show e1 ++ " + " ++ show e2
  show (And e1 e2)  = show e1 ++ " ∧ " ++ show e2
  show (EqZero e)   = show e  ++ " == 0"
  show (If p e1 e2) = "if " ++ show p ++ " then " ++ show e1 ++ " else "
  ↪   ++ show e2


-- NB: this is *typed* evaluation of expressions:
eval :: Expr a -> a
eval (ValI n)     = n
eval (ValB b)     = b
eval (Add e1 e2)  = eval e1 + eval e2
eval (And e1 e2)  = eval e1 && eval e2
eval (EqZero e)   = eval e == 0
eval (If p e1 e2) = if eval p then eval e1 else eval e2
```

```
1  import ExprDeepGADTTyped
2
3  e1 :: Expr Integer
4  e1 = If (EqZero (Add (ValI 0) (ValI 0))) (ValI 42) (ValI 43)
5
6  -- e2 yields compile-time type error
7
8  e2 :: Expr Bool
9  e2 = EqZero (ValB True)
10
11 main :: IO ()
12 main = do
13    print $ e1
14    print $ eval e1
```

5.3 Shallow embedding of a String Matching DSL

- **Pattern**:

  1. Given a String, a pattern returns the list of matches. Match failure? Returns the empty list.
  2. A match consists of a value (e.g. the matched characters, tokens, parse trees) and the residual String left to match.

  Thus: `type Pattern a = String -> [(a, String)]`

5.3.1 DSL design

Pattern		DSL function
match lit. char	"x"	`lit :: Char -> Pattern Char`
match empty string	ϵ	`empty :: a -> Pattern a`
fail always	$\emptyset$	`fail :: Pattern a`
alternative	—	`alt :: Pattern a -> Pattern a -> Pattern a`
sequence	.	`seq :: (a -> b -> c) ->` `Pattern a -> Pattern b -> Pattern c`
repetition	*	`rep :: Pattern a -> Pattern [a]`

```
module PatternMatching (Pattern,
                        module Prelude,
                        lit, empty, fail,
                        alt, seq, rep, rep1,
```

```haskell
                         alts, seqs, lits, app) where

import Prelude hiding (seq, fail)

-- Given a string, a pattern returns the (possibly empty) list of
-- possible matches.  A match consists of a match value (e.g., matched
-- the matched character(s), token, or parse tree) and the residual
↪  string
-- left to match:

type Pattern a = String -> [(a, String)]

-- BASIC PATTERNS

-- match character c, returning the matched character
lit ::  Char -> Pattern Char
lit _c []                  = []
lit c  (x:xs) | c == x     = [(c, xs)]
              | otherwise = []

-- match the empty string, return v
empty :: a -> Pattern a
empty v xs = [(v, xs)]

-- fail always (yields empty list of matches)
fail :: Pattern a
fail _ = []

-- COMBINE PATTERNS

-- match p or q
alt :: Pattern a -> Pattern a -> Pattern a
alt p q xs = p xs ++ q xs

-- match p and q in sequence (use f to combine match values)
seq :: (a -> b -> c) -> Pattern a -> Pattern b -> Pattern c
seq f p q xs = concat (map (\(v1, xs1) ->
                         map (\(v2, xs2) -> (f v1 v2, xs2))
                             (q xs1))
                        (p xs))

-- An alternative (more consise and readable) implementation of seq
```

```haskell
-- based on list comprehension syntax:
--
-- seq f p q xs = [ (f v1 v2, xs2) | (v1, xs1) <- p xs, (v2, xs2) <- q
↪  xs1 ]

-- match p repeatedly (including 0 times)
rep :: Pattern a -> Pattern [a]
rep p = alt (seq (:) p (rep p)) (empty [])

-- match p repeatedly, but at least once
rep1 :: Pattern a -> Pattern [a]
rep1 p = seq (:) p (rep p)

-- CONVENIENCE

-- build "or" choice pattern from a list of alternatives
alts :: [Pattern a] -> Pattern a
alts = foldr alt fail

-- build "and" sequence pattern from a list of patterns
seqs :: [Pattern a] -> Pattern [a]
seqs = foldr (seq (:)) (empty [])

