Informatik 2: Functional Programming

Tobias Nipkow

Fakultät für Informatik
TU München

http://fp.in.tum.de

Wintersemester 2013/14
February 4, 2014
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Organisatorisches

Functional Programming: The Idea

Basic Haskell

Lists

Proofs

Higher-Order Functions

Type Classes

Algebraic data Types

I/O

Modules and Abstract Data Types

Case Study: Two Efficient Algorithms

Lazy evaluation

Complexity and Optimization
1. Organisatorisches
Siehe http://fp.in.tum.de
Wochenplan

Dienstag  Vorlesung
  Harter Abgabetermin für Übungsblatt
  Neues Übungsblatt

Mi–Fr  Übungen: Laptop mitbringen
Literatur

- Vorlesung orientiert sich stark an
  Thompson: *Haskell, the Craft of Functional Programming*

- Für Freunde der kompakten Darstellung:
  Hutton: *Programming in Haskell*

- Für Naturtalente: Es gibt sehr viel Literatur online.
  Qualität wechselhaft, nicht mit Vorlesung abgestimmt.
Klausur und Hausaufgaben

• Klausur am Ende der Vorlesung
• Hausaufgabenstatistik vom letzten Jahr:
  Wahrscheinlichkeit, die Klausur (oder W-Klausur) zu bestehen:
    • ≥ 40% der Hausaufgabenpunkte → 100%
    • < 40% der Hausaufgabenpunkte → < 50%
• Aktueller persönlicher Punktestand im WWW über Statusseite
Individuelle Punktekontrolle

### Punkte

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Programmierwettbewerb — Der Weg zum Ruhm

- Jede Woche eine Wettbewerbsaufgabe
- Punktetabellen im Internet:
  - Die Top 20 jeder Woche
  - Die kumulative Top 20
- Ende des Semesters: Trophäen für die Top $k$ Studenten
2. Functional Programming: The Idea
Functions are pure/mathematical functions:
Always same output for same input

Computation = Application of functions to arguments
Example 1

In Haskell:

```haskell
calc = sum [1..10]
```

In Java:

```java
total = 0;
for (i = 1; i <= 10; ++i) {
    total = total + i;
}
```
Example 2

In Haskell:

\[
\text{wellknown } [] = [] \\
\text{wellknown } (x:xs) = \text{wellknown } ys ++ [x] ++ \text{wellknown } zs \\
\text{where } ys = [y \mid y \leftarrow xs, y \leq x] \\
zs = [z \mid z \leftarrow xs, x < z]
\]
In Java:

```java
void sort(int[] values) {
    if (values == null || values.length == 0) { return; }
    this.numbers = values;
    number = values.length;
    quicksort(0, number - 1);
}

void quicksort(int low, int high) {
    int i = low, j = high;
    int pivot = numbers[low + (high-low)/2];
    while (i <= j) {
        while (numbers[i] < pivot) { i++; }
        while (numbers[j] > pivot) { j--; }
        if (i <= j) { exchange(i, j); i++; j--; }
    }
    if (low < j) quicksort(low, j);
    if (i < high) quicksort(i, high);
}

void exchange(int i, int j) {
    int temp = numbers[i];
    numbers[i] = numbers[j];
    numbers[j] = temp;
}
```
There are two ways of constructing a software design:

One way is to make it so simple that there are obviously no deficiencies.

The other way is to make it so complicated that there are no obvious deficiencies.

From the Turing Award lecture by Tony Hoare (1985)
Characteristics of functional programs

- elegant
- expressive
- concise
- readable
- predictable: pure functions, no side effects
- provable: it’s just (very basic) mathematics!
Aims of functional programming

- Program at a high level of abstraction: not bits, bytes and pointers but whole data structures
- Minimize time to read and write programs: ⇒ reduced development and maintenance time and costs
- Increased confidence in correctness of programs: clean and simple syntax and semantics ⇒ programs are easier to
  - understand
  - test (Quickcheck!)
  - prove correct
Historic Milestones

1930s

Alonzo Church develops the lambda calculus, the core of all functional programming languages.
1950s

John McCarthy (Turing Award 1971) develops Lisp, the first functional programming language.
Robin Milner (FRS, Turing Award 1991) & Co. develop ML, the first modern functional programming language with polymorphic types and type inference.
Historic Milestones

1987

An international committee of researchers initiates the development of Haskell, a standard lazy functional language.
Popular languages based on FP

F# (Microsoft) = ML for the masses

Erlang (Ericsson) = distributed functional programming

Scala (EPFL) = Java + FP
FP concepts in other languages

Garbage collection: Java, C#, Python, Perl, Ruby, Javascript

Higher-order functions: Java, C#, Python, Perl, Ruby, Javascript

Generics: Java, C#

List comprehensions: C#, Python, Perl 6, Javascript

Type classes: C++ “concepts”
Why we teach FP

• FP is a fundamental programming style (like OO!)

