

# Haskell

*A Purely Functional Language*

featuring static typing, higher-order functions,  
polymorphism, type classes and monadic effects

## Funkcie a funkcionály

a ich  
referečná transparentosť

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): I-18 :(

<http://dai.fmph.uniba.sk/courses/FPRO/>



Všetko, čo by ste chceli vedieť o Haskellí, ale báli ste sa spýtať...

# Funkcia

a čo s ňou

- aplikovať – na argument/y

- Haskell: `f 5, goo 17 21, fib (n-2)` -- zátvorky píšeme kvôli zložitému argumentu, `(fib n)-2`
- inde: `f(5), goo(17,21) fib(n-2)`

Celá pravda o Haskellí:

že **`a b c d = (((a b) c) d)`**...lebo operátor aplikácie funkcie na argument je *ľavo asociatívny*, teda, ak zabudnem zátvorky, tak ich iniciatívne chápe grupované doľava

- abstrahovať / abstrakcia

- jazyk je funkcionálny, ak viete vytvoriť funkciu ( $\lambda$ -abstrakciu) počas behu program

- Haskell: `(+) = \x -> \y -> x+y`
  - Python: `lambda x, y: x + y`
  - JS: `(a, b) => a + b`
  - Java: `(a, b) -> a + b`
  - Kotlin: `a:Int, b:Int -> a + b`
  - Swift: `a, b in a+b`
- clojure:  
`fib n = cyklus`

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# Funkcia

a čo s ňou

## ■ má typ

- Python, JS, ...: ☹
- Haskell:
  - $(+) :: \text{Int} \rightarrow \text{Int} \rightarrow \text{Int}$ , čo **nie je** to isté ako  $:: (\text{Int}, \text{Int}) \rightarrow \text{Int}$
- Currying  $(+ 4) :: \text{Int} \rightarrow \text{Int}$ ,  $(+ 4 7) :: \text{Int} = 11$
- Celá pravda o Haskellí:
- **$\text{Int} \rightarrow \text{Int} \rightarrow \text{Int} \rightarrow \text{Char} = \text{Int} \rightarrow (\text{Int} \rightarrow (\text{Int} \rightarrow \text{Char}))$**  ... lebo operátor funkčného typu  $\rightarrow$  je *pravo asociatívny*, teda ak zabudnem zátvorky, tak ich chápe doprava. Explicitne,  $(\text{Int} \rightarrow \text{Int}) \rightarrow (\text{Int} \rightarrow \text{Int})$
- **$\text{Int} \rightarrow \text{Int} \rightarrow \text{String} \neq (\text{Int}, \text{Int}) \rightarrow \text{String}$**  ... lebo prvé je funkcia, ktorá vráti funkciu, ktorá vráti String. Vďaka *currying* ju volám takto:  $f\ 4\ 5$ , čo je  $(f\ 4)\ 5$ . Druhé je funkcia, ktorá čaká dvojicu. Musím ju volať takto:  $g\ (4,5)$ , a vyzerám skôr Javista, a nie Haskellista
- Príklad:

```
f :: Int -> (Int -> Int)
f a b = 10*a+b
f 5 7 = 57
f 5 :: Int -> Int
f 5 = \b -> 10*5+b
f 5 b = 10*5+b
f 5 y = 10*5+y
```

```
g :: (Int -> Int) -> Int
g h = h 7
g (+11) = 18
g (\x->x+11) = 18
g (^2) = 49
g (\x->x^2) = 49
g (*5) = 35
```

Všetko, čo by ste chceli vedieť o Haskellí, ale báli ste sa spýtať...

# Funkcia

a čo s ňou

- komponovať –  $f \cdot g$  - z matematiky  $(f \circ g)(x) = f(g(x))$
- je asociatívne, nie je komutatívne, identita  $\text{id} = \lambda x \rightarrow x$  je neutrálny prvok

## Haskell:

```
(.) :: (b->c) -> (a->b) -> (a->c)
(.) = \f -> \g -> \x -> f (g x)
f . g = \x -> f (g x)
(f . g) x = f (g x)
```

```
composeMany [] = id
composeMany (f:fs) = f . composeMany fs
```

```
-- ak poznáte reduce.py  $\approx$  foldr
composeMany :: [a->a] -> (a->a)
composeMany xs = foldr (.) id xs
```

Bezargumentový snobizmus  
`composeMany = foldr (.) id`

pramení tiež z matematiky, lebo  
matematik tiež radšej napíše  
 $f = g$  miesto  $\forall x: f(x) = g(x)$

## Python, JS, ...:

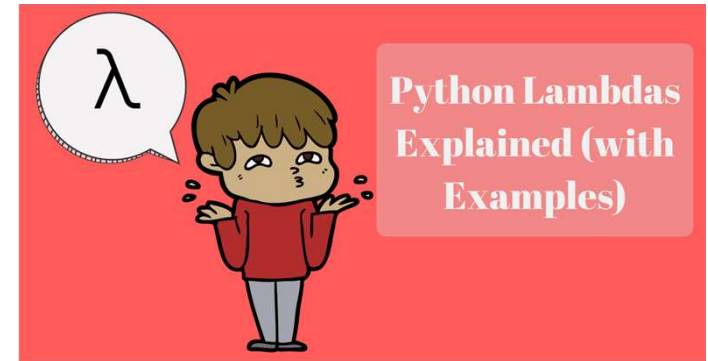
```
def compose(f, g):
    return lambda x: f(g(x))
```

```
def composeMany(*fs):
    return reduce(compose, fs)
```

```
print(composeMany(
    lambda x: x+1,
    lambda x: x+2,
    lambda x: x*3
)(10))
```

# Python Kvíz

pre aplikovancov



```
print(map(lambda x: x*x, [1,2,3,4,5]))  
print(list(map(lambda x: x*x, [1,2,3,4,5])))  
print(list(filter(lambda y:y>10,map(lambda x: x*x, [1,2,3,4,5]))))
```

<map object at 0x037  
[1, 4, 9, 16, 25]  
[16, 25]

**from functools import reduce**

```
print(reduce((lambda x, y: x * y), [1, 2, 3, 4]))
```

24

```
print(reduce((lambda x, y: x + y), [1, 2, 3, 4]))
```

10

```
print(reduce((lambda x, y: x - y), [1, 2, 3, 4]))
```

-8

```
def compose(f, g):
```

```
    return lambda x: f(g(x))
```

```
print(compose( lambda x: x+1, lambda x: x*3 )(10))
```

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```
def composeMany(*fs):
```

```
    return reduce(compose, fs)
```

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```
print(composeMany(lambda x:x+1, lambda x:x+2, lambda x:x*3)(10))
```

[lambdas.hs](http://lambdas.hs)

Všetko, čo by ste chceli  
vedieť o Haskellí, ale  
báli ste sa spýtať

# Otázka z interview

a ako na ňu

## Haskell:

```
dvojica a b = pair
  where pair f = f a b
```

```
dvojica :: s->t->((s->t->v)->v)
-- inak
dvojica a b = \f -> f a b
dvojica a b f = f a b
```

```
prvy p = p (\ a-> \b -> a)
druhy p = p (\ a-> \b -> b)
```

```
print $ prvý (dvojica 4 5)
print $ druhy (dvojica 4 5)
```

```
prvy p = p true
  where true a b = a
druhy p = p false
  where false a b = b
```

## Python, JS, ...:

```
def dvojica(a, b):
    def pair(f):
        return f(a, b)
    return pair
```

```
# inak
def dvojica(a,b):
    return lambda f: f(a,b)
```

```
def head(p):
    return p(lambda a,b :a)
```

```
def tail(p):
    return p(lambda a,b:b)
```

```
print(head(dvojica(4,5)))
print(tail(dvojica(4,5)))
```

Často sa *obrábajú* zoznamov  
prezentuje ako funkcionálne  
programovanie, pritom je to len  
nevyhnutný úvod k lepšiemu...