-- match a string (= sequence of characters)
lits :: String -> Pattern String
lits cs = seqs [ lit c | c <- cs ]

-- apply function f to match value (for match post-processing)
app :: (a -> b) -> Pattern a -> Pattern b
app f p xs = [ (f v1, xs1) | (v1, xs1) <- p xs ]

{-

-- Using rep leads to longest match first:

rep p xs
  = alt (seq (:) p (rep p)) (empty []) xs
  = seq (:) p (rep p) xs ++ empty [] xs
  = seq (:) p (rep p) xs ++ [([], xs)]
  = [ (v1:v2, xs2) | (v1,xs1) <- p xs, (v2,xs2) <- rep p xs1 ] ++ [([],
↪  xs)]
```

```
rep P'a' "aab"
  = [ (v1:v2, xs2) | (v1,xs1) <- P'a' "aab", (v2,xs2) <- rep P'a' xs1 ]
↪  ++ [([], "aab")]
  = [ (v1:v2, xs2) | (v1,xs1) <- [('a',"ab")], (v2,xs2) <- rep P'a' xs1
↪  ] ++ [([], "aab")]
  = [ ('a':v2,xs2) | (v2,xs2) <- rep P'a' "ab" ] ++ [([], "aab")]


-}
```

```haskell
1   import Prelude ()
2
3   import PatternMatching
4
5   fortytwo :: Pattern (Char,Char)
6   fortytwo = seq (,) (lit '4') (lit '2')
7
8   digit :: Pattern Char
9   digit = lit '0' `alt` lit '1' `alt` lit '2' `alt` lit '3' `alt`
10          lit '4' `alt` lit '5' `alt` lit '6' `alt` lit '7' `alt`
11          lit '8' `alt` lit '9'
12
13  number :: Pattern String
14  number = rep digit
15
16  smiley :: Pattern String
17  smiley = seq (:) (alt (lit ':') (lit ';'))
18                   (seq (:) (lit '-')
19                            (seq (:) (alt (lit '(') (lit ')'))
20                                     (empty [])))
21
22  main :: IO ()
23  main = do
24    print $ fortytwo "42 rules"
25    print $ rep digit "42 rules"
26    print $ smiley ";-)"
```

```
import Prelude ()
import PatternMatching
-- Make use of the fact that the pattern matching DSL is *embedded*
-- into Haskell: define new functions (abstractions) that combine
-- simple patterns
```

```haskell
-- Example:
-- Match a fully parenthesized arithmetic expression over integers,
-- e.g. ((4*10)+2)

-- Variant 1: return list of matched characters
digit :: Pattern Char
digit = alts [ lit d | d <- ['0'..'9'] ]

number :: Pattern String
number = rep1 digit

op :: Pattern String
op = alts [ lits o | o <- ["+", "-", "*", "/"] ]

expr :: Pattern String
expr = alts [ number, app concat (seqs [lits "(", expr, op, expr, lits
  ↪ ")"]) ]

-- Variant 2: return a simple AST for the matched expression
data Expr a =
    Num a
  | Op (Expr a) String (Expr a)
  deriving (Show)

number' :: Pattern (Expr Integer)
number' = app (Num . read) (rep1 digit)

expr' :: Pattern (Expr Integer)
expr' = alts [ number', seq (\_ (e1,(o,(e2,_))) -> Op e1 o e2)
                             (lit '(') (seq (,)
                                        expr' (seq (,)
                                               op (seq (,)
                                                  expr' (lit ')'))))
            ]

main :: IO ()
main = do
  print $ rep1 digit "1234.56"
  print $ lits "abc" "abcdef"
  print $ expr "((4*10)+2)"
  print $ expr' "((4*10)+2)"
```

6   Lazy Evaluation

To execute a program, Haskell reduces expressions to values. Haskell uses normal order reduction to select the next expression to reduce:

1. The outermost reducible expression (redex) is reduced first

2. ⇒ Function applications are reduced first before their arguments.

3. If no further redex is found, the expression is in normal form and reduction terminates.

