Overview

1. Introduction on purity and evaluation
2. Basic Haskell
3. More advanced concepts
We will consider now some basic concepts of Haskell, by implementing them in Scheme:

- What is a *pure* functional language?
- *Non-strict* evaluation strategies
- *Currying*
What is a **functional** language?

- In mathematics, **functions** do not have **side-effects**
- e.g. if $f : \mathbb{N} \rightarrow \mathbb{N}$, $f(5)$ is a fixed value in $\mathbb{N}$, and do not depend on *time* (also called **referential transparency**)
- this is clearly not true in conventional programming languages, Scheme included
- Scheme is *mainly* functional, as programs are **expressions**, and computation is evaluation of such expressions
- but some expressions have **side-effects**, e.g. `vector-set!`
- Haskell is **pure**, so we will see later how to manage inherently side-effectful computations (e.g. those with I/O)
Evaluation of functions

We have already seen that, in **absence of side effects** (purely functional computations) from the point of view of the result the **order** in which functions are applied **does not matter** (almost).

However, it matters in other aspects, consider e.g. this function:

```scheme
(define (sum-square x y)
  (+ (* x x)
      (* y y)))
```
A possible evaluation:

```
(sum-square (+ 1 2) (+ 2 3))
;; applying the first +
= (sum-square 3 (+ 2 3))
;; applying +
= (sum-square 3 5)
;; applying sum-square
= (+ (* 3 3)(* 5 5))
... 
= 34
```

is it that of Scheme?
The two evaluations differ in the **order** in which function applications are evaluated.

A function application ready to be performed is called a **reducible expression** (or **redex**).
in the first example of evaluation of mult, redexes are evaluated according to a (leftmost) **innermost strategy**

i.e., when there is more than one redex, the leftmost one that does not contain other redexes is evaluated

e.g. in \((\text{sum-square} \,(+\,1\,2) \,(+\,2\,3))\) there are 3 redexes: \((\text{sum-square} \,(+\,1\,2) \,(+\,2\,3)))\), \((+\,1\,2)\) and \((+\,2\,3)\) the innermost that is also leftmost is \((+\,1\,2)\), which is applied, giving expression \((\text{sum-square} \,3 \,(+\,2\,3))\)

in this strategy, **arguments** of functions are always evaluated **before** evaluating the function itself - this corresponds to passing arguments **by value**.

note that Scheme does not require that we take the **leftmost**, but this is very common in mainstream languages
Evaluation strategies: call-by-name

- a dual evaluation strategy: redexes are evaluated in an **outermost** fashion
- we start with the redex that is **not contained in any other redex**, i.e. in the example above, with `(sum-square (+ 1 2) (+ 2 3))`, which yields `(+ (* (+ 1 2)(+ 1 2))(* (+ 2 3)(+ 2 3)))`
- in the outermost strategy, functions are always **applied before their arguments**, this corresponds to passing arguments **by name** (like in Algol 60).
Termination and call-by-name

- e.g. first we define the following two simple functions:

  ```scheme
  (define (infinity)
    (+ 1 (infinity)))
  
  (define (fst x y) x)
  ```

- consider the expression `(fst 3 (infinity))`:
  - Call-by-value: `(fst 3 (infinity)) = (fst 3 (+ 1 (infinity))) = (fst 3 (+ 1 (+ 1 (infinity)))) = ...`
  - Call-by-name: `(fst 3 (infinity)) = 3`

- if there is an evaluation for an expression that terminates, **call-by-name terminates**, and produces the same result (Church-Rosser confluence)
Haskell is lazy: call-by-need

- In call-by-name, if the argument is not used, it is never evaluated; if the argument is used several times, it is **re-evaluated each time**
- **Call-by-need** is a **memoized** version of call-by-name where, if the function argument is evaluated, that value is **stored for subsequent uses**
- In a “pure” (effect-free) setting, this produces the same results as call-by-name, and it is usually faster
we saw that macros are different from function, as they do not evaluate and are expanded at compile time

a possible idea to overcome the nontermination of \((\text{fst} \ 3 \ (\text{infinity}))\), could be to use thunks to prevent evaluation, and then force it with an explicit call

indeed, there is already an implementation in Racket based on delay and force

we’ll see how to implement them with macros and thunks
Delay is used to return a **promise** to execute a computation (implements **call-by-name**)

moreover, it caches the result (**memoization**) of the computation on its first evaluation and returns that value on subsequent calls (implements **call-by-need**)

(struct promise
   (proc ; thunk or value
       value? ; already evaluated?
       ) #:mutable)
Delay (code)

```
(define-syntax delay
  (syntax-rules ()
    ((_ (expr ...))
     (promise (lambda ()
               (expr ...)) ; a thunk
            #f))) ; still to be evaluated
```
**force** is used to force the evaluation of a promise:

```scheme
(define (force prom)
  (cond
    ; is it already a value?
    ((not (promise? prom)) prom)
    ; is it an evaluated promise?
    ((promise-value? prom) (promise-proc prom))
    (else
      (set-promise-proc! prom
        ((promise-proc prom)))
      (set-promise-value?! prom #t)
      (promise-proc prom))))
```
Examples

(define x (delay (+ 2 5))) ; a promise
(force x) ;; => 7

(define lazy-infinity (delay (infinity)))
(force (fst 3 lazy-infinity)) ; => 3
(fst 3 lazy-infinity) ; => 3
(force (delay (fst 3 lazy-infinity))) ; => 3

- here we have call-by-need only if we make every function call a promise
- in Haskell call-by-need is the default: if we need call-by-value, we need to force the evaluation (we’ll see how)
in Haskell, functions have only one argument!

this is not a limitation, because functions with more arguments are curried

we see here in Scheme what it means. Consider the function:

```scheme
(define (sum-square x y)
  (+ (* x x)
      (* y y)))
```

it has signature \( \text{sum-square} : \mathbb{C}^2 \rightarrow \mathbb{C} \), if we consider the most general kind of numbers in Scheme, i.e. the complex field
Currying (cont.)