• FP is everywhere: Javascript, Scala, Erlang, F# . . .

• It gives you the edge over Millions of Java/C/C++ programmers out there

• FP concepts make you a better programmer, no matter which language you use

• To show you that programming need not be a black art with magic incantations like public static void but can be a science
3. Basic Haskell

- Notational conventions
- Type `Bool`
3.1 Notational conventions

\( e :: T \) means that expression \( e \) has type \( T \)

Function types:  Mathematics  Haskell
\[ f : A \times B \rightarrow C \quad f :: A \rightarrow B \rightarrow C \]

Function application:  Mathematics  Haskell
\[ f(a) \quad f \ a \]
\[ f(a, b) \quad f \ a \ b \]
\[ f(g(b)) \quad f \ (g \ b) \]
\[ f(a, g(b)) \quad f \ a \ (g \ b) \]

Prefix binds stronger than infix:

\[ f \ a + b \] means \( (f \ a) + b \)
not \( f \ (a + b) \)
3.2 Type `Bool`

Predefined: True False not && || ==

Defining new functions:

```haskell
xor :: Bool -> Bool -> Bool
xor x y = (x || y) && not(x && y)
```

```haskell
xor2 :: Bool -> Bool -> Bool
xor2 True True = False
xor2 True False = True
xor2 False True = True
xor2 False False = False
```

This is an example of pattern matching.
The equations are tried in order. More later.

Is \(\text{xor } x \ y == \text{xor2 } x \ y\) true?
Testing with QuickCheck

Import test framework:

```haskell
import Test.QuickCheck
```

Define property to be tested:

```haskell
prop_xor2 x y =
    xor x y == xor2 x y
```

Note naming convention prop_...

Check property with GHCi:

```haskell
> quickCheck prop_xor2
```

GHCi answers

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

- Essential tool for Haskell programmers
- Invaluable for regression tests
- Important part of exercises & homework
- Helps you to avoid bugs
- Helps us to discover them

Every nontrivial Haskell function should come with one or more QuickCheck properties/tests

Typical test:

```haskell
prop_f x y =
  f_efficient x y == f_naive x y
```
V1.hs

For GHCi commands (:l etc) see home page
3.3 Type Integer

Unlimited precision mathematical integers!
Predefined: + − * ^ div mod abs == /= < <= > >=

There is also the type Int of 32-bit integers.
Warning: Integer: \( 2^{32} = 4294967296 \)
Int: \( 2^{32} = 0 \)

==, <= etc are overloaded and work on many types!
Example:

\[ \text{sq} :: \text{Integer} \rightarrow \text{Integer} \]
\[ \text{sq} \ n \ = \ n \times n \]

Evaluation:

\[ \text{sq} (\text{sq} \ 3) = \text{sq} \ 3 \times \text{sq} \ 3 \]
\[ = (3 \times 3) \times (3 \times 3) \]
\[ = 81 \]

Evaluation of Haskell expressions means
Using the defining equations from left to right.
3.4 Guarded equations

Example: maximum of 2 integers.

max :: Integer -> Integer -> Integer
max x y
  | x >= y   = x
  | otherwise = y

Haskell also has if-then-else:

max x y = if x >= y then x else y

True?

prop_max_assoc x y z =
  max x (max y z) == max (max x y) z
3.5 Recursion

Example: \( x^n \) (using only *, not ^)

```haskell
-- pow x n returns x to the power of n
pow :: Integer -> Integer -> Integer
pow x n = ???
```

Cannot write \( \underbrace{x \times \cdots \times x}_n \) times

Two cases:

```haskell
pow x n
| n == 0  = 1                        -- the base case
| n > 0   = x * pow x (n-1)          -- the recursive case
```

More compactly:

```haskell
pow x 0  = 1
pow x n | n > 0   = x * pow x (n-1)
```
Evaluating pow

\[
\begin{align*}
\text{pow } x 0 & \quad = \quad 1 \\
\text{pow } x n \mid n > 0 & \quad = \quad x \ast \text{pow } x (n-1)
\end{align*}
\]

\[
\begin{align*}
\text{pow } 2 3 & \quad = \quad 2 \ast \text{pow } 2 2 \\
& \quad = \quad 2 \ast (2 \ast \text{pow } 2 1) \\
& \quad = \quad 2 \ast (2 \ast (2 \ast \text{pow } 2 0)) \\
& \quad = \quad 2 \ast (2 \ast (2 \ast 1)) \\
& \quad = \quad 8
\end{align*}
\]

> pow 2 (-1)

GHCi answers

*** Exception: PowDemo.hs:(1,1)-(2,33):
Non-exhaustive patterns in function pow
Partially defined functions

\[ \text{pow } x \ n \mid n > 0 \ = \ x \ast \text{pow } x \ (n-1) \]

versus

\[ \text{pow } x \ n \ = \ x \ast \text{pow } x \ (n-1) \]

- call outside intended domain raises exception
- call outside intended domain leads to arbitrary behaviour, including nontermination

In either case:

State your preconditions clearly!