```haskell
fst :: (a, b) -> a
fst (x, y) = x
sqr :: Num a => a -> a
sqr x = x * x


-- ->: reduces to
fst (sqr (1+3), sqr 2) -> sqr (1 + 3) [fst]
                       -> (1+3) * (1+3) [sqr]
                       -> 4 * 4 [+/+]
                       -> 16 [*]
```

Haskell avoids the duplication of work through graph reduction. Expression are shared (referenced more than once) instead of duplicated.
Lazy evaluation: normal order reduction and sharing.

6.1   WHNF

An expression e is in weak head normal form (WHNF) if it is of the following form

1. v (where v is an atomic value

   `Integer`, `Bool`, `Char`, ...

)

2. `c` e1 e2 ... en

   (where c is an n-ary constructor, like

   `(:)`

)

3. `f` e1 e2 ... em

   (where f is an n-ary function, $m < n$)

Haskell reduces values to WHNF only (stop criterium for reduction) unless we request reduction to normal form (e.g. when printing results).

Example expressions in WHNF:

- `42` `--1.`

- `(sqr 2, sqr 4)` `--2. (,)`

- `f x : map f xs` `--2. (:)`

- `Just (40+2)` `--2. Just`

- `(* (40+2))` `--3. * binär`

- `(\x -> 40+2)` `--3. unary function w/o args`

6.2   Lazy Evaluation and Bottom

Some Haskell expressions have the value bottom. Examples:

`error, undefined, bomb`

. Lazy evaluation admits functions that return a non-bottom value even if they receive bottom as argument (also: non-strict functions). N-ary function f is strict in its i-th argument, if

`f x1 .. xi-1 bottom xi+1 ... xn = bottom`

Examples:

- `const :: a -> b -> a` `--strict in first, non-strict in second argument`

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

If a function pattern matches on an argument, Haskell semantics define it to be strict in that argument.
Example:

```
1  data T = T Int
2  f :: T -> Int
3  f (T x) = 42
4
5  f undefined -> undefined
6  f (T undefined) -> 42
```

7 Infinite Lists (Data Structures)

One consequence of lazy evaluation: programs can handle infinite Lists as long as any run will inspect only a finite prefix of such a list. Enables a modular programming style:

1. generator functions produce an infinite number of solutions / approximations / ...

2. test functions select one (or finite number of) solutions from this infinite list.

7.1 Example: Newton-Raphson square root approximation

Iteratively approximate the square root of x:

1. $a_0 = \frac{x}{2}$

2. $a_{i+1} = \frac{a_i + \frac{x}{a_i}}{2}$

```haskell
-- Demonstrate modular program construction through laziness:
-- value generation (here: iterate) and consume/test (here: within)
-- can be implemented separately.
-- Can replace test (within → relative) without modifying the
   generator.
-- See John Hughes, "Why Functional Programming Matters", Section 4.1
import Prelude hiding (iterate)
-- [x, f x, f (f x), f (f (f x)), ...]
iterate :: (a -> a) -> a -> [a]
iterate f x = x : iterate f (f x)
-- Consume list until two adjacent elements are
-- 1. within eps of each other
-- 2. differ by a factor less than eps
within :: (Ord a, Num a) => a -> [a] -> a
within eps (x1:x2:xs) | abs (x1 - x2) <= eps = x2
                      | otherwise            = within eps (x2:xs)

relative :: (Ord a, Fractional a) => a -> [a] -> a
relative eps (x1:x2:xs) | abs (x1/x2 - 1) <= eps = x2
                        | otherwise              = relative eps (x2:xs)
-- Square root of x using the Newton-Raphson algorithm:
--    a0   = x / 2
--    ai+1 = (ai + x / ai) / 2
-- Why does this work?  If the approximations ai converge to some
-- limit a, then:
--    a = (a + x / a) / 2
--   2a = a + x / a
--    a = x / a
--   a² = x
--    a = √x
sqroot :: Double -> Double -> Double
sqroot eps x = within eps (iterate next a0)
--             relative
  where
    -- initial approximation
    a0 :: Double
    a0 = x / 2
    -- find next ai+1, given ai
    next :: Double -> Double
    next a = (a + x / a) / 2