# Zoznamová zoznamka

## Haskell:

```
xs = [1,2,3,4,5] [1..5]
length xs
xs!!i
neexistuje-immutable list
head xs
tail xs
last xs
init xs
take n xs
xs[:n]
drop n xs
take m (drop n xs)
xs++xs
reverse xs
```

## Python:

```
[1,2,3,4,5]
len xs
xs[i]           .. indexy 0..length xs-1
xs[i]=...
xs[0]           1
xs[1:]          [2,3,4,5]
xs[len(xs)-1]   5
xs[:len(xs)-1]  [1,2,3,4]
xs[:n]
xs[n:]
xs[n:n+m]
xs+xs           [1,2,3,4,5,1,2,3,4,5]
xs.reverse()    returns void
```



# import Data.List

<http://hackage.haskell.org/package/base-4.12.0.0/docs/Data-List.html>

base-4.12.0.0: Basic libraries

Quick Jump

## Data.List

Operations on lists.

### Basic functions

Copyright	(c) The University of Glasg
License	BSD-style (see the file lib
Maintainer	libraries@haskell.org
Stability	stable
Portability	portable
Safe Haskell	Trustworthy
Language	Haskell2010

**(++)** :: [a] -> [a] -> [a] # Source infixr 5

Append two lists, i.e.,

```
[x1, ..., xm] ++ [y1, ..., yn] == [x1, ..., xm, y1, ..., yn]
[x1, ..., xm] ++ [y1, ...] == [x1, ..., xm, y1, ...]
```

If the first list is not finite, the result is the first list.

**head** :: [a] -> a # Source

Extract the first element of a list, which must be non-empty.

**last** :: [a] -> a # Source

Extract the last element of a list, which must be finite and non-empty.

**tail** :: [a] -> [a] # Source

Extract the elements after the head of a list, which must be non-empty.

**init** :: [a] -> [a] # Source

Return all the elements of a list except the last one. The list must be non-empty.

### Contents

- Basic functions
- List transformations
- Reducing lists (folds)
  - Special folds
- Building lists
  - Scans
  - Accumulating maps
  - Infinite lists
  - Unfolding
- Sublists
  - Extracting sublists
  - Predicates
- Searching lists
  - Searching by equality
  - Searching with a predic
- Indexing lists
- Zippping and unzipping lists
- Special lists
  - Functions on strings
  - "Set" operations
  - Ordered lists
- Generalized functions
  - The "By" operations





# Možno vás to prekvapí

## ■ ale zoznam – list – [a]

- **je immutable/nemenný asi ako String v Java**
- raz, keď ho vytvoríte, nikdy ho už nezmeníte, len môžete vytvoriť nový, trochu iný
- inak povedané
  - indexovanie `xs[i]` existuje, ale niečo ako nahradenie `xs[i] = a` neexistuje

Chce to objaviť inú dátovú štruktúru, a sú: `Data.Array`, `Data.Set`, ...

- ale tie sú tiež immutable/nemenné
- lebo filozófia
- prvý pocit mutable dátovej štruktúry poskytnú až monády, state monad

### • **je homogénny v type**

- v zozname `[a]` sú len hodnoty typu `a`
- žiaden `Any`, `Object`, ... neexistuje, našťastie



# List-comprehension

---

Každý poriadny kurz FP začína funkcionálmi map a filter:

...ale my sme trénovali list-comprehension:

$[f\ x \mid x \leftarrow xs, p\ x]$        $[f(x) \text{ for } x \text{ in } xs \text{ if } p(x)]$

map, filter sú deriváti list-comprehension

`map`             $:: (a \rightarrow b) \rightarrow [a] \rightarrow [b]$

`map f xs`       $= [f\ x \mid x \leftarrow xs]$

`filter`         $:: (a \rightarrow \text{Bool}) \rightarrow [a] \rightarrow [a]$

`filter p xs`     $= [x \mid x \leftarrow xs, p\ x]$

# Všetko, čo ste chceli zmeniť, a nikdy sa vám to nepodarilo

- zoznam ("pole") xs vieme indexovať indexami  $i <- [0..length\ xs-1]$   
xs!!i -- getter

- neexistuje setter xs[i] = value

set :: [t] -> Int -> t -> [t]

```
set xs i value | i < 0           = xs    -- out of range
                | i >= length xs = xs    -- out of range
                | otherwise      = (if i == 0 then value else y):set ys (i-1) value
                                where (y:ys) = xs
                | otherwise      = let (y:ys) = xs in
                                (if i == 0 then value else y):set' ys (i-1) value
```

set'' :: [t] -> Int -> t -> [t]

```
set'' xs i value | i < 0           = xs    -- out of range
                | i >= length xs = xs    -- out of range
                | otherwise      = [xs!!j | j <- [0.. i-1] ] ++ [value] ++
                                [xs!!j | j <- [i+1..length xs-1] ]
```



# Zoznamová rekurzia

```
-- vyber prvých n prvkov zo zoznamu
take      :: Int -> [a] -> [a]
take 0 _  = []
take _ [] = []
take n (x:xs) = x : (take (n-1) xs)
```

```
-- dĺžka zoznamu
length    :: [a] -> Int
length [] = 0
length (x:xs) = 1 + length xs
```

Hypotéza (pre ľubovoľné n a xs) platí:

- $\text{length (take n xs)} = n$
- $\text{length \$ take n xs} = n$       -- dolárová notácia
- $(\text{length} . \text{take n}) \text{ xs} = n$       -- kompozícia funkcií z matematike

```
"?: " take 5 [1,3..100]
[1,3,5,7,9]
"?: " length (take 5 [1,3..100])
5
"?: " length $ take 5 [1,3..100]
5
```



# Dôkaz - $\text{length (take } n \text{ xs)} = n$

(matematická indukcia)

Indukcia (vzhľadom na dĺžku/štruktúru xs):

- **xs = []**

$\text{length (take } n \text{ [])} = 0$

$0 = 0$

*č.b.t.d.*

- **xs = (y:ys)**

$\text{length (take } n \text{ (y:ys))} = n$

$\text{length (y:take (n-1) ys)} = n$

$1 + \text{length (take (n-1) ys)} = n$

indukčný predpoklad,  $|ys| < |xs|$

$1 + \text{(n-1)} = n$

*č.b.t.d.*

Definície z predošlej strany:

$\text{take} \quad \quad \quad :: \text{Int} \rightarrow [a] \rightarrow [a]$

$\text{take } 0 \text{ } \_ = []$

$\text{take } \_ [] = []$

$\text{take } n \text{ (x:xs)} = x : \text{take (n-1) xs}$

$\text{length} \quad \quad \quad :: [a] \rightarrow \text{Int}$

$\text{length } [] = 0$

$\text{length (x:xs)} = 1 + \text{length xs}$



# QuickCheck

---

Elegantný nástroj na testovanie (!!! nie dôkaz !!!) hypotéz

```
"?: " import Test.QuickCheck
```

```
"?: " quickCheck (\(xs,n) -> length (take n xs) == n)
```

```
*** Failed! Falsifiable (after 2 tests and 1 shrink):
```

```
"?: " verboseCheck (\(xs,n) -> length (take n xs) == n)
```

```
Passed:
```

```
([],0)
```

```
Passed:
```

```
([()],1)
```

```
Failed:
```

```
([],-1)
```

```
*** Failed! Failed:
```

Neplatí to pre  $n$  záporne, lebo napr.  $\text{take } (-3) [1..100] = []$ ,

resp. naša definícia nepokrýva prípad  $n < 0$

!!! ALE MY SME TO AJ TAK "DOKÁZALI"... !!!



# QuickCheck

Podmienka: miesto písania

**if n >= 0 then** length (take n s) == n **else True**

Napíšeme pre-condition pomocou ==>

"?: " verboseCheck (\(xs,n) -> **n>=0** ==> length (take n xs) == n)

Passed:

([],0)

Failed:

([()],2)

Neplatí to pre ak length xs < n ☹️

"?: " quickCheck (\(xs,n) -> **n>=0 && length xs >= n** ==>

length (take n xs) == n)

\*\*\* Gave up! Passed only 35 tests.