- curried version:

```
(define (sum-square x)
  (lambda (y)
    (+ (* x x)
      (* y y))))
```

```
;; shorter version:
(define ((sum-square x) y)
  (+ (* x x)
    (* y y)))
```

- it can be used *almost* as the usual version: `((sum-square 3) 5)`
- the curried version has signature `sum-square : \mathbb{C} \rightarrow (\mathbb{C} \rightarrow \mathbb{C})`
  i.e. \(\mathbb{C} \rightarrow \mathbb{C} \rightarrow \mathbb{C}\) (\(\rightarrow\) is right associative)
Currying in Haskell

- in Haskell every function is automatically curried and consequently managed
- the name *currying*, coined by Christopher Strachey in 1967, is a reference to logician Haskell Curry
- the alternative name *Schönfinkelisation* has been proposed as a reference to Moses Schönfinkel but didn’t catch on
Haskell

- Born in 1990, designed by committee to be:
  - purely functional
  - call-by-need (sometimes called lazy evaluation)
  - strong polymorphic and static typing

- Standards: Haskell ’98 and ’10
- Motto: "Avoid success at all costs"
  - ex. usage: Google’s Ganeti cluster virtual server management tool

- I mainly follow
  Hudak, Peterson, Fasel, A Gentle Introduction to Haskell 98, 1999

- Beware! There are many bad tutorials on Haskell and monads, in particular, available online
A taste of Haskell’s syntax

• more complex and "human" than Scheme: parentheses are optional!
• function call is similar, though: \( f \ x \ y \) stands for \( f(x,y) \)
• there are infix operators and are made of non-alphabetic characters (e.g. *, +, but also <++>)
• \textit{elem} is \( \in \). If you want to use it infix, just use ‘\textit{elem}‘
• \texttt{- - this is a comment}
• \texttt{lambda}: \texttt{(lambda (x y) (+ 1 x y))} is written \texttt{\lambda y \rightarrow 1+y}
Haskell has **static** typing, i.e. the type of everything must be known at **compile time**

- there is **type inference**, so usually we do not need to explicitly declare types
- *has type* is written :: instead of : (the latter is **cons**)
- e.g.

```
5 :: Integer
'a' :: Char
inc :: Integer -> Integer
[1, 2, 3] :: [Integer] – equivalent to 1:(2:(3:[]))
('b', 4) :: (Char, Integer)
strings are **lists of characters**
```
Function definition

- functions are declared through a sequence of equations
- e.g.

```
inc n = n + 1

length :: [Integer] -> Integer
length [] = 0
length (x:xs) = 1 + length xs
```

- this is also an example of **pattern matching**
- arguments are matched with the right parts of equations, top to bottom
- if the match succeeds, the function body is called
the previous definition of \texttt{length} could work with any kind of lists, not just those made of integers

indeed, if we omit its type declaration, it is inferred by Haskell as having type

\begin{verbatim}
length :: [a] -> Integer
\end{verbatim}

lower case letters are \textbf{type variables}, so \([a]\) stands for \textit{a list of elements of type} \textit{a, for any a}
Main characteristics of Haskell’s type system

- every well-typed expression is guaranteed to have a **unique principal type**
  - it is (roughly) the *least general type that contains all the instances of the expression*
  - e.g. `length :: a -> Integer` is too general, while `length :: [Integer] -> a` is too specific
- Haskell adopts a variant of the **Hindley-Milner** type system (used also in ML variants, e.g. F#)
- and the principal type can be **inferred automatically**
User-defined types

- are based on **data declarations**

```haskell
-- a "sum" type (union in C)
data Bool = False | True
```

- **Bool** is the (nullary) **type constructor**, while **False** and **True** are **data constructors** (nullary as well)

- data and type constructors live in separate name-spaces, so it is possible (and common) to use the same name for both:

```haskell
-- a "product" type (struct in C)
data Pnt a = Pnt a a
```

- if we apply a data constructor we obtain a **value** (e.g. Pnt 2.3 5.7), while with a type constructor we obtain a **type** (e.g. Pnt Bool)
Recursive types

- classical recursive type example:

  ```haskell
  data Tree a = Leaf a | Branch (Tree a) (Tree a)
  ```

- e.g. data constructor `Branch` has type:

  ```haskell
  Branch :: Tree a -> Tree a -> Tree a
  ```

- An example tree:

  ```haskell
  aTree = Branch (Leaf 'a')
  (Branch (Leaf 'b') (Leaf 'c'))
  ```

- in this case `aTree` has type `Tree Char`
Lists are recursive types

- Of course, also lists are recursive. Using Scheme jargon, they could be defined by:

```haskell
data List a = Null | Cons a (List a)
```

- but Haskell has special syntax for them; in "pseudo-Haskell":

```haskell
data [a] = [] | a : [a]
```