As a guard, a comment or using QuickCheck:

\[ P \ x \Longrightarrow \text{isDefined}(f \ x) \]

where \( \text{isDefined } y \ = \ y \ == \ y \).
Example sumTo

The sum from 0 to \( n \) = \( n + (n-1) + (n-2) + \ldots + 0 \)

\[
\text{sumTo} :: \text{Integer} \rightarrow \text{Integer} \\
\text{sumTo} 0 = 0 \\
\text{sumTo} n \mid n > 0 = \\
\]

\[
\text{prop_sumTo} n = \\
\text{n} \geq 0 \implies \text{sumTo} n = \text{n}*(\text{n}+1) \div 2 \\
\]

Properties can be *conditional*
Typical recursion patterns for integers

\[
f :: \text{Integer} \rightarrow \ldots
f \ 0 \ = \ e \quad \quad \quad \quad \quad \quad \text{-- base case}
f \ n \ | \ n > 0 \ = \ \ldots \ f(n - 1) \ \ldots \quad \text{-- recursive call(s)}
\]

Always make the base case as simple as possible, typically 0, not 1

Many variations:

- more parameters
- other base cases, e.g. \( f \ 1 \)
- other recursive calls, e.g. \( f(n - 2) \)
- also for negative numbers
Recursion in general

- Reduce a problem to a *smaller* problem, e.g. \( \text{pow} \ x \ n \) to \( \text{pow} \ x \ (n-1) \)
- Must eventually reach a *base case*
- Build up solutions from smaller solutions

General problem solving strategy
in *any* programming language
3.6 Syntax matters

Functions are defined by one or more equations. In the simplest case, each function is defined by one (possibly conditional) equation:

\[
f \quad x_1 \ldots x_n \\
| \quad test_1 = e_1 \\
| \quad \vdots \\
| \quad test_n = e_n
\]

Each right-hand side \( e_i \) is an expression.

Note: \( \text{otherwise} = \text{True} \)

Function and parameter names must begin with a lower-case letter (Type names begin with an upper-case letter)
An expression can be

- a literal like 0 or "xyz",
- or an identifier like True or x,
- or a function application \( f e_1 \ldots e_n \)
  where \( f \) is a function and \( e_1 \ldots e_n \) are expressions,
- or a parenthesised expression \((e)\)

Additional syntactic sugar:

- if then else
- infix
- where
- ...
Local definitions: where

A defining equation can be followed by one or more local definitions.

```haskell
pow4 x = x2 * x2  where x2 = x * x

pow4 x = sq (sq x)  where sq x = x * x

pow8 x = sq (sq x2)
  where x2 = x * x
  sq y = y * y

myAbs x
  | x > 0     = y
  | otherwise = -y

where y = x
```
Local definitions: \texttt{let}

\begin{align*}
\texttt{let } x &= e_1 \text{ in } e_2 \\
\text{defines } x \text{ locally in } e_2
\end{align*}

Example:

\begin{align*}
\texttt{let } x &= 2+3 \text{ in } x^2 + 2*x \\
&= 35
\end{align*}

Like \texttt{e_2 where } x = e_1

But can occur anywhere in an expression

\texttt{where: only after function definitions}
In a sequence of definitions, each definition must begin in the same column. A definition ends with the first piece of text in or to the left of the start column.
Prefix and infix

Function application: \( f \ a \ b \)

Functions can be turned into infix operators by enclosing them in back quotes.

Example
5 \('mod'\) 3 = mod 5 3

Infix operators: \( a + b \)

Infix operators can be turned into functions by enclosing them in parentheses.