Tvrdenie sme **overili** na niekoľkých prípadoch, ale to **nie je dôkaz**.

V dôkaze môžeme urobiť chybu (ako na slajde 2), QuickCheck slúži ako

nástroj na hľadanie/odhaľovanie kontrapríkladov, kedy naše tvrdenie neplatí.

Don't write tests!

Generate them  
from properties



- miesto písania unit testov, quickcheck vám ich (nejaké) vygeneruje
- vy potom nepíšete testy, ale vlastnosti vašich programov.

O niečom podobnom dávno snívali/dúfali Hoare, Dijkstra, ...

- s rozdielom, že vlastnosti programov chceli dokázať,
- miesto hľadania kontrapríkladu.

Quickcheck:

- generuje náhodné vstupné hodnoty, pre základné aj definované typy
  - Int, Bool, ...
  - [Int], String, ...
  - Int->Int, Int->Bool
- ak nájde kontrapríklad (už vieme, že to neplatí), snaží sa ho zminimalizovať/zjednodušiť, napr: `length (take n xs) == n` neplatí pre `length (take 21 [5,-192,3981,-291,2220,-192,22,12,-192,-1]) == 21`



Don't write tests!

Generate them  
from properties



# QuickCheck

autori: [Koen Claessen](#), [John Hughes](#)

Príklad Parretovho pravidla 20:80 - za 20% energie chytíte 80% problémov

Príklad (viac [tu](#)):

Collatz (viac [tu](#)) je funkcia  $f(n) = \text{if } n \bmod 2 == 0 \text{ then } n/2 \text{ else } 3n+1$ .

```
f      :: Integer -> Integer
```

```
f n    | even(n) = n `div` 2
```

```
        | odd(n)  = 3*n + 1
```

```
collatz :: Integer -> Bool
```

```
collatz 1 = True
```

```
collatz n = collatz (f n)
```

```
"?: " quickCheck (\n -> n > 0 ==> collatz(n))
```

```
+++ OK, passed 100 tests.
```

```
"?: " quickCheckWith stdArgs{ maxSuccess = 100000 }
```

```
      (\n -> n > 0 ==> collatz(n))
```

```
+++ OK, passed 100000 tests.
```

[Paul Erdős](#): "Mathematics may not be ready for such problems." offered \$500 for its solution.



# Kritérium deliteľnosti 11

- rodné číslo 786115 3333 (ženské, \*15.nov1978)
- $7861153333 \mod 11 == 0$
- $11 \mid 7861153333$  iff  $11 \mid 7+6+1+3+3 - (8+1+5+3+3) = 0$
- naše rodné čísla sú deliteľné 11, ľahká kontrola
- čísla kariet majú tiež kontrolu, Luhnnovo algo, DÚ1
- čo bankové účty
- 7000155733 / 8180 – soc.poist'ovňa
- cifry násobíme váhami 6,3,7,9,10,5,8,4,2,1, sčítame, výsledok deliteľný 11
- $11 \mid 7*6+0*3+0*7+0*9+1*10+5*5+5*8+7*4+3*2+3*1$
- $(\text{sum } \$ \text{ zipWith } (*) [7,0,0,0,1,5,5,7,3,3] [6,3,7,9,10,5,8,4,2,1]) \mod 11$
- $(\text{sum } \$ \text{ zipWith } (*) [2,7,0,1,1,3,2,4,4,3] [6,3,7,9,10,5,8,4,2,1]) \mod 11$



# Počet cifier ešte raz

funkcionálny štýl

---

```
pocetCifier :: Integer -> Int
```

```
pocetCifier n = length $ show n
```

```
pocetCifier = length . Show
```

```
pocetCifier' :: Integer -> Int
```

```
pocetCifier' n = fromIntegral $ ceiling $ (logBase 10 (fromIntegral n))
```

```
pocetCifier' = fromIntegral . ceiling . (logBase 10) . fromIntegral
```

```
pocetCifier'' :: Integer -> Int
```

```
pocetCifier'' n = length $ takeWhile (/=0) $ iterate (`div` 10) n
```

```
pocetCifier'' = length . takeWhile (/=0) . iterate (`div` 10)
```

```
hypoteza1 = quickCheck(\n -> (n > 0) ==> pocetCifier n == pocetCifier'' n)
```

```
hypoteza2 = quickCheck(\n -> (n > 0) ==> pocetCifier n == pocetCifier' n)
```

```
hypoteza2' = quickCheck(\n -> (n > 1) ==> pocetCifier n == pocetCifier' n)
```

```
hypoteza2'' = quickCheck(\n -> (n > 10) ==> pocetCifier n == pocetCifier' n)
```

```
-- platí/neplatí ?
```

# Kvíz - platí/neplatí ?

(neseriózny prístup ale intuíciu treba tiež trénovať)

- `length [m..n] == n-m+1` 😞  
"?: " `quickCheck ((\ (n,m) -> length [m..n] == n-m+1))`  
\*\*\* Failed! Falsifiable (after 3 tests and 1 shrink):  
"?: " `quickCheck ((\ (n,m) -> m <= n ==> length [m..n] == n-m+1))` 😊  
+++ OK, passed 100 tests.
- `length (xs ++ ys) == length xs + length ys` 😊  
"?: " `quickCheck((\xs->\ys->(length (xs++ys)==length xs + length ys)))`  
+++ OK, passed 100 tests.
- `length (reverse xs) == length xs` 😊  
`quickCheck((\xs -> (length (reverse xs) == length xs )))`  
+++ OK, passed 100 tests.
- `(xs, ys) == unzip (zip xs ys)` 😞  
`quickCheck((\xs -> \ys -> ( (xs, ys) == unzip (zip xs ys) )))`  
\*\*\* Failed! Falsifiable (after 3 tests and 1 shrink):  
`quickCheck((\xs -> \ys -> ( length xs == length ys ==>`  
`(xs, ys) == unzip (zip xs ys) )))` 😊



# Funkcia/predikát argumentom

- zober zo zoznamu tie prvky, ktoré spĺňajú podmienku (test)  
Booleovská podmienka príde ako argument funkcie a má typ  $(a \rightarrow \text{Bool})$ :

`filter`  $:: (a \rightarrow \text{Bool}) \rightarrow [a] \rightarrow [a]$

`filter p xs`  $= [x \mid x \leftarrow xs, p\ x]$

alternatívna definícia:

`filter p []`  $= []$

`filter p (x:xs)`  $= \text{if } p\ x \text{ then } x:(\text{filter } p\ xs) \text{ else } \text{filter } p\ xs$

**> filter even [1..10]  
[2,4,6,8,10]**

vlastnosti (zväčša úplne zrejmé ?):

- `filter True xs`  $= xs$   $\dots [x \mid x \leftarrow xs, \text{True}] = [x \mid x \leftarrow xs] = xs$
- `filter False xs`  $= []$   $\dots [x \mid x \leftarrow xs, \text{False}] = []$
- `filter p1 (filter p2 xs)`  $= \text{filter } (p1 \ \&\& \ p2)\ xs$
- `(filter p1 xs) ++ (filter p2 xs)`  $= \text{filter } (p1 \ || \ p2)\ xs$

$$\begin{aligned}\text{filter } p \ [] &= [] \\ \text{filter } p \ (x:xs) &= \text{if } p \ x \text{ then } x:(\text{filter } p \ xs) \text{ else } \text{filter } p \ xs\end{aligned}$$

# Dôkaz

$\text{filter } p1 \ (\text{filter } p2 \ xs) = \text{filter } (p1 \ \&\& \ p2) \ xs$