- `[]` is a data and type constructor, while `:` is an infix data constructor.
An example function on Trees

\[
\text{fringe} :: \text{Tree } a \rightarrow [a] \\
\text{fringe} (\text{Leaf } x) = [x] \\
\text{fringe} (\text{Branch left right}) = \text{fringe left } ++ \text{ fringe right}
\]

\((++\) denotes list concatenation, what is its type?\)
as we saw, *product types* (e.g. `data Point = Point Float Float`) are like *struct* in C or in Scheme (analogously, *sum types* are like *union*).

the access is positional, for instance we may define accessors:

```
pointx Point x _ = x
pointy Point _ y = y
```

there is a C-like syntax to have **named fields**:

```
data Point = Point {pointx, pointy :: Float}
```

this declaration automatically defines two field names `pointx`, `pointy` and their corresponding **selector functions**.
Type synonyms

- are defined with the keyword `type`
- some examples

```haskell
type String = [Char]
type Assoc a b = [(a,b)]
```

- usually for readability or shortness
newtype is used when we want to define a type with the same representation and behavior of an existing type (like type) but having a separate identity in the type system (e.g. we want to define a kind of string \( \neq \) [Char])

e.g.

newtype Str = Str [Char]

note: we need to define a data constructor, to distinguish it from String

its data constructor is not lazy (difference with data)
Haskell has \texttt{map}, and it can be defined as:

\[
\begin{align*}
\text{map } f \; [] &= [] \\
\text{map } f \; (x:xss) &= f \; x : \text{map } f \; xss
\end{align*}
\]

we can partially apply also infix operators, by using parentheses: 
\((+ \; 1)\) or \((1 \; +)\) or \((+)\)

\[
\text{map } (1 \; +) \; [1,2,3] \quad \text{-- => [2,3,4]}
\]
:t at the prompt is used for getting **type**, e.g.

```
Prelude> :t (+1)
(+1) :: Num a => a -> a
Prelude> :t +
<interactive>:1:1: parse error on input ‘+’
Prelude> :t (+)
(+) :: Num a => a -> a -> a
```

**Prelude** is the standard library

we’ll see later the exact meaning of **Num a =>** with **type classes**. Its meaning here is that **a** must be a **numerical type**
Function composition and $\cdot$

- $\cdot$ is used for composing functions (i.e. $(f \cdot g)(x)$ is $f(g(x)))$

```haskell
Prelude> let dd = (*2) . (1+)
Prelude> dd 6
14
Prelude> :t (.)
(.) :: (b -> c) -> (a -> b) -> a -> c
```

- $\cdot$ syntax for avoiding parentheses, e.g. $(10*) (5+3) = (10*) \cdot 5+3$
Infinite computations

- Call-by-need is very convenient for dealing with never-ending computations that provide data.
- Here are some simple example functions:

\[
\begin{align*}
\text{ones} &= 1 : \text{ones} \\
\text{numsFrom } n &= n : \text{numsFrom } (n+1) \\
\text{squares} &= \text{map } (\sim^2) (\text{numsFrom } 0)
\end{align*}
\]

- Clearly, we cannot evaluate them (why?), but there is \textbf{take} to get finite slices from them.
- E.g.

\[
\text{take 5 squares} = [0,1,4,9,16]
\]
Infinite lists

- Convenient syntax for creating infinite lists:
  - e.g. `ones` before can be also written as `[1,1..]`
  - `numsFrom 6` is the same as `[6..]`
- `zip` is a useful function having type `zip :: [a] -> [b] -> [(a, b)]`
  - `zip [1,2,3] "ciao"
    -- => [(1,'c'),(2,'i'),(3,'a')]`

- List comprehensions
  - `[(x,y) | x <- [1,2], y <- "ciao"]`
    -- => [(1,'c'),(1,'i'),(1,'a'),(1,'o'),(2,'c'),(2,'i'),(2,'a'),(2,'o')]`
a list with all the Fibonacci numbers
(note: tail is cdr, while head is car)

\[
\text{fib} = 1 : 1 :
  [a+b \mid (a,b) \leftarrow \text{zip} \ \text{fib} \ \text{tail fib}]
\]
**Error**

- **bottom** (aka ⊥) is defined as `bot = bot`
- all errors have value `bot`, a value shared by all types
- `error :: String -> a` is strange because is polymorphic only in the output
- the reason is that it returns **bot** (in practice, an exception is raised)
Pattern matching

- the matching process proceeds top-down, left-to-right
- patterns may have **boolean guards**

```
sign x | x > 0 = 1
   | x == 0 = 0
   | x < 0 = -1
```

- _ stands for *don’t care*
- e.g. definition of **take**

```
take 0 _ = []
take _ [] = []
take n (x:xs) = x : take (n-1) xs
```
the order of definitions **matters**:

Prelude> :t bot
bot :: t
Prelude> take 0 bot
[]

on the other hand, take bot [] does not terminate

what does it change, if we swap the first two defining equations?
**take with case:**

```
take m ys = case (m,ys) of
  (0,_) -> []
  (_,[]) -> []
  (n,x:xs) -> x : take (n-1) xs
```
let and where

- **let** is like Scheme’s letrec*:

  ```
  let x = 3
  y = 12
  in x+y  --  =>  15
  ```

- **where** can be convenient to scope binding over equations, e.g.:

  ```
  powset set = powset’ set [[]] where
  powset’ [] out = out
  powset’ (e:set) out = powset’ set (out ++
  [ e:x | x <- out ])
  ```