main :: IO ()
main = print $ sqroot 0.001 81
```

7.2   Example: Tic-Tac-Toe game tree

Build the (potentially huge) tree of possible moves for the Tic-Tac-Toe board game. Evaluate promise of game position. Plan:

1. Find representation of game position (board + player next up)

   ```
   |1|2|3| next: x
   |4|5|6| square #6: open
   |0|x|0| spare #9: occupied by player 0
   ```

2. Provide pretty-printing for game positions.

3. Define initial position and possible moves:

   ```
   moves :: Position -> [Position]
   ```

4. Evaluate a given position:

   ```
   static :: Position -> Int
   ```

   (1 / -1: x/0 won the game, 0 draw)

5. Build a game tree of positions:

   ```
   gameTree :: Position -> Tree Position
   ```

6. Rather than simple static evaluation, now evaluate positions based on possible game futures. $\Rightarrow$ in game tree, perform evaluation bottom up.

7. Optimization ($\alpha - \beta$ algorithm)

 Code: tic-tac-toe.hs

8   Functors

Type class Functor embodies the application of a function to the elements (or: inside) of a structure, which leaving structure (or: outside) alone.

8.1   Examples

```haskell
map :: (a -> b) -> [a] -> [b]
mapTree :: (a -> b) -> Tree a -> Tree b

--Note: f is a type constructor that receives exactly one argument
--(Functor is also called a constructor class).
class Functor f where
   fmap :: (a -> b) -> f a -> f b

--Examples:
instance Functor [] where
   fmap = map

instance Functor Tree where
   fmap = mapTree

instance Functor Maybe where
   fmap f (Just x) = Just (f x)
   fmap f Nothing  = Nothing
```

Type constructors can be partially applied. Uses prefix notation:

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

--Examples (defines type constructors):
type Flagged = (,) Bool
type Indexed (->) Int
--MayFail e a: computation may yield value a or fail with error e
type MayFail e = Either e

instance Functor (Either e) where
    fmap f (Left e)  = Left e
    fmap f (Right x) = Right (f x)

instance Functor Flagged where
--fmap :: (a -> b) -> (Bool, a) -> (Bool, b)
    fmap f (b, x) = (b, f x)

instance Functor Indexed where
    fmap f g = f . g

--Functor Laws
fmap id ≡ id
fmap (f . g) = fmap f . fmap g
```

8.2   Kinds - Types for Types

kind	describes...	example
*	types	`Int`, `Bool`, `(Bool, Int)`, `[Char]`, ...
* -> *	unary type constructor	`Maybe`, `[]`
* -> * -> *	binary type constructor	`Either`, `(,)`, `(->)`

9   Applicative

```
--Compare:
($) :: (a -> b) -> a -> b
fmap :: Functor f => (a -> b) -> f a -> f b  --<$>
(<*>) :: Applicative f => f (a -> b) -> f a -> f b
```

Read <*> as (ap)ply, "tiefighter".

```
1  class Functor f => Applicative f where
2      pure :: a -> f a
3      (<*>) :: f (a -> b) -> f a -> f b
4
5  --Make any Applicative f a Functor:
6  fmap g x = pure g <*> x
```

Applicative embodies

1. function <u>application</u> on the level of (contained) values.

2. <u>combination</u> on the level of structures.

9.1   Applicative instances

```
1  instance Applicative Maybe where
2      pure x = Just x
3      Just f <*> Just x = Just (f x)
4      _ <*> _ = Nothing
5
6  instance Monoid c => Applicative ((,) c) where
7      pure x = (mempty, x)
8      (c_1, f) <*> (c_2, x) = (c_1 `mappend` c_2, f x)
9
10 instance Applicative [] where
11     pure x = [x]
12     fs <*> xs = [f x | f <- fs, x <- xs]
```

10   Interlude: Monoid

Type class Monoid a represents combinable values of type a:

```
1  class Monoid a where
2      mempty :: a  -- empty, neutral element for mappend
3      mappend :: a -> a -> a  -- combination
4      mconcat :: [a] -> a
```

Examples: $(0, +), (1, \cdot), (\text{true}, \wedge), (\text{false}, \vee), (\{\}, \cup), ([], (++))$