Indukcia vzhľadom na parameter xs

- []  
L.S. =  $\text{filter } p1 \ (\text{filter } p2 \ []) = \text{filter } p1 \ [] = [] = \text{filter } (p1 \ \&\& \ p2) \ [] = \text{P.S.}$
- (x:xs)  
L.S. =  $\text{filter } p1 \ (\text{filter } p2 \ (x:xs)) = \dots \text{definícia}$   
 $\text{filter } p1 \ (\text{if } p2 \ x \text{ then } x:(\text{filter } p2 \ xs) \text{ else } \text{filter } p2 \ xs) = \dots \text{filter dnu cez if}$   
 $\text{if } p2 \ x \text{ then } \text{filter } p1 \ (x:(\text{filter } p2 \ xs)) \text{ else } \text{filter } p1 \ (\text{filter } p2 \ xs) = \dots \text{indukcia}$   
 $\text{if } p2 \ x \text{ then } \text{filter } p1 \ (x:(\text{filter } p2 \ xs)) \text{ else } \text{filter } (p1 \ \&\& \ p2) \ xs = \dots \text{definícia}$   
 $\text{if } p2 \ x \text{ then}$ 
  - $\text{if } p1 \ x \text{ then } x:(\text{filter } p1 \ (\text{filter } p2 \ xs)) \text{ else } \text{filter } p1 \ (\text{filter } p2 \ xs)$ $\text{else } \text{filter } (p1 \ \&\& \ p2) \ xs = \dots \text{2 x indukcia}$   
 $\text{if } p2 \ x \text{ then}$ 
  - $\text{if } p1 \ x \text{ then } x:(\text{filter } (p1 \ \&\& \ p2) \ xs) \text{ else } \text{filter } (p1 \ \&\& \ p2) \ xs$ $\text{else } \text{filter } (p1 \ \&\& \ p2) \ xs =$

$\text{filter } p [] = []$   
 $\text{filter } p (x:xs) = \text{if } p \ x \text{ then } x:(\text{filter } p \ xs) \text{ else } \text{filter } p \ xs$

# Dôkaz

$\text{filter } p1 (\text{filter } p2 \ xs) = \text{filter } (p1 \ \&\& \ p2) \ xs$

if  $p2 \ x$  then

if  $p1 \ x$  then  $x:(\text{filter } (p1 \ \&\& \ p2) \ xs)$  else  $\text{filter } (p1 \ \&\& \ p2) \ xs$

else  $\text{filter } (p1 \ \&\& \ p2) \ xs = \dots$  **požívame vlastnosť if-then-else**

if  $A$  then

if  $A \ \&\& \ B$  then  $C$

if  $B$  then  $C$

else  $D$

else  $D$

else  $D$

if  $(p1 \ \&\& \ p2) \ x$  then  $x:(\text{filter } (p1 \ \&\& \ p2) \ xs)$  else  $\text{filter } (p1 \ \&\& \ p2) \ xs = \dots$  **def.**

$\text{filter } (p1 \ \&\& \ p2) \ (x:xs) = \text{P.S.}$

*č.b.t.d.*



# QuickCheck a funkcie

Funkcie sú hodnoty ako každé iné  
Ako vie QuickCheck pracovať s funkciami ?

- je skladanie funkcií komutatívne ?

```
"?: " import Text.Show.Functions
```



```
"?: " quickCheck(
```

```
  (\x -> \f -> \g -> (f.g) x == (g.f) x)::Int->(Int->Int)->(Int->Int)->Bool)
```

```
*** Failed! Falsifiable (after 2 tests):
```

- je skladanie funkcií asociatívne ?

```
"?: " quickCheck(
```

```
  (\x -> \f -> \g -> \h -> (f.(g.h)) x == ((f.g).h) x)
```



```
  ::Int->(Int->Int)->(Int->Int)->(Int->Int)->Bool)
```

```
+++ OK, passed 100 tests.
```

Opäť to NIE je DÔKAZ, len 100 pokusov.



# QuickCheck a predikáty

Predikát je len funkcia s výsledným typom Bool

- `filter p1 (filter p2 xs) = filter (p1 && p2) xs` ☹️

?: " quickCheck ( \xs -> \p1 -> \p2 ->

filter p1 (filter p2 xs) == filter (p1 && p2) xs)

:: [Int] -> (Int->Bool) -> (Int->Bool) -> Bool)

<interactive>:113:91: Couldn't match expected type 'Bool' ---

NEPLATÍ LEBO ANI TYPY NESEDIA, && je definovaný na Bool, a nie na funkciách Int->Bool

- `filter p1 (filter p2 xs) = filter (\x-> p1 x && p2 x) xs` 😊

+++ OK, passed 100 tests.

Opäť to NIE je DÔKAZ (ten už bol), len 100 pokusov.

- `(filter p1 xs) ++ (filter p2 xs) = filter (\x -> p1 x || p2 x) xs`

"?: " quickCheck ( \xs -> \p1 -> \p2 ->

(filter p1 xs) ++ (filter p2 xs) == filter (\x -> p1 x || p2 x) xs)

:: [Int] -> (Int->Bool) -> (Int->Bool) -> Bool)

\*\*\* Failed! Falsifiable (after 3 tests):

[0] <function> <function>



# Rekapitulácia

---

videli sme tzv. **Property Based Testing** pomocou **QuickCheck**:

- najznámejšie dva funkcionály: map, filter – ktoré poznáte aj z Pythonu
- quickCheck náhodne generujúci testy/kontrapríklady pre typy
  - základné typy: Int, Bool, String...
  - zoznamy: [Int], [t]
  - funkcie: Int->Int, a->b, ...
- množstvo 'ekvivalentných' tvrdení, niektoré boli neekvivalentné...

Property Based Testing (PBT):

- rôzne implementácie QuickCheck v jazykoch:
  - Scala (Scala Check), F# (FsCheck), Clojure (test.check), Python (Hypothesis)
- musí implementovať:
  - generovanie dát pre základné typy, parametrické typy, funkčné typy, ...
  - generovanie dát pre používateľom definované typy
  - zjednodušovanie kontrapríkladu (shrinking)

# Funkcia argumentom

## map

- funktor, ktorý aplikuje funkciu (1.argument) na všetky prvky zoznamu

`map`  $:: (a \rightarrow b) \rightarrow [a] \rightarrow [b]$

`map f []`  $= []$

`map f (x:xs)`  $= f\ x : \text{map } f\ xs$

`map f xs`  $= [ f\ x \mid x \leftarrow xs ]$

- Príklady:

`map (+1) [1,2,3,4,5]`  $= [2,3,4,5,6]$

`map odd [1,2,3,4,5]`  $= [\text{True}, \text{False}, \text{True}, \text{False}, \text{True}]$

`and (map odd [1,2,3,4,5])`  $= \text{False}$

`map head [ [1,0,0], [2,1,0], [3,0,1] ]`  $= [1, 2, 3]$

`map tail [ [1,0,0], [2,1,0], [3,0,1] ]`  $= [ [0,0], [1,0], [0,1] ]$

`map (0:) [[1],[2],[3]]`  $= [[0,1],[0,2],[0,3]]$



# Vlastnosti map

- $\text{map id } xs = xs$  ☒  $\text{map id} = \text{id}$
- $\text{map } (f.g) \text{ } xs = \text{map } f (\text{map } g \text{ } xs)$  ☒  $\text{map } f . \text{map } g = \text{map } (f.g)$
- ~~$\text{head } (\text{map } f \text{ } xs) = f (\text{head } xs)$~~  ☒  ~~$\text{head} . \text{map } f = f . \text{head}$~~
- ~~$\text{tail } (\text{map } f \text{ } xs) = \text{map } f (\text{tail } xs)$~~  ☒  ~~$\text{tail} . \text{map } f = \text{map } f . \text{tail}$~~
- $\text{map } f (xs ++ ys) = \text{map } f \text{ } xs ++ \text{map } f \text{ } ys$  ☒
- $\text{length } (\text{map } f \text{ } xs) = \text{length } xs$  ☒  $\text{length} . \text{map } f = \text{length}$
- $\text{map } f (\text{reverse } xs) = \text{reverse } (\text{map } f \text{ } xs)$  ☒  $\text{map } f . \text{reverse} = \text{reverse} . \text{map } f$
- ~~$\text{sort } (\text{map } f \text{ } xs) = \text{map } f (\text{sort } xs)$~~  ☒  ~~$\text{sort} . \text{map } f = \text{map } f . \text{sort}$~~
- $\text{map } f (\text{concat } xss) = \text{concat } (\text{map } (\text{map } f) \text{ } xss)$  ☒