- layout is like in Python, with meaningful whitespaces, but we can also use a C-like syntax:

  ```
  let {x = 3 ; y = 12} in x+y
  ```
Call-by-need and memory usage

- **fold-left** is efficient in Scheme, because its definition is naturally tail-recursive:

  \[
  \begin{align*}
  \text{foldl } f \; z \; [] & = z \\
  \text{foldl } f \; z \; (x:xs) & = \text{foldl } f \; (f \; z \; x) \; xs
  \end{align*}
  \]

  *note: in Racket it is defined with \((f \times z)\)*

- this is not as efficient in Haskell, because of call-by-need:

  - `foldl (+) 0 [1,2,3]`
  - `foldl (+) (0 + 1) [2,3]`
  - `foldl (+) ((0 + 1) + 2) [3]`
  - `foldl (+) (((0 + 1) + 2) + 3) []`
  - `(((0 + 1) + 2) + 3) = 6`
Haskell is too lazy: an interlude on strictness

There are various ways to enforce strictness in Haskell (analogously there are classical approaches to introduce laziness in strict languages)

- e.g. on data with **bang patterns** (a datum marked with ! is considered **strict**)

```haskell
data Complex = Complex !Float !Float
```

- there are extensions for using ! also in function parameters
Forcing evaluation

- Canonical operator to **force evaluation** is \( \text{seq} :: \, a \rightarrow t \rightarrow t \)
- \( \text{seq} \, x \, y \) returns \( y \), **only if** the evaluation of \( x \) **terminates** (i.e. it performs \( x \) then returns \( y \))
- a strict version of **foldl** (available in *Data.List*)

\[
\begin{align*}
\text{foldl}' \, f \, z \, [] & = z \\
\text{foldl}' \, f \, z \, (x:xs) & = \text{let } z' = f \, z \, x \\
& \text{ in seq } z' \, (\text{foldl}' \, f \, z' \, xs)
\end{align*}
\]

- strict versions of standard functions are usually primed
Special syntax for `seq`

- There is a convenient *strict* variant of $ (function application) called $!
- Here is its definition:

```haskell
($!) :: (a -> b) -> a -> b
f $! x = seq x (f x)
```
not much to be said: Haskell has a simple module system, with `import`, `export` and namespaces

a very simple example

```haskell
module CartProd where --- export everything
infixr 9 -*-
-- right associative
-- precedence goes from 0 to 9, the strongest
x -*- y = [(i,j) | i <- x, j <- y]
```
import/export

```haskell
module Tree ( Tree (Leaf , Branch ) , fringe ) where
  data Tree a = Leaf a | Branch ( Tree a ) ( Tree a )
  fringe :: Tree a -> [ a ] ...

module Main ( main ) where
  import Tree ( Tree (Leaf , Branch ) )
  main = print ( Branch ( Leaf 'a' ) ( Leaf 'b' ) )
```
modules provide the only way to build abstract data types (ADT)

the characteristic feature of an ADT is that the representation type is hidden: all operations on the ADT are done at an abstract level which does not depend on the representation

e.g. a suitable ADT for binary trees might include the following operations:

```haskell
data Tree a -- just the type name
leaf :: a -> Tree a
branch :: Tree a -> Tree a -> Tree a
cell :: Tree a -> a
left, right :: Tree a -> Tree a
isLeaf :: Tree a -> Bool
```
ADT implementation

```haskell
module TreeADT (Tree, leaf, branch, cell,
    left, right, isLeaf) where

data Tree a = Leaf a | Branch (Tree a) (Tree a)
leaf = Leaf
branch = Branch
cell (Leaf a) = a
left (Branch l r) = l
right (Branch l r) = r
isLeaf (Leaf _) = True
isLeaf _ = False
```

- in the export list the type name Tree appears without its constructors
- so the only way to build or take apart trees outside of the module is by using the various (abstract) operations
- the advantage of this information hiding is that at a later time we could change the representation type without affecting users of the type
we already saw *parametric polymorphism* in Haskell (e.g. in *length*)

*type classes* are the mechanism provided by Haskell for *ad hoc* polymorphism (aka *overloading*)

the first, natural example is that of numbers: 6 can represent an integer, a rational, a floating point number...

e.g.

```haskell
Prelude> 6 :: Float
6.0
Prelude> 6 :: Integer -- unlimited
6
Prelude> 6 :: Int -- fixed precision
6
Prelude> 6 :: Rational
6 % 1
```
Type classes: equality

- also numeric operators and equality work with different kinds of numbers
- let’s start with equality: it is natural to define equality for many types (but not every one, e.g. functions - it’s undecidable)
- we consider here only value equality, not pointer equality (like Java’s `==` or Scheme’s `eq?`), because pointer equality is clearly not referentially transparent
- let us consider `elem`

```haskell
x `elem` [] = False
x `elem` (y:ys) = x==y || (x `elem` ys)
```

- its type should be: `a -> [a] -> Bool`. But this means that `(==) :: a -> a -> Bool`, even though equality is not defined for every type
**class Eq**

- **type classes** are used for overloading: a class is a "container" of overloaded operations
- we can declare a type to be an **instance** of a type class, meaning that it implements its operations
- e.g. class Eq