Example
\((+)\) 1 2 = 1 + 2
Comments

Until the end of the line: --

id x = x  -- the identity function

A comment block: {- ... -}

{- Comments
    are
    important
-}
3.7 Types Char and String

Character literals as usual: ‘a’, ‘$’, ‘\n’, ...
Lots of predefined functions in module Data.Char

String literals as usual: "I am a string"
Strings are lists of characters.
Lists can be concatenated with ++:
"I am" ++ "a string" = "I ama string"
More on lists later.
3.8 Tuple types

(True, 'a', "abc") :: (Bool, Char, String)

In general:

If \( e_1 :: T_1 \) \ldots \( e_n :: T_n \)
then \( (e_1, \ldots, e_n) :: (T_1, \ldots, T_n) \)

In mathematics: \( T_1 \times \ldots \times T_n \)
3.9 Do’s and Don’ts
True and False

Never write

\[ b == \text{True} \]

Simply write

\[ b \]

Never write

\[ b == \text{False} \]

Simply write

\[ \text{not}(b) \]
isBig :: Integer -> Bool

isBig n
  | n > 9999 = True
  | otherwise = False

isBig n = n > 9999

if b then True else False  b

if b then False else True  not b

if b then True else b'      b || b'

...
Try to avoid (mostly):
\[ f (x, y) = \ldots \]

Usually better:
\[ f \, x \, y = \ldots \]

Just fine:
\[ f \, x \, y = (x + y, x - y) \]
4. Lists

- List comprehension
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- Generic functions: Polymorphism
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- Case study: Pictures
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Lists are the most important data type in functional programming.
[1, 2, 3, -42] :: [Integer]

[False] :: [Bool]

['C', 'h', 'a', 'r'] :: [Char]

"Char" :: String

because

type String = [Char]

[not, not] ::

[] :: [T] -- empty list for any type T

[[True], []] ::
Typing rule

If \( e_1 :: T \ldots e_n :: T \) then \([e_1, \ldots, e_n] :: [T]\)

Graphical notation:

\[
\frac{e_1 :: T \ldots e_n :: T}{[e_1, \ldots, e_n] :: [T]}
\]

[True, ’c’] is not type-correct!!!

All elements in a list must have the same type
(True, 'c') ::

[(True, 'c'), (False, 'd')] ::

([True, False], ['c', 'd']) ::
List ranges

\[
[1 \ldots 3] = [1, 2, 3] \\
[3 \ldots 1] = [] \\
['a' \ldots 'c'] = ['a', 'b', 'c']
\]
Concatenation: ++

Concatenates two lists of the same type:

\[
[1, 2] \; ++ \; [3] \; = \; [1, 2, 3]
\]

\[
[1, 2] \; ++ \; [\text{'a'}]
\]
4.1 List comprehension

Set comprehensions:

\[ \{ x^2 \mid x \in \{1, 2, 3, 4, 5\}\} \]

*The set of all \( x^2 \) such that \( x \) is an element of \( \{1, 2, 3, 4, 5\} \)*

List comprehension:

\[ [ x \cdot 2 \mid x \leftarrow [1 .. 5]] \]

*The list of all \( x^2 \) such that \( x \) is an element of \( [1 .. 5] \)*
List comprehension — Generators

\[ [ x^2 | x <- [1 .. 5]] \]
= \[1, 4, 9, 16, 25\]

\[ [ \text{toLowerCase} \ c | c <- "Hello, World!" ] \]
= "hello, world!"

\[ [(x, \text{even} \ x) | x <- [1 .. 3]] \]
= \[ [(1, \text{False}), (2, \text{True}), (3, \text{False})] \]

\[ [ x+y | (x,y) <- [(1,2), (3,4), (5,6)] ] \]
= \[3, 7, 11\]

\textit{pattern <- list expression}

is called a \textit{generator}

Precise definition of \textit{pattern} later.
List comprehension — Tests

\[
\begin{align*}
[ & \ x \times x \mid x \leftarrow [1 \ldots 5], \text{odd } x \\
= & \ [1, 9, 25] \\
[ & \ x \times x \mid x \leftarrow [1 \ldots 5], \text{odd } x, x > 3 \\
= & \ [25] \\
[ & \ \text{toLowerCase } c \mid c \leftarrow "Hello, World!", \text{isAlpha } c \\
= & \ "helloworld"
\end{align*}
\]

Boolean expressions are called \textit{tests}.
Defining functions by list comprehension

Example

```haskell
factors :: Int -> [Int]
factors n = [m | m <- [1 .. n], n `mod` m == 0]
```

⇒ factors 15 = [1, 3, 5, 15]

```haskell
prime :: Int -> Bool
prime n = factors n == [1, n]
```

⇒ prime 15 = False

```haskell
primes :: Int -> [Int]
primes n = [p | p <- [1 .. n], prime p]
```

⇒ primes 100 = [2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31,]
List comprehension — General form

\[
\left[ \text{expr} \mid E_1, \ldots, E_n \right]
\]

where \textit{expr} is an expression and each \( E_i \) is a generator or a test.
Multiple generators

\[[i,j) \mid i \leftarrow [1..2], j \leftarrow [7..9]\] \]

= \([(1,7), (1,8), (1,9), (2,7), (2,8), (2,9)]\]

Analogy: each generator is a for loop:

for all i \leftarrow [1..2]
  for all j \leftarrow [7..9]
    ...