$\text{map } f . \text{concat} = \text{concat} . \text{map } (\text{map } f)$

$\text{concat} :: [[a]] \rightarrow [a]$

$\text{concat } [] = []$

$\text{concat } (xs:xss) = xs ++ \text{concat } xss$



$\text{concat } [[1], [2,3], [4,5,6], []] = [1,2,3,4,5,6]$



# Vlastnosti map, filter

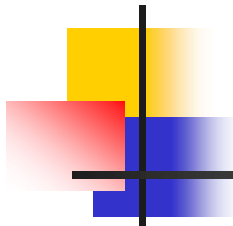
---

Na zamyslenie:

- `filter p (map f xs)` = `???` `(filter (p.f) xs)` 
- `filter p (map f xs)` = `map f (filter (p.f) xs)` 
- `filter p . map f` = `map f . filter (p.f)`

Dôkaz:

`filter p (map f xs)`  
= `filter p [ f x | x<-xs]`  
= `[y | y <- [ f x | x<-xs], p y]`  
= `[f x | x<-xs, p (f x)]`  
= `map f [x | x<-xs, p (f x)]`  
= `map f (filter (p.f))`



# Quíz - prémia

nájdite pravdivé a zdôvodnite

---

- $\text{map } f . \text{take } n = \text{take } n . \text{map } f$
- $\text{map } f . \text{filter } p = \text{map } \text{fst} . \text{filter } \text{snd} . \text{map } (\text{fork } (f,p))$   
where  $\text{fork} :: (a \rightarrow b, a \rightarrow c) \rightarrow a \rightarrow (b,c)$   
 $\text{fork } (f,g) x = (f x, g x)$
- $\text{filter } (p . g) = \text{map } (\text{inverzna\_g}) . \text{filter } p . \text{map } g$   
ak  $\text{inverzna\_g} . g = \text{id}$
- $\text{reverse} . \text{concat} = \text{concat} . \text{reverse} . \text{map } \text{reverse}$
- $\text{filter } p . \text{concat} = \text{concat} . \text{map } (\text{filter } p)$

# QuickSort s QuickCheck

(na cvičeniach)

```
import Test.QuickCheck
```

```
import Data.List (sort)
```

```
qsort :: Ord a => [a] -> [a]
```

-- Ord a – vieme triediť len porovnateľné typy

```
qsort [] = []
```

-- analógia interface Comparable<a>

```
qsort (p:xs) = qsort (filter (< p) xs) ++ [p] ++ qsort (filter (>= p) xs)
```

```
quickCheck(\xs -> length (qsort xs) == length xs)
```

```
quickCheck((\xs -> length (qsort xs) == length xs)::[Int]->Bool)
```

```
quickCheck((\xs -> qsort xs == sort xs)::[Int]->Bool)
```

```
quickCheck((\xs -> qsort(qsort xs) == qsort xs)::[Int]->Bool)
```

```
isSorted :: Ord a => [a] -> Bool
```

```
isSorted xs = sort xs == xs
```

```
isSorted' :: Ord a => [a] -> Bool
```

```
isSorted' [] = True
```

```
isSorted' xs = and $ zipWith (<=) (init xs) (tail xs)
```

```
quickCheck((\xs -> isSorted (qsort xs))::[Int]->Bool)
```

```
quickCheck((\xs -> isSorted' (qsort xs))::[Int]->Bool)
```



# Kombinatorika

(podobné nájdete v Prémii QC & Kombinatorika)

```
module Kombinatorika where
import Test.QuickCheck
import Data.List
```

```
fact n = product [1..n]
comb n k = (fact n) `div` ((fact k) * (fact (n-k)))
```

```
-- permutácie
perms :: [t] -> [[t]]
perms [] = [[]]
perms (x:xs) = [ insertInto x i ys | ys <- perms xs, i <- [0..length ys] ]
               where insertInto x i xs = (take i xs) ++ (x:drop i xs)
qchPERM = quickCheck(\n -> (n > 0 && n < 10) ==> length (perms [1..n]) == fact n)
```

```
kbo :: [t] -> Int -> [[t]]
kso :: [t] -> Int -> [[t]]
vbo :: (Eq t) => [t] -> Int -> [[t]]
vso :: [t] -> Int -> [[t]]
```

?

```
n!
(n nad k)
((n+k-1) nad k)
n.(n-1). ... .(n-k+1)
```





- Introduction to QuickCheck  
[https://wiki.haskell.org/Introduction to QuickCheck2](https://wiki.haskell.org/Introduction_to_QuickCheck2)
- Introduction to QuickCheck by example: Number theory and Okasaki's red-black trees  
<http://matt.might.net/articles/quick-quickcheck/>
- K.Claessen, J.Hughes:QuickCheck:A Lightweight Tool for Random Testingof Haskell Programs  
<https://www.eecs.northwestern.edu/~robby/courses/395-495-2009-fall/quick.pdf>
- A QuickCheck Tutorial: Generators  
<https://www.stackbuilders.com/news/a-quickcheck-tutorial-generators>



# Definované typy

---

Ak definujeme vlastnú dátovú štruktúru, ako využiť quickCheck ?

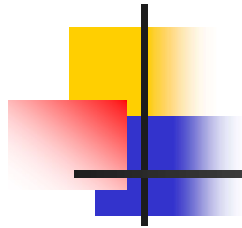
```
data BVS t = Nil | Node (BVS t) t (BVS t) deriving(Show, Eq)
```

- dva konštruktory **Nil** a **Node** \_ \_ \_
- deriving popisuje patričnosť do triedy class - (resp. implements interface)
  - Show – automaticky vygenerovaná funkcia `show :: BVS t -> String`
  - Eq – automaticky vygenerované funkcie `==,/= :: BVS t -> BVS t -> Bool`

Ako definovať funkciu, ktorá vracia náhodný strom, napr. `BVS Int` ?

Existuje nejaká náhodná funkcia, napr. `nextInt :: Int` ?

Nie je to v rozpore s Referenčnou transparentnosťou ?



# Java a Reflexivita

(malá odbočka)

Skúsme si tú istú otázku preformulovať v Jave, ktorú poznáme

- Napíšte funkciu, ktorá vytvorí náhodnú inštanciu ľubovoľnej triedy  
**Object gener(String className)**
- Nechceme mať náhodný generátor pre každú triedu, lebo pre nami definované triedy by sme ho museli písať sami...
- Reflexivita (Java Reflection Model), od slajdu 11
- [https://github.com/Programovanie4/Prednasky/blob/master/13/13\\_java.pdf](https://github.com/Programovanie4/Prednasky/blob/master/13/13_java.pdf)
- java primitívne typy (int, char, double, ...), String...
- polia (int[], ...)
- triedy s default konštruktorom (Stvorec(), ...)
- triedy s konštruktorom s parametrami – rekurzívne pre každý parameter konšuktora, potom zavolanie konšuktora s náhodnými parametrami
- generické triedy



# QuickCheck – Generátor

(pre základné typy)

- trieda Arbitrary t definuje generátor Gen t pre hodnoty typu t:  
class Arbitrary a where  
    arbitrary :: Gen t  
a volá sa pomocou funkcie generate :: Gen t -> IO t

Pre preddefinované typy to už niekto zdefinoval:

"?: " (generate arbitrary) :: IO Int	23, 45, 12, 49, 12, ...
"?: " generate arbitrary :: IO Char	't','w', '\199', ...
"?: " generate arbitrary :: IO (Char, Int)	('6',0), ('<','-7)
"?: " generate arbitrary :: IO [Int]	[-29,-17,10], [-10,9]
"?: " generate arbitrary :: IO Double	-5.5026813
"?: " generate arbitrary :: IO Bool	True, False, False
"?: " do { fst <- generate arbitrary::IO Int; snd <- generate arbitrary::IO Char; return (fst, snd) }	(-6, 'r'), (15, 'a'), ...