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

- now the type of (==) is

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

- Eq a is a **constraint** on type a, it means that a must be an instance of Eq
e.g. `elem` has type \((\text{Eq } a) \Rightarrow a \rightarrow [a] \rightarrow \text{Bool}\)

we can define instances like this:

\[
\begin{align*}
\text{instance } (\text{Eq } a) & \Rightarrow \text{Eq } (\text{Tree } a) \text{ where} \\
\text{Leaf } a & \equiv \text{Leaf } b \equiv a \equiv b \\
(\text{Branch } l1 \text{ r1}) & \equiv (\text{Branch } l2 \text{ r2}) \equiv (l1 \equiv l2) \land (r1 \equiv r2) \\
_ & \equiv _ \equiv \text{False}
\end{align*}
\]

an implementation of \((\equiv)\) is called a **method**

**CAVEAT** do not confuse all these concepts with the homonymous concepts in OO programming: there are similarities but also big differences
### Haskell vs Java concepts

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- in Java, an Object is an *instance* of a Class
- in Haskell, a Type is an *instance* of a Class
Eq and Ord in the Prelude

- Eq offers also a standard definition of $\neq$, derived from $(==)$:

  ```haskell
class Eq a where
    (==), (/=) :: a -> a -> Bool
    x /= y = not (x == y)
  
we can also extend Eq with comparison operations:

  ```haskell
class (Eq a) => Ord a where
    (<), (<=), (>=), (>) :: a -> a -> Bool
    max, min :: a -> a -> a
  
Ord is also called a **subclass** of Eq

- it is possible to have **multiple inheritance**: class (X a, Y a) => Z a
Another important class: Show

- it is used for **showing**: to have an instance we must implement `show`
- e.g., functions do not have a standard representation:

```haskell
Prelude> (+)
<interactive>:2:1:
    No instance for `(Show (a0 -> a0 -> a0))`
    arising from a use of `print`
Possible fix:
    add an instance declaration for `(Show (a0 -> a0 -> a0))`
```

- well, we can just use a trivial one:

```haskell
instance Show (a -> b) where
    show f = "<< a function >>"
```
we can also represent binary trees:

instance Show a => Show (Tree a) where
    show (Leaf a) = show a
    show (Branch x y) = "<" ++ show x ++ " | " ++ show y ++ ">"

e.g.

Branch
    (Branch
        (Leaf 'a') (Branch (Leaf 'b') (Leaf 'c')))
    (Branch
        (Leaf 'd') (Leaf 'e'))

is represented as

<<'a' | 'b' | 'c'>> | <'d' | 'e'>>
usually it is not necessary to explicitly define instances of some classes, e.g. Eq and Show
Haskell can be quite smart and do it automatically, by using `deriving` for example we may define binary trees using an infix syntax and automatic Eq, Show like this:

```haskell
infixr 5 :^:
data Tr a = Lf a | Tr a :^: Tr a
 deriving (Show, Eq)
```

e.g.

```haskell
*Main> let x = Lf 3 :^: Lf 5 :^: Lf 2
*Main> let y = (Lf 3 :^: Lf 5) :^: Lf 2
*Main> x == y
False
*Main> x
Lf 3 :^: (Lf 5 :^: Lf 2)
```
An example with class Ord

- Rock-paper-scissors in Haskell
  
  ```haskell
data RPS = Rock | Paper | Scissors deriving (Show, Eq)

instance Ord RPS where
  x <= y | x == y    = True
  Rock   <= Paper   = True
  Paper  <= Scissors = True
  Scissors <= Rock   = True
  _       <= _      = False
  ```

- note that we only needed to define (<=) to have the instance
An example with class Num

- a simple re-implementation of rational numbers

```haskell
data Rat = Rat !Integer !Integer deriving Eq

simplify (Rat x y) = let g = gcd x y
       in Rat (x 'div' g) (y 'div' g)
makeRat x y = simplify (Rat x y)

instance Num Rat where
  (Rat x y) + (Rat x' y') = makeRat (x*y'+x'*y) (y*y')
  (Rat x y) - (Rat x' y') = makeRat (x*y'-x'*y) (y*y')
  (Rat x y) * (Rat x' y') = makeRat (x*x') (y*y')
  abs (Rat x y) = makeRat (abs x) (abs y)
  signum (Rat x y) = makeRat (signum x * signum y) 1
  fromInteger x = makeRat x 1
```
An example with class Num (cont.)

- **Ord:**

  ```haskell
  instance Ord Rat where
  (Rat x y) <= (Rat x' y') = x*y' <= x'*y
  ```

- **a better show:**

  ```haskell
  instance Show Rat where
  show (Rat x y) = show x ++ "/" ++ show y
  ```

- **note:** Rationals are in the Prelude!

- **moreover, there is class Fractional for / (not covered here)**

- **but we could define our version of division as follows:**

  ```haskell
  x // (Rat x' y') = x * (Rat y' x')
  ```
what is the type of the standard function `getChar`, that gets a character from the user? `getChar :: theUser -> Char`?

first of all, it is not **referentially transparent**: two different calls of `getChar` could return different characters

In general, IO computation is based on **state change** (e.g. of a file), hence if we perform a **sequence of operations**, they must be performed in **order** (and this is not easy with **call-by-need**).
getChar can be seen as a function \( \text{getChar} : \text{Time} \rightarrow \text{Char} \).

indeed, it is an **IO action** (in this case for Input):
\[
\text{getChar} : : \text{IO Char}
\]

quite naturally, to print a character we use **putChar**, that has type:
\[
\text{putChar} : : \text{Char} \rightarrow \text{IO ()}
\]

**IO** is an instance of the **monad** class, and in Haskell it is considered as an **indelible stain of impurity**
A very simple example of an IO program