Key difference:

Loops do something
Expressions produce something
Dependent generators

\[
[(i,j) \mid i \leftarrow [1 .. 3], j \leftarrow [i .. 3]]
\]

\[
= [(1,j) \mid j \leftarrow [1..3]] ++
[(2,j) \mid j \leftarrow [2..3]] ++
[(3,j) \mid j \leftarrow [3..3]]
\]

\[
= [(1,1), (1,2), (1,3), (2,2), (2,3), (3,3)]
\]
The meaning of list comprehensions

\[ [e \mid x <- [a_1, \ldots, a_n]] \]
\[ = (\text{let } x = a_1 \text{ in } [e]) ++ \cdots ++ (\text{let } x = a_n \text{ in } [e]) \]

\[ [e \mid b] \]
\[ = \text{if } b \text{ then } [e] \text{ else } [] \]

\[ [e \mid x <- [a_1, \ldots, a_n], \overline{E}] \]
\[ = (\text{let } x = a_1 \text{ in } [e \mid \overline{E}]) ++ \cdots ++ \]
\[ (\text{let } x = a_n \text{ in } [e \mid \overline{E}]) \]

\[ [e \mid b, \overline{E}] \]
\[ = \text{if } b \text{ then } [e \mid \overline{E}] \text{ else } [] \]
Example: concat

$$
\text{concat xss } = \ [x \mid \text{xss }<- \text{xss, x }<- \text{xs}]
$$

$$
\text{concat }[[1,2], [4,5,6]]
= [x \mid \text{xss }<- \[[1,2], [4,5,6]], x <- \text{xs}]
= [x \mid x <- [1,2]] ++ [x \mid x <- [4,5,6]]
= [1,2] ++ [4,5,6]
= [1,2,4,5,6]
$$

What is the type of concat?

$$[[a]] \rightarrow [a]$$
4.2 Generic functions: Polymorphism

Polymorphism = one function can have many types

Example

\[
\text{length :: } [\text{Bool}] \rightarrow \text{Int} \\
\text{length :: } [\text{Char}] \rightarrow \text{Int} \\
\text{length :: } [[\text{Int}]] \rightarrow \text{Int}
\]

The most general type:

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

where \( a \) is a type variable

\[\Rightarrow \text{length :: } [T] \rightarrow \text{Int} \text{ for all types } T\]
Type variable syntax

Type variables must start with a lower-case letter
Typically: a, b, c, ...
Two kinds of polymorphism

Subtype polymorphism as in Java:

\[ f :\! : T \rightarrow U \quad T' \leq T \quad \frac{\text{f}}{\text{f} : T' \rightarrow U} \]

(remember: horizontal line = implication)

Parametric polymorphism as in Haskell:

Types may contain type variables ("parameters")

\[ f :\! : T \quad \frac{\text{f}}{\text{f} : T[U/a]} \]

where \( T[U/a] = "T with a replaced by U" \)

Example: \((a \rightarrow a)[\text{Bool}/a] = \text{Bool} \rightarrow \text{Bool}\)

(Of ten called *ML-style polymorphism*)
Defining polymorphic functions

id :: a -> a
id x = x

fst :: (a,b) -> a
fst (x,y) = x

swap :: (a,b) -> (b,a)
swap (x,y) = (y,x)

silly :: Bool -> a -> Char
silly x y = if x then 'c' else 'd'

silly2 :: Bool -> Bool -> Bool
silly2 x y = if x then x else y
Polymorphic list functions from the Prelude

\[
\text{length} :: [a] \rightarrow \text{Int} \\
\text{length} [5, 1, 9] = 3
\]

\[
(++) :: [a] \rightarrow [a] \rightarrow [a] \\
[1, 2] ++ [3, 4] = [1, 2, 3, 4]
\]

\[
\text{reverse} :: [a] \rightarrow [a] \\
\text{reverse} [1, 2, 3] = [3, 2, 1]
\]

\[
\text{replicate} :: \text{Int} \rightarrow a \rightarrow [a] \\
\text{replicate} 3 'c' = "ccc"
\]
Polymorphic list functions from the Prelude

head, last :: [a] -> a
head "list" = 'l',  last "list" = 't'

tail, init :: [a] -> [a]
tail "list" = "ist",  init "list" = "lis"

take, drop :: Int -> [a] -> [a]
take 3 "list" = "lis",  drop 3 "list" = "t"