# QuickCheck – Generátor

(pre funkčné typy)

```
"?: " generate arbitrary :: IO (Int->Int)
```

<function>

```
"?: " do {f<-generate arbitrary :: IO (Integer->Integer); return (f 7)} 9, 11
```

```
"?: " do {
```

```
  f<-generate arbitrary :: IO (Integer->Integer);
```

```
  g<-generate arbitrary :: IO (Integer->Integer);
```

```
  x<-generate arbitrary :: IO Integer;
```

```
  return (((f.g) x) == ((g.f) x)) }
```

False, False, False, True

```
"?: " do {
```

```
  f<-generate arbitrary :: IO (Integer->Integer);
```

```
  g<-generate arbitrary :: IO (Integer->Integer);
```

```
  h<-generate arbitrary :: IO (Integer->Integer);
```

```
  x<-generate arbitrary :: IO Integer;
```

```
  return (((((f.g).h) x) == (((f.g).h) x)) }
```

True, True, True, True



# Generátory

(pre definované typy)

```
kocka :: Gen Int
```

```
kocka = choose(1,6)
```

```
-- "?: " generate kocka
```

```
-- "?: " generate (choose(1,10))
```

```
yesno :: Gen Bool
```

```
yesno = choose(True, False)
```

```
-- "?: " generate yesno
```

```
-- "?: " generate (choose(True, False))
```

```
data Minca = Hlava | Panna deriving (Show)
```

```
instance Arbitrary Minca where
```

```
    arbitrary = oneof [return Hlava, return Panna]
```

Pre nami definované typy  
XXX musíme definovať  
inštanciu triedy Arbitrary XXX

```
"?: " generate (arbitrary::Gen Minca)
```

```
"?: " (generate arbitrary)::IO Minca
```

```
falosnaMinca :: Gen Minca
```

```
falosnaMinca = frequency [(1,return Hlava), (2,return Panna)]
```

```
-- "?: " generate falosnaMinca
```

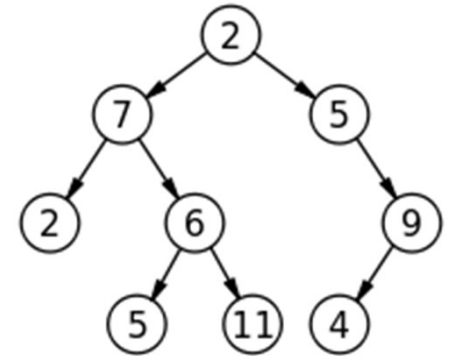


# Generátory - zoznam

```
arbitraryListMax8Len :: Arbitrary a => Gen [a]    -- náhodný zoznam len <= 8
arbitraryListMax8Len =
    do {                                           "?: " generate (arbitraryListMax8Len::Gen [Int])
        [-21,12,17,16,4,-20]
        k <- choose (0, 8)::(Gen Int);
        sequence [ arbitrary | _ <- [1..k] ] }

arbitraryList :: Arbitrary a => Gen [a]
arbitraryList =
    mysized ( \n -> do {                           "?: " generate (arbitraryList::Gen [Int])
        [-9,7,14,24,18,28,-4,0,22,12,-14]
        k <- choose (0, n) ;
        sequence [ arbitrary | _ <- [1..k] ] }
    )
mysized :: (Int -> Gen a) -> Gen a                "?: " generate
mysized f = f 50                                (mysized (\n -> choose(n,n)))
50
```

# Generátory - strom



```
data Tree t = Leaf t | Node (Tree t) t (Tree t)
  deriving (Show, Ord, Eq)
```

```
instance Arbitrary a => Arbitrary (Tree a) where
  arbitrary = frequency
```

```
  [
    (1, liftM Leaf arbitrary )    "?: " generate (arbitrary :: Gen (Tree Int))
    , (1, liftM3 Node arbitrary arbitrary arbitrary)
  ]
  Leaf (-18)
```

```
strom :: Gen (Tree Int)    "?: " generate strom
strom = frequency [
  (1, liftM Leaf arbitrary )
  , (10, liftM3 Node arbitrary arbitrary arbitrary)
]
Node (Node (Leaf (-2)) 3 (Leaf (-6))) 23 (Leaf 22)
```





# BVS – binárny vyhľadávací

```
data BVS t = Nil | Node (BVS t) t (BVS t) deriving(Show, Ord, Eq)
```

-- je binárny vyhľadávací strom

```
isBVS :: (Ord t) => BVS t -> Bool -- t vieme porovnávať <
```

-- nájsť v binárnom vyhľadávacom strome

```
find :: (Ord t) => t -> (BVS t) -> Bool -- analógia Comparable<t>
```

```
find _ Nil = False
```

```
find x (Node left value right) | x == value = True  
                                | x < value  = find x right  
                                | x > value  = find x left
```

```
flat :: BVS t -> [t]
```

```
flat Nil = []
```

```
flat (Node left value right) = flat left ++ [value] ++ flat right
```



# BVS - isBVS

---

Príšerne neefektívne riešenie, prepíšte lepšie:

```
isBVS  :: (Ord t) => BVS t -> Bool
```

```
isBVS Nil = True
```

```
isBVS (Node left value right) =
```

```
    (all (<value) (flat left))
```

```
    &&
```

```
    (all (>value) (flat right))
```

```
    &&
```

```
    isBVS left
```

```
    &&
```

```
    isBVS right
```



# BVS - testy

---

```
qch1 = verbose((\x -> \tree -> find x tree)::Int->(BVS Int)->Bool)
qch2 = quickCheck((\x -> \tree -> ((find x tree) == (elem x (flat tree))))
                ::Int->BVS Int->Bool)
```

```
{--
"?: " qch2
*** Failed! Falsifiable (after 3 tests):
1 ; Node Nil (-2) (Node Nil 1 Nil)
--}
```

```
qch3 = quickCheck((\x -> \tree -> (isBVS tree) ==>
                ((find x tree) == (elem x (flat tree))))::Int->BVS Int->Property)
```

```
{--
*** Failed! Falsifiable (after 2 tests):
0 ; Node (Node Nil (-1) (Node Nil 0 Nil)) 1 Nil
--}
```

KDE je chyba v definícii BVS ??

Don't write tests!

Generate them  
from properties



# BVS – tajnička

```
find :: (Ord t) => t -> (BVS t) -> Bool
```

```
find _ Nil = False
```

```
find x (Node left value right) | x == value = True
```

```
    | x < value = find x right
```

```
    | x > value = find x left
```

```
    | x < value = find x left
```

```
    | x > value = find x right
```

# Haskell – foldr

`foldr`  $:: (a \rightarrow b \rightarrow b) \rightarrow b \rightarrow [a] \rightarrow b$

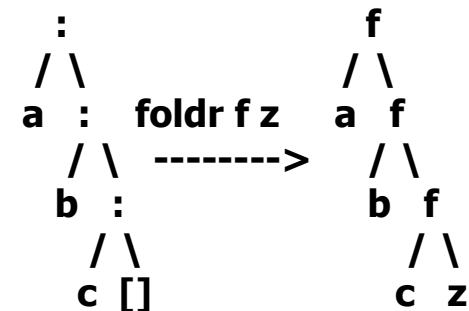
`foldr f z []` = `z`

`foldr f z (x:xs)` = `f x (foldr f z xs)`

`a : b : c : []`  $\rightarrow$  `f a (f b (f c z))`

```
Main> foldr (+) 0 [1..100]
5050
```

```
Main> foldr (\x y->10*y+x) 0 [1,2,3,4]
4321
```