- **main** is the default entry point of the program (like in C)

```haskell
main = do {
    putStr "Please, tell me something>";
    thing <- getLine;
    putStrLn $ "You told me " ++ thing ++ "\".";
}
```

- special syntax for working with IO: **do**, `<-`

- we will see its real semantics later, used to define an IO action as an **ordered sequence** of IO actions

- "<-" (note: not =) is used to obtain a value from an IO action

- types:

```haskell
main    :: IO ()
putStr  :: String -> IO ()
getLine :: IO String
```
compile with e.g. **ghc readme.hs**

```haskell
import System.IO
import System.Environment

readfile = do {
    args <- getArgs; -- command line arguments
    handle <- openFile (head args) ReadMode;
    contents <- hGetContents handle; -- note: lazy
    putStrLn contents;
    hClose handle;
}
main = readFile
```

**readfile stuff.txt** reads "stuff.txt" and shows it on the screen

**hGetContents** reads lazily the contents of the file
Of course, purely functional Haskell code can raise exceptions: \texttt{head []}, \texttt{3 `div` 0}, \ldots

but if we want to catch them, we need an IO action:

\begin{verbatim}
handle :: Exception e => (e -> IO a) -> IO a -> IO a;
\end{verbatim}

the 1st argument is the \textit{handler}

Example: we catch the errors of \texttt{readfile}

\begin{verbatim}
import Control.Exception
import System.IO.Error
...
main = handle handler readFile
  where handler e
      | isDoesNotExistError e = putStrLn "This file does not exist."
      | otherwise = putStrLn "Something is wrong."
\end{verbatim}
Other classical data structures

- What about usual, practical data structures (e.g. arrays, hash-tables)?
- Traditional versions are imperative! If really needed, there are libraries with imperative implementations living in the IO monad.
- Idiomatic approach: use immutable arrays (Data.Array), and maps (Data.Map, implemented with balanced binary trees)
- find are respectively $O(1)$ and $O(\log n)$; update $O(n)$ for arrays, $O(\log n)$ for maps
- of course, the update operations copy the structure, do not change it
import Data.Map

exmap = let m = fromList [("nose", 11), ("emerald", 27)]
          n = insert "rug" 98 m
          o = insert "nose" 9 n
          in (m ! "emerald", n ! "rug", o ! "nose")

  exmap evaluates to (27,98,9)
Example code: Arrays

- (//) is used for update/insert
- listArray’s first argument is the range of indexing (in the following case, indexes are from 1 to 3)

```haskell
import Data.Array

exarr = let m = listArray (1,3) ['alpha','beta','gamma']
    n = m // [(2,"Beta")]
    o = n // [(1,"Alpha"), (3,"Gamma")]
  in (m ! 1, n ! 2, o ! 1)

exarr evaluates to ("alpha","Beta","Alpha")
```
How to reach Monads

- We saw that IO is a type constructor, instance of Monad
- But we still do not know what a Monad is
- Recent versions of GHC make the trip a bit longer, because we need first to introduce the following classes:
  - Foldable (not required, but useful)
  - Functor
  - Applicative (Functor)
Class **Foldable**

- **Foldable** is a class used for *folding*, of course.
- The main idea is the one we know from *foldl* and *foldr* for lists:
  - we have a container, and a binary operation $f$, and we want to apply $f$ to all the elements in the container.
- A minimal implementation of Foldable requires *foldr*. 
Example: foldable binary trees

Let’s go back to our binary trees

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

we can easily define a foldr for them

tfoldr f z Empty = z
tfoldr f z (Leaf x) = f x z
tfoldr f z (Node l r) = tfoldr f (tfoldr f z r) l

instance Foldable Tree where
    foldr = tfoldr

> foldr (+) 0 (Node (Node (Leaf 1) (Leaf 3)) (Leaf 5))
9
Maybe

- **Maybe** is used to represent computations that may fail: we either have *Just v*, if we are lucky, or *Nothing*.
- It is basically a simple "conditional container"
  
  ```haskell
data Maybe a = Nothing | Just a
```
- It is adopted in many recent languages, to avoid NULL and limit exceptions usage.
- Examples are Scala (basically the ML family approach): Option[T], with values None or Some(v); Swift, with Optional<T>.
- It is quite simple, so we will use it in our examples with Functors & C.
instance Foldable Maybe where
    foldr _ z Nothing = z
    foldr f z (Just x) = f x z
Functor

- **Functor** is the class of all the types that offer a *map* operation
- (so there is an analogy with Foldable vs folds)
- the map operation of functors is called **fmap** and has type:
  \[ \text{fmap} :: (a \to b) \to f~a \to f~b \]
- it is quite natural to define map for a container, e.g.:

  ```haskell
  instance Functor Maybe where
      fmap _ Nothing = Nothing
      fmap f (Just a) = Just (f a)
  ```
Functor laws

Well-defined functors should obey the following laws:

- $\text{fmap id} = \text{id}$ (where $\text{id}$ is the identity function)
- $\text{fmap (f . g)} = \text{fmap f . fmap g}$

You can try, as an exercise, to check if the functors we are defining obey the laws.
Trees can be functors, too

First, let us define a suitable \textit{map} for trees:

\begin{align*}
tmap \ f \ \text{Empty} &= \text{Empty} \\
tmap \ f \ (\text{Leaf} \ x) &= \text{Leaf} \ \&\ f \ x \\
tmap \ f \ (\text{Node} \ l \ r) &= \text{Node} \ (tmap \ f \ l) \ (tmap \ f \ r)
\end{align*}