-- A property:
prop_take_drop n xs =
  take n xs ++ drop n xs == xs
Polymorphic list functions from the Prelude

concat :: [[a]] -> [a]
concat [[1, 2], [3, 4], [0]] = [1, 2, 3, 4, 0]

zip :: [a] -> [b] -> [(a,b)]
zip [1,2] "ab" = [(1, 'a'), (2, 'b')]

unzip :: [(a,b)] -> ([a], [b])
unzip [(1, 'a'), (2, 'b')] = ([1,2], "ab")

-- A property
prop_zip xs ys = length xs == length ys ==> unzip(zip xs ys) == (xs, ys)
Haskell libraries

- **Prelude and much more**
- **Hoogle** — searching the Haskell libraries
- **Hackage** — a collection of Haskell packages

See Haskell pages and Thompson’s book for more information.
Further list functions from the Prelude

and :: [Bool] -> Bool
and [True, False, True] = False

or :: [Bool] -> Bool
or [True, False, True] = True

-- For numeric types a:
sum, product :: [a] -> a
sum [1, 2, 2] = 5, product [1, 2, 2] = 4

What exactly is the type of sum, prod, +, *, ==, ...???
Polymorphism versus Overloading

**Polymorphism:** one definition, many types

**Overloading:** different definition for different types

**Example**

Function `(+)` is overloaded:

- on type `Int`: built into the hardware
- on type `Integer`: realized in software

So what is the type of `(+)`?
Numeric types

(+) :: Num a => a -> a -> a

Function (+) has type \( a \rightarrow a \rightarrow a \) for any type of class Num

- Class \textbf{Num} is the class of \textit{numeric types}.
- Predefined numeric types: \texttt{Int}, \texttt{Integer}, \texttt{Float}
- Types of class Num offer the basic arithmetic operations:
  (+) :: Num a => a -> a -> a
  (-) :: Num a => a -> a -> a
  (*) :: Num a => a -> a -> a
  :
  sum, product :: Num a => [a] -> a
Other important type classes

- The class `Eq` of *equality types*, i.e. types that possess
  
  \[
  \texttt{(==) :: Eq } a \Rightarrow \texttt{ a } \rightarrow \texttt{ a } \rightarrow \texttt{ Bool} \\
  \texttt{(/=) :: Eq } a \Rightarrow \texttt{ a } \rightarrow \texttt{ a } \rightarrow \texttt{ Bool}
  \]
  
  Most types are of class Eq. Exception:

- The class `Ord` of *ordered types*, i.e. types that possess
  
  \[
  \texttt{(\langle\rangle) :: Ord } a \Rightarrow \texttt{ a } \rightarrow \texttt{ a } \rightarrow \texttt{ Bool} \\
  \texttt{(\langle\rangle) :: Ord } a \Rightarrow \texttt{ a } \rightarrow \texttt{ a } \rightarrow \texttt{ Bool}
  \]

  More on type classes later. Don’t confuse with OO classes.
null xs = xs == []

Why?

== on [a] may call == on a

Better:

null :: [a] -> Bool
null [] = True
null _ = False

In Prelude!
Warning: QuickCheck and polymorphism

QuickCheck does not work well on polymorphic properties

Example
QuickCheck does not find a counterexample to

prop_reverse :: [a] -> Bool
prop_reverse xs = reverse xs == xs

The solution: specialize the polymorphic property, e.g.

prop_reverse :: [Int] -> Bool
prop_reverse xs = reverse xs == xs

Now QuickCheck works
Conditional properties have result type Property

Example

```haskell
prop_rev10 :: [Int] -> Property
prop_rev10 xs =
    length xs <= 10 ==> reverse(reverse xs) == xs
```
4.3 Case study: Pictures

type Picture = [String]

uarr :: Picture
uarr = 
["  #  ",
 "  ### ",
 " #####",
 "  #  ",
 "  #  ",
 "  #  ",
]

larr :: Picture
larr = 
["  #  ",
 "  ##  ",
 "  #  ",
 "  #  ",
 "  #  ",
]
flipH :: Picture -> Picture
flipH = reverse

flipV :: Picture -> Picture
flipV pic = [ reverse line | line <- pic]

rarr :: Picture
rarr = flipV larr

darr :: Picture
darr = flipH uarr

above :: Picture -> Picture -> Picture
above = (++)

beside :: Picture -> Picture -> Picture
beside pic1 pic2 = [ l1 ++ l2 | (l1,l2) <- zip pic1 pic2]
Pictures.hs
Chessboards

bSq = replicate 5 (replicate 5 '#')

wSq = replicate 5 (replicate 5 ' ')

alterH :: Picture -> Picture -> Int -> Picture
alterH pic1 pic2 1 = pic1
alterH pic1 pic2 n = pic1 'beside' alterH pic2 pic1 (n-1)

alterV :: Picture -> Picture -> Int -> Picture
alterV pic1 pic2 1 = pic1
alterV pic1 pic2 n = pic1 'above' alterV pic2 pic1 (n-1)

chessboard :: Int -> Picture
chessboard n = alterV bw wb n where
    bw = alterH bSq wSq n
    wb = alterH wSq bSq n
Exercise