-- g je vnorená lokálna funkcia

```
foldr :: (a -> b -> b) -> b -> [a] -> b
foldr f z = g
  where g []      = z
        g (x:xs) = f x (g xs)
```



# Haskell – foldl

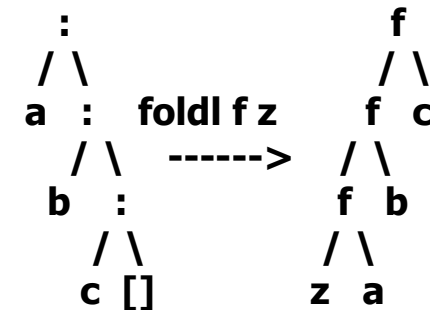
---

`foldl`  $:: (a \rightarrow b \rightarrow a) \rightarrow a \rightarrow [b] \rightarrow a$

`foldl f z []` = `z`

`foldl f z (x:xs)` = `foldl f (f z x) xs`

`a : b : c : []`  $\rightarrow f (f (f z a) b) c$



```
Main> foldl (+) 0 [1..100]
5050
```

```
Main> foldl (\x y->10*x+y) 0 [1,2,3,4]
1234
```



# Vypočítajte

---

- `foldr max (-999) [1,2,3,4]`  
`foldl max (-999) [1,2,3,4]`
- `foldr (\_ -> \y ->(y+1)) 0 [3,2,1,2,4]`  
`foldl (\x -> \_ ->(x+1)) 0 [3,2,1,2,4]`

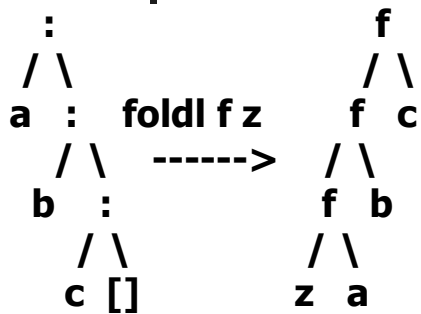
- `foldr (-) 0 [1..100] =`

$$(1-(2-(3-(4-\dots-(100-0)))))) = 1-2 + 3-4 + 5-6 + \dots + (99-100) = -50$$

- `foldl (-) 0 [1..100] =`

$$(\dots(((0-1)-2)-3) \dots - 100) = -5050$$

# Kvíz

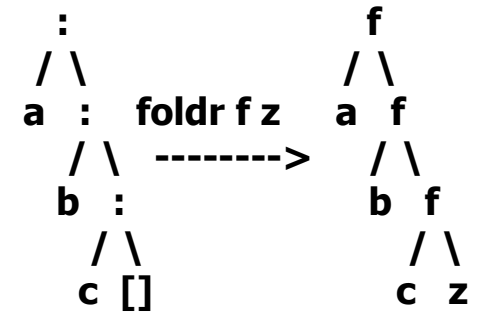


$$\text{foldr } (:) [] \text{ xs} = \text{xs}$$

$$\text{foldr } (:) \text{ ys xs} = \text{xs} ++ \text{ys}$$

$$\text{foldr } ? ? \text{ xs} = \text{reverse xs}$$

$$\text{foldr } ((:) . h) [] = ???$$



<http://foldl.com/>



Pre tých, čo zvládli kvíz, odmena !

kliknite si podľa vašej politickej orientácie

<http://foldr.com/>







# Funkcia je hodnotou

- $[a \rightarrow a]$  je zoznam funkcií typu  $a \rightarrow a$   
napríklad:  $[(+1), (+2), (*3)]$  je  $[\backslash x \rightarrow x+1, \backslash x \rightarrow x+2, \backslash x \rightarrow x*3]$

- čo je foldr (.) id  $[(+1), (+2), (*3)]$  ??

akého je typu

foldr (.) id  $[(+1), (+2), (*3)]$  100

foldl (.) id  $[(+1), (+2), (*3)]$  100

$[a \rightarrow a]$

303

???

lebo skladanie fcií je asociatívne:

- $((f \cdot g) \cdot h) x = (f \cdot g) (h x) = f (g (h x)) = f ((g \cdot h) x) = (f \cdot (g \cdot h)) x$
- funkcie nevieme porovnávať, napr.  $\text{head } [(+1), (+2), (*3)] == \text{id}$
- funkcie vieme permutovať,  $\text{length } \$ \text{permutations } [(+1), (+2), (*3), (^2)]$



# Maximálna permutácia funkcií

- zoznam funkcií aplikujeme na zoznam argumentov

```
apply      :: [a -> b] -> [a] -> [b]
apply fs args = [ f a | f <- fs, a <- args]
```

```
apply [(+1),(+2),(*3)] [100, 200]
[101,201,102,202,300,600]
```

Dokážte/vyvráťte: `map f . apply fs = apply (map (f.) fs)`

- čo počíta tento výraz

```
maximum $
```

```
  apply
```

```
    (map (foldr (.) id) (permutations [(+1),(^2),(*3),(+2),(/3)]))
    [100]
```

```
31827
```

- `((+1).(+2).(*3).(^2).(/3)) 100`

```
3336.333333333334
```

- `((/3).(^2).(*3).(+2).(+1)) 100`

```
31827.0
```



# take pomocou foldr/fold

Výsledkom foldr `?f? ?z?` xs je funkcia, do ktorej keď dosadíme n, vráti take n:  
... preto aj `?z?` musí byť funkcia, do ktorej keď dosadíme n, vráti take n []:

`take' :: Int -> [a] -> [a]`

`take' n xs = (foldr pomfcia (\_ -> []) xs) n` **where**

`pomfcia x h = \n -> if n == 0 then []`  
`else x:(h (n-1))`

`alebo`

`pomfcia x h n = if n == 0 then [] else x:(h (n-1))`

`alebo`

`take''' n xs = foldr (\a -> \h -> \n -> case n of`  
`0 -> []`  
`n -> a:(h (n-1)) )`

`(\_ -> [])`

`xs`

`n`



# Zákon fúzie – pre foldr

Fussion Law:

Nech  $g_1, g_2$  sú binárne funkcie,  $z_1, z_2$  konštanty

Ak pre funkciu  $f$  platí :

$$f \ z_1 = z_2 \ \&\& \ f \ (g_1 \ a \ b) = g_2 \ a \ (f \ b)$$

potom platí

$$f \ . \ (\text{foldr } g_1 \ z_1 \ xs) = \text{foldr } g_2 \ z_2 \ xs$$

Príklad použitia Fussion Law:

$$(n^*). \underbrace{\text{foldr } (+) \ 0}_{\text{sum}} = \text{foldr } ((+).(n^*)) \ 0$$

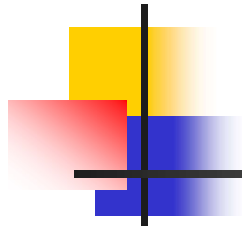
**Dôkaz** (pomocou Fussion Law): overíme predpoklady

čo je čo ?!:

$$f = (n^*), \ z_1 = z_2 = 0, \ g_1 = (+), \ g_2 = (+).(n^*)$$

treba overiť:

- $(n^*) \ 0 = 0$  ☒
- $L.S. = (n^*) \ (a+b) = (n^*a + n^*b) = (+).(n^*) \ a \ ((n^*) \ b) = P.S.$  ☒



# Vlastnosti



Acid Rain (fold/build/deforestation theorem)

$$\underbrace{\text{foldr } f \text{ } z}_{[x] \rightarrow u} . \underbrace{g \text{ } (:) \text{ } []}_{t \rightarrow [x]} = g \text{ } f \text{ } z$$

$\underbrace{\hspace{10em}}_{t \rightarrow u}$

Intuícia: Keď máme vytvoriť zoznam pomocou funkcie  $g$  zo zoznamových konštruktorov  $(:) []$ , na ktorý následne pustíme  $\text{foldr}$ , ktorý nahradí  $(:)$  za  $f$  a  $[]$  za  $z$ , namiesto toho môžeme konštruovať priamo výsledný zoznam pomocou  $g \text{ } f \text{ } z$ .