That's all we need:

\begin{verbatim}
instance Functor Tree where
    fmap = tmap
\end{verbatim}

\begin{verbatim}
-- example
> fmap (+1) (Node (Node (Leaf 1) (Leaf 2)) (Leaf 3))
Node (Node (Leaf 2) (Leaf 3)) (Leaf 4)
\end{verbatim}
Applicative Functors

- In our voyage toward monads, we must consider also an extended version of functors, i.e. **Applicative functors**
- The definition looks indeed exotic:
  ```haskell
  class (Functor f) => Applicative f where
    pure :: a -> f a
    (<*>) :: f (a -> b) -> f a -> f b
  
  note that f is a type constructor, and f a is a Functor type
  moreover, f must be parametric with one parameter
  if f is a container, the idea is not too complex:
    - pure takes a value and returns an f containing it
    - <*> is like fmap, but instead of taking a function, takes an f containing a function, to apply it to a suitable container of the same kind
Maybe is an Applicative Functor

Here is its definition:

```haskell
instance Applicative Maybe where
    pure = Just
    Just f <*> m = fmap f m
    Nothing <*> _ = Nothing
```
Of course, lists are instances of Foldable and Functor. What about Applicative?

For that, it is first useful to introduce `concat`

\[
\text{concat} :: \text{Foldable } t \Rightarrow t [a] \rightarrow [a]
\]

So we start from a container of lists, and get a list with the \textit{concatenation} of them:

\[
\text{concat } [[[1,2]], [3], [4,5]] \text{ is } [1,2,3,4,5]
\]

it can be defined as: \[
\text{concat } l = \text{foldr } (++) \emptyset l
\]

its composition with \textit{map} is called \texttt{concatMap}

\[
\text{concatMap } f l = \text{concat } \text{\$ map } f l
\]

\[
> \text{concatMap } (\lambda x \rightarrow [x, x+1]) [1,2,3] [1,2,2,3,3,4]
\]
Lists are instances of Applicative

- With `concatMap`, we get the standard implementation of `<*>` for lists:

  ```haskell
  instance Applicative [] where
      pure x = [x]
      fs <*> xs = concatMap (\f -> map f xs) fs
  ```

- What can we do with it? For instance we can apply list of operations to lists:

  ```haskell
  > [(+1),(*2)] <*> [1,2,3]
  [2,3,4,2,4,6]
  ```

- Note that we *map* the operations in sequence, then we *concatenate* the resulting lists.
Trees and Applicative

- Following the list approach, we can make our binary trees an instance of Applicative Functors.
- First, we need to define what we mean by tree concatenation:
  
  \[
  \begin{align*}
  \text{tconc } & \quad \text{Empty } t = t \\
  \text{tconc } & \quad t \quad \text{Empty} = t \\
  \text{tconc } & \quad t_1 \quad t_2 = \text{Node } t_1 \quad t_2 \\
  \end{align*}
  \]

- now, concat and concatMap (here tconcmap for short) are like those of lists:
  
  \[
  \begin{align*}
  \text{tconcat } & \quad t = \text{tfoldr } \text{tconc } \quad \text{Empty} \quad t \\
  \text{tconcmap } & \quad f \quad t = \text{tconcat } \quad \text{s } \quad \text{tmap } \quad f \quad t \\
  \end{align*}
  \]
Here is the natural definition (practically the same of lists):

```haskell
instance Applicative Tree where
  pure = Leaf
  fs <*> xs = tconcmap (\f -> tmap f xs) fs
```

Let’s try it:

```haskell
> (Node (Leaf (+1))(Leaf (*2))) <*>
  Node (Node (Leaf 1) (Leaf 2)) (Leaf 3)

Node (Node (Node (Leaf 2) (Leaf 3))
  (Leaf 4))
  (Node (Node (Leaf 2) (Leaf 4))
  (Leaf 6))
```
introduced by Eugenio Moggi in 1991, a monad is a kind of algebraic data type used to represent computations (instead of data in the domain model) - we will often call these computations actions.

monads allow the programmer to chain actions together to build an ordered sequence, in which each action is decorated with additional processing rules provided by the monad and performed automatically.

monads are flexible and abstract. This makes some of their applications a bit hard to understand.
monads can also be used to make imperative programming easier in a pure functional language

in practice, through them it is possible to define an imperative sub-language on top of a purely functional one

there are many examples of monads and tutorials (many of them quite bad) available in the Internet
The Monad Class

class Applicative m => Monad m where
    -- Sequentially compose two actions, passing any value produced
    -- by the first as an argument to the second.
    (>>=) :: m a -> (a -> m b) -> m b
    -- Sequentially compose two actions, discarding any value produced
    -- by the first, like sequencing operators (such as the semicolon)
    -- in imperative languages.
    (>>) :: m a -> m b -> m b
    m >> k = m >>= \_ -> k
    -- Inject a value into the monadic type.
    return :: a -> m a
    return = pure
    -- Fail with a message.
    fail :: String -> m a
    fail s = error s
Note that only >>= is required, all the other methods have standard definitions.

>>>= and >> are called **bind**

m a is a *computation* (or action) resulting in a value of type a

**return** is by default **pure**, so it is used to create a single monadic action. E.g. return 5 is an action containing the value 5.

**bind** operators are used to compose actions

- x >>= y performs the computation x, takes the resulting value and passes it to y; then performs y.
- x >> y is analogous, but "throws away" the value obtained by x
Maybe is a Monad

- Its definition is straightforward