Ensure that the lower left square of chessboard $n$ is always black.
4.4 Pattern matching

Every list can be constructed from []
by repeatedly adding an element at the front
with the “cons” operator (\(::\)) \(\cdot\) a \(\rightarrow\) [a] \(\rightarrow\) [a]

syntactic sugar in reality

\[
\begin{align*}
[3] & \quad 3 : [] \\
[2, 3] & \quad 2 : 3 : [] \\
[1, 2, 3] & \quad 1 : 2 : 3 : [] \\
[x_1, \ldots, x_n] & \quad x_1 : \ldots : x_n : [] \\
\end{align*}
\]

Note: \(x : y : zs = x : (y : zs)\)
(\(::\) associates to the right)
Every list is either \([\ ]\) or of the form \(x : xs\) where

\(x\) is the **head** (first element, *Kopf*), and
\(xs\) is the **tail** (rest list, *Rumpf*)

\([\ ]\) and (\(:\) ) are called **constructors**
because every list can be **constructed uniquely** from them.

Every non-empty list can be decomposed uniquely into head and tail.

Therefore these definitions make sense:

\[
\text{head } (x : xs) = x \\
\text{tail } (x : xs) = xs
\]
(++) is not a constructor:
\[ [1,2,3] \text{ is not uniquely constructable with } (++) : \]
\[ [1,2,3] = [1] ++ [2,3] = [1,2] ++ [3] \]

Therefore this definition does not make sense:
nonsense \((xs ++ ys) = \text{length } xs - \text{length } ys\)
Patterns are expressions consisting only of constructors and variables. No variable must occur twice in a pattern.

⇒ Patterns allow unique decomposition = pattern matching.

A pattern can be

- a variable such as x or a wildcard _ (underscore)
- a literal like 1, ’a’, "xyz", . . .
- a tuple (p₁, . . ., pₙ) where each pᵢ is a pattern
- a constructor pattern C p₁ . . . pₙ
  where C is a constructor and each pᵢ is a pattern

Note: True and False are constructors, too!
Function definitions by pattern matching

Example

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

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

null :: [a] -> Bool
null [] = True
null (_ : _) = False
Function definitions by pattern matching

\[
\begin{align*}
  f \ pat_1 &= e_1 \\
  \vdots \\
  f \ pat_n &= e_n
\end{align*}
\]

If \( f \) has multiple arguments:

\[
\begin{align*}
  f \ pat_{11} \ldots \ pat_{1k} &= e_1 \\
  \vdots \\
\end{align*}
\]

Conditional equations:

\[
\begin{align*}
  f \ patterns \mid condition &= e
\end{align*}
\]

When \( f \) is called, the equations are tried in the given order
Function definitions by pattern matching

Example (contrived)

```haskell
true12 :: [Bool] -> Bool
true12 (True : True : _) = True
true12 _ = False

same12 :: Eq a => [a] -> [a] -> Bool
same12 (x : _) (_ : y : _) = x == y

asc3 :: Ord a => [a] -> Bool
asc3 (x : y : z : _) = x < y && y < z
asc3 (x : y : _) = x < y
asc3 _ = True
```
4.5 Recursion over lists

Example

length [] = 0
length (_ : xs) = length xs + 1

reverse [] = []
reverse (x : xs) = reverse xs ++ [x]

sum :: Num a => [a] -> a
sum [] = 0
sum (x : xs) = x + sum xs
**Primitive recursion** on lists:

\[
\begin{align*}
  f \ [\] &= \text{base} \quad -- \text{base case} \\
  f \ (x : xs) &= \text{rec} \quad -- \text{recursive case}
\end{align*}
\]

- **base**: no call of \( f \)
- **rec**: only call(s) \( f \ x s \)

\( f \) may have additional parameters.
Finding primitive recursive definitions

Example

concat :: [[a]] -> [a]
concat [] = []
concat (xs : xss) = xs ++ concat xss

(++) :: [a] -> [a] -> [a]
[] ++ ys = ys
(x:xs) ++ ys = x : (xs ++ ys)
Example

\[
inSort :: \text{Ord}~a \Rightarrow [a] \rightarrow [a] \\
inSort [] = [] \\
inSort (x:xs) = \text{ins}~x~(\text{inSort}~xs)
\]

\[
\text{ins} :: \text{Ord}~a \Rightarrow a \rightarrow [a] \rightarrow [a] \\
\text{ins}~x~[] = [x] \\
\text{ins}~x~(y:ys) \mid x \leq y = x : y : ys \\
\mid \text{otherwise} = y : \text{ins}~x~ys
\]
Beyond primitive recursion: Complex patterns