Otypujme si to (aspoň):

Ak  $z :: u$ , potom  $f :: x \rightarrow u \rightarrow u$ ,  $\text{foldr } f \text{ } z :: [x] \rightarrow u$ .

Ľavá strana:  $([x] \rightarrow u).(t \rightarrow [x])$  výsledkom je typ  $t \rightarrow u$

Pravá strana:  $g :: (x \rightarrow u \rightarrow u) \rightarrow u \rightarrow (t \rightarrow u)$

$$\text{foldr } f \ z \ . \ g \ (:) \ [] = g \ f \ z$$

**length . map \_ = length**

map :: (a -> b) -> [a] -> [b]

map h = foldr ((:) . h) []

-- (:) . h a as = (:) (h a as) = h a : as

=  $(\underbrace{\lambda x \rightarrow \lambda y \rightarrow \text{foldr } (x . h) \ y}_{g}) (:) \ []$

length :: [a] -> Int

length = foldr  $(\underbrace{\lambda \_ \rightarrow \lambda n \rightarrow n+1}_{f}) \ (\underbrace{0}_{z})$

**length . map h = .... length**

L.S. =  $(\text{foldr } (\lambda \_ \rightarrow \lambda n \rightarrow n+1) \ 0) \ . \ (\text{foldr } ((:) \ . \ h) \ []) =$

= podľa Acid Rain theorem ( $f = (\lambda \_ \rightarrow \lambda n \rightarrow n+1)$ ,  $z = 0$ , ale čo je  $g$  ? ...

$g \ x \ y = (\text{foldr } (x . h) \ y)$

$g \ f \ z = (\text{foldr } (f . h) \ z) = \text{foldr } ((\lambda \_ \rightarrow \lambda n \rightarrow n+1) . h) \ 0 =$

$\text{foldr } ((\lambda \_ \rightarrow \lambda n \rightarrow n+1)) \ 0 = \text{length} = \text{P.S.}$

lebo (tento krok pomalšie):

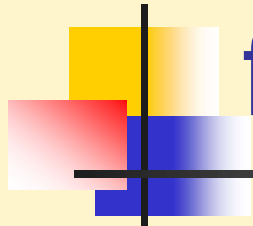
$((\lambda \_ \rightarrow \lambda n \rightarrow n+1) . h) \ x \ y = (\lambda \_ \rightarrow \lambda n \rightarrow n+1) \ (h \ x) \ y = (\lambda n \rightarrow n+1) \ y = y+1$

$$g \ h \ w \ n = h \ n \ (g \ h \ w \ (n-1))$$

93326215443944152681699238856266700490715968264381621468592963895217599993229915608941463976156518286253697920827223758251185210916864000000000000000000000

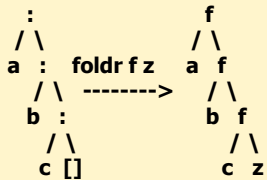
933262154439441526816992388562667004907159682643816214685929638952175999932299156089414639761565182862536979208272237582511852109168640000000000000000000000

$$g' n = n : (g' (n-1))$$
$$g''_n = n * (g''_{n-1})$$

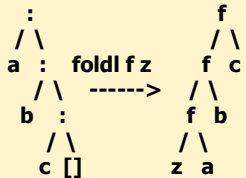


# foldr a foldl pre pokročilejších

definujte foldl pomocou foldr, alebo naopak:



$\text{myfoldl } f \ z \ xs = \text{foldr } (\backslash x \rightarrow \backslash y \rightarrow (f \ y \ x)) \ z \ (\text{myReverse } xs)$   
 $\text{myfoldr } f \ z \ xs = \text{foldl } (\backslash x \rightarrow \backslash y \rightarrow (f \ y \ x)) \ z \ (\text{myReverse } xs)$



- odstránime myReverse

$\text{myReverse } xs = \text{foldr } (\backslash x \rightarrow \backslash y \rightarrow (y ++ [x])) \ [] \ xs$

$\text{myfoldl}' f \ z \ xs = \text{foldr } (\backslash x \rightarrow \backslash y \rightarrow (f \ y \ x)) \ z$   
 $(\text{foldr } (\backslash x \rightarrow \backslash y \rightarrow (y ++ [x])) \ [] \ xs)$

- odstránime ++

$xs ++ ys = \text{foldr } (:) \ ys \ xs$

$\text{myfoldl}'' f \ z \ xs = \text{foldr } (\backslash x \rightarrow \backslash y \rightarrow (f \ y \ x)) \ z$   
 $(\text{foldr } (\backslash x \rightarrow \backslash y \rightarrow (\text{foldr } (:) \ [x] \ y)) \ [] \ xs)$

hmmm..., teoreticky (možno) zaujímavé, prakticky nepoužiteľné ...



# foldr a foldl posledný krát

Zamyslime sa, ako z foldr urobíme foldl:

induktívne predpokladajme, že rekurzívne volanie foldr nám vráti výsledok, t.j. hodnotu  $y$ , ktorá zodpovedá foldl:

- $y = \text{myfoldl } f \text{ } [b,c] = \lambda z \rightarrow f (f z b) c$

nech  $x$  je ďalší prvok zoznamu, t.j.

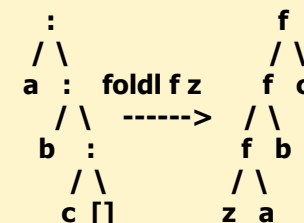
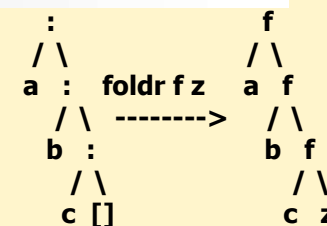
- $x = a$

ako musí vyzerat' funkcia  $?$ , ktorou fold-r-ujeme, aby sme dostali  $\text{myfoldl } f \text{ } [a,b,c] = \lambda z' \rightarrow f (f (f z' a) b) c = ? \ x \ y$

- $? = (\lambda x \ y \ z' \rightarrow y (f z' x))$

dosad'me:

- $(\lambda z' \rightarrow (\lambda z \rightarrow f (f z b) c) (f z' a)) =$
- $(\lambda z' \rightarrow f (f (f z' a) b) c) =$
- $\lambda z' \rightarrow f (f (f z' a) b) c$



# Pre tých, čo neveria, fakt posledný krát

$$? = (\lambda x y z' \rightarrow y (f z' x))$$

$$\blacksquare \text{ myfoldl'''' } f \text{ xs } z = \text{ foldr } (\lambda x y z \rightarrow y (f z x)) \text{ id } \text{ xs } z$$

$$\blacksquare \text{ myfoldl'''' } f [] = \text{ id }$$

$$\blacksquare \text{ myfoldl'''' } f [c] = (\lambda x y z \rightarrow y (f z x)) c \text{ id} = \lambda z \rightarrow f z c$$

$$\blacksquare \text{ myfoldl'''' } f [b,c] = (\lambda x y z \rightarrow y (f z x)) b (\lambda w \rightarrow f w c) = \\ \lambda z \rightarrow (\lambda w \rightarrow f w c) (f z b) = \\ \lambda z \rightarrow f (f z b) c$$

$$\blacksquare \text{ myfoldl'''' } f [a,b,c] = (\lambda x y z \rightarrow y (f z x)) a (\lambda w \rightarrow f (f w b) c) = \\ \lambda z \rightarrow (\lambda w \rightarrow f (f w b) c) (f z a) = \\ \lambda z \rightarrow f (f (f z a) b) c$$

$$\blacksquare \text{ myfoldl'''''' } f z \text{ xs} = \text{ foldr } (\lambda x y z \rightarrow y (f x z)) \text{ id } \text{ xs } z$$

... doma skúste foldr pomocou foldl ...