```haskell
instance Monad Maybe where
    (Just x) >>= k = k x
    Nothing  >>= _ = Nothing
    fail _ = Nothing
```
Examples with Maybe

- The information managed automatically by the monad is the “bit” which encodes the **success** (i.e. `Just`) or failure (i.e. `Nothing`) of the action sequence.
- e.g. `Just 4 >> Just 5 >> Nothing >> Just 6` evaluates to `Nothing`.
- a variant: `Just 4 >>= Just >>= Nothing >>= Just 6` (what is the result in this case?)
- another: `Just 4 >> Just 1 >>= Just >>= Nothing >>= Just 6`
for a monad to behave correctly, method definitions must obey the following laws:

1) \textbf{return} is the \textbf{identity element}:

\begin{align*}
\text{(return x) >>= f} & \iff f x \\
\text{m >>= return} & \iff m
\end{align*}

2) \textbf{associativity} for binds:

\begin{align*}
\text{(m >>= f) >>= g} & \iff \text{m >>= (\x \to (f x >>= g))}
\end{align*}

\text{(monads are analogous to \textbf{monoids}, with return = 1 and >>= = \cdot)}
Example: monadic laws application with Maybe

- \( (\text{return 4 :: Maybe Integer} \gg= \ x \rightarrow \text{Just (x+1)}) \)
  
  Just 5

- \( \text{Just 5} \gg= \text{return} \)
  
  Just 5

- \( (\text{return 4 } \gg= \ x \rightarrow \text{Just (x+1)}) \)
  
  \( \gg= \ x \rightarrow \text{Just (x*2)} \)

  Just 10

- \( \text{return 4} \gg= (\ y \rightarrow \)
  
  \( \begin{align*}
  & (\ (\ x \rightarrow \text{Just (x+1)}) \ y) \\
  & \gg= \ x \rightarrow \text{Just (x*2)}
  \end{align*} \)

  Just 10
Syntactic sugar: the **do** notation

- The **do** syntax is used to avoid the explicit use of `>>=` and `>>`
- The essential translation of **do** is captured by the following two rules:

  \[
  \text{do e}_1 \ ; \ e_2 \quad \leftrightarrow \quad e_1 \ >> e_2 \\
  \text{do } p \ <- \ e_1 \ ; \ e_2 \quad \leftrightarrow \quad e_1 \ >>= \ p \ -> \ e_2
  \]

  note that they can also be written as:

  \[
  \text{do } e_1 \quad e_2 \\
  \text{do } p \ <- \ e_1 \quad e_2
  \]

  or:

  \[
  \text{do } \{ \ e_1 \ ; \ e_2 \ } \\
  \text{do } \{ \ p \ <- \ e_1 \ ; \ e_2 \ }
  \]
Caveat: **return** does not return

- IO is a build-in monad in Haskell: indeed, we used the `do` notation for performing IO
- there are some catches, though – it looks like an imperative sub-language, but its semantics is based on bind and pure
- For example:

  ```haskell
esp :: IO Integer
esp = do x <- return 4
        return (x+1)
```

  ```
  > esp
  5
  ```
The List Monad

- **List**: monadic binding involves joining together a set of calculations for each value in the list
- In practice, *bind* is `concatMap`

```
instance Monad [] where
  xs >>= f = concatMap f xs
  fail _ = []
```
Lists: do vs comprehensions

- List comprehensions can be expressed in do notation
- E.g. this comprehension
  \[
  \{(x,y) \mid x \leftarrow [1,2,3], y \leftarrow [1,2,3]\}
  \]
  is equivalent to:
  ```plaintext
do x \leftarrow [1,2,3]
  y \leftarrow [1,2,3]
  return (x,y)
```
to understand our example of comprehension, i.e.

testcomp = do x <- [1,2,3]
    y <- [1,2,3]
    return (x,y)

we can rewrite it following the monad definition:

testcomp’ =
    [1,2,3] >>= (\x -> [1,2,3] >>=
                    (\y ->
                        return (x,y)))
that is:

testcomp'' =
  concatMap f0 [1,2,3]
where f0 x = concatMap f1 [1,2,3]
  where f1 y = [(x,y)]
We can now define our own monad with binary trees. Knowing about lists, it is not too hard:

```
instance Monad Tree where
    xs >>= f = tconcmap f xs
    fail _ = Empty
```
Now some examples

- Monads are abstract, so monadic code is very flexible, because it can work with **any** instance of Monad

- A simple monadic comprehension:

  ```haskell
  exmon :: (Monad m, Num r) => m r -> m r -> m r
  exmon m1 m2 = do x <- m1
                  y <- m2
                  return $ x - y
  ```
Let’s apply it to lists and trees

- First, we try with lists:
  
  > exmon [10, 11] [1, 7]
  
  [9,3,10,4]

- on trees is not much different

  > exmon (Node (Leaf 10) (Leaf 11)) (Node (Leaf 1) (Leaf 7))
  
  Node (Node (Leaf 9) (Leaf 3))
  
  (Node (Leaf 10) (Leaf 4))
Not just simple containers

- Monads can be used to implement parsers, continuations, ... 
- and, of course, IO
- Let's try exmon with IO Int:

```haskell
-- read is like in Scheme, here is used to parse the number
exmon (do putStrLn "?> "
    x <- getLine;
    return (read x :: Int))
(return 10)
```

- What is the result, if we enter 12?