10.1   Monoid Laws

```
1  mempty `mappend` xs ≡ xs
2  xs `mappend` (ya `mappend` zs) ≡ (xs `mappend` ys) `mappend` zs`
3  mconcat xs ≡ foldr mempty mappend xs
```

11   Sequencing Functions

```
1  (.) :: (b -> c) -> (a -> b) -> (a -> c)
2  f . g = \x -> f (g x)
3
4  (>=>) :: (a -> b) -> (b -> c) -> (a -> c)
5  f >=> g = g . f
6
7  f1 >=> f2 >=> ... >=> fn -- composes the fi in left-to-right order
8  -- (>=>, id) forms a monoid.
```

11.1   Sequencing partial functions (a -¿ Maybe b)

Return Nothing as soon as first function in pipeline returns Nothing

```
1  (>=>) :: (a -> Maybe b) -> (b -> Maybe c) -> (a -> Maybe c)
2  f >=> g = \x -> case f x of
3                                Nothing -> Nothing
4                                Just y -> g y
```

11.2   Sequencing exception-generating functions (a -¿ Exc b)

```
1  type Exc b = Either Error b
2  type Error = String
```

Exceptions are propagated once occurred:

```
1  (>=>) :: (a -> Exc b) -> (b -> Exc c) -> (a -> Exc c)
2  f >=> g = \x -> case f x of
3                                Left err -> Left err
4                                Right y -> g y
```

11.3   Sequencing non-deterministic functions

```
1  (a -> NonDet b)
2  --Non-determinism: any answer in a list of answers:
3  type NonDet b = [b]
4  --Take all possible answers into account:
5  (>=>) :: (a -> NonDet b) -> (b -> NonDet c) -> (a -> NonDet c)
6  f >=> g = \x -> concat [g y | y <- f x]
```

11.4 Sequencing "stateful" functions

```
a -> State -> (State, b)
--State Transformer:
type ST b = State -> (State, b)
--Stateful function: a -> ST b
(>=>) :: (a -> ST b) -> (b -> ST c) -> (a -> ST c)
f >=> g = \ x s0 -> let (s1, y) = f x s0
                        let (s2, z) = g y s1 -- <=> in g y s1
                        in (s2, z)
```

11.5 Sequencing side-effecting functions

```
a -> World -> (World, b)
--Side effects: functions consume current world
--return new world along with result:
type World = ... -- abstract (defined by Haskell runtime)
type IO b = World -> (World, b)
--Value of type IO b: an action that
--1. when performed has a side-effect on the world, and then
--2. returns a value of type b.
```

Haskell build-ins:

- `print :: Show a => a -> IO ()`

- `putStrLn :: String -> IO ()`

- `getLine :: IO String`

- `readFile :: FilePath -> IO String`

12 Type class Monad

```
class Applicative m => Monad m where
    return :: a -> m a
    (>>=) :: m a -> (a -> m b) -> m b -- bind
```

12.1 Lifting

Monad	Lifting (return x)
Maybe	`Just x`
Exc	`Right x`
NonDet	`[x]`
ST	`\s -> (s , x)`

```haskell
--Make Maybe an instance of Monad:
instance Monad Maybe where
    return = Just
    Nothing >>= g = Nothing
    Just y >>= g = g y

--Kleisli composition
(>=>) :: Monad m => (a -> m b) -> (b -> m c) -> (a -> m c)
f >=> g = \x -> f x >>= g
```

Let m be a Monad. Then m is also an Applicative:

```haskell
pure = return
u <*> v = u >>= \f -> v >>= \x -> return (f x)
```

```haskell
($) :: (a -> b) -> a -> b
(<$>) :: Functor m => (a -> b) -> m a -> m b
(<*>) :: Applicative m => m (a -> b) -> m a -> m b
(=<<) :: Monad m => (a -> m b) -> m a -> m b -- (=<<) = flip (>>=)
```

12.2   do-Notation

```haskell
--(e : expression of type m a, es: sequence of ;-separated expression):
do { e } ≡ e
do {x <- e; es} ≡ e >>= \x -> do {es}
do {e; es} ≡ e >>= \_ -> do {es}
do {let v = x; es} = let v = x in do {es}
```