Example

```
ascending :: Ord a => [a] -> bool
ascending [] = True
ascending [_] = True
ascending (x : y : zs) = x <= y && ascending (y : ys)
```
Beyond primitive recursion: Multiple arguments

Example

\[ \text{zip} :: [a] \rightarrow [b] \rightarrow [(a,b)] \]
\[ \text{zip} \ (x:xs) \ (y:ys) \ = \ (x,y) : \text{zip} \ xs \ ys \]
\[ \text{zip} \ _ \ _ \ = \ [] \]

Alternative definition:

\[ \text{zip'} \ [] \ [] \ = \ [] \]
\[ \text{zip'} \ (x:xs) \ (y:ys) \ = \ (x,y) : \text{zip'} \ xs \ ys \]

\text{zip'} \ is \ undefined \ for \ lists \ of \ different \ length!
Beyond primitive recursion: Multiple arguments

Example

take :: Int -> [a] -> [a]
take 0 _ = []
take _ [] = []
take i (x:xs) | i>0 = x : take (i-1) xs
General recursion: Quicksort

Example

quicksort :: Ord a => [a] -> [a]
quicksort [] = []
quicksort (x:xs) =
    quicksort below ++ [x] ++ quicksort above
    where
        below = [y | y <- xs, y <= x]
        above = [y | y <- xs, x < y]
Accumulating parameter

Idea: Result is accumulated in parameter and returned later

Example: list of all (maximal) ascending sublists in a list
ups [3,0,2,3,2,4] = [[3], [0,2,3], [2,4]]

ups2 :: Ord a => [a] -> [a] -> [[a]]
-- 1st param: input list
-- 2nd param: partial ascending sublist (reversed)
ups2 (x:xs) (y:ys)
  | x >= y = ups2 xs (x:y:ys)
  | otherwise = reverse (y:ys) : ups2 (x:xs) []
ups2 (x:xs) [] = ups2 xs [x]
ups2 [] ys = [reverse ys]

ups :: Ord a => [a] -> [[a]]
ups xs = ups2 xs []
How can we quickCheck the result of ups?
Convention

Identifiers of list type end in ‘s’: xs, ys, zs, . . .
Mutual recursion

Example

\textbf{even} :: \texttt{Int} \rightarrow \texttt{Bool}
\textbf{even} \ n \ = \ n == 0 \ || \ n > 0 \ && \ \textbf{odd} \ (n-1) \ || \ \textbf{odd} \ (n+1)

\textbf{odd} :: \texttt{Int} \rightarrow \texttt{Bool}
\textbf{odd} \ n \ = \ n /= 0 \ && \ (n > 0 \ && \ \textbf{even} \ (n-1) \ || \ \textbf{even} \ (n+1))
Scoping by example

\begin{align*}
x &= y + 5 \\
y &= x + 1 \text{ where } x = 7 \\
f\ y &= y + x \\
> f\ 3
\end{align*}

- Binding occurrence
- Bound occurrence
- Scope of binding
Scoping by example

\[ x = y + 5 \]
\[ y = x + 1 \text{ where } x = 7 \]
\[ f \ y = y + x \]

> \( f \ 3 \)

**Binding occurrence**

**Bound occurrence**

**Scope of binding**
Scoping by example

\[ x = y + 5 \]
\[ y = x + 1 \text{ where } x = 7 \]
\[ f \; y = y + x \]

> \texttt{f 3}

**Binding occurrence**

**Bound occurrence**

**Scope of binding**
x = y + 5
y = x + 1 where x = 7
f y = y + x

> f 3

Binding occurrence
Bound occurrence
Scope of binding
x = y + 5
y = x + 1 where x = 7
f y = y + x

> f 3

**Binding occurrence**
**Bound occurrence**
**Scope of binding**
Scoping by example

Summary:

- Order of definitions is irrelevant
- Parameters and where-defs are local to each equation
5. Proofs

Proving properties
Proving properties
Proving properties
Definedness
Definedness
Definedness
Definedness
Definedness
Definedness
Definedness
Definedness
Definedness
Aim

Guarantee functional (I/O) properties of software

• Testing can guarantee properties for some inputs.
• Mathematical proof can guarantee properties for all inputs.

QuickCheck is good, proof is better

Beware of bugs in the above code;
I have only proved it correct, not tried it.

Donald E. Knuth, 1977
5.1 Proving properties

What do we prove?

Equations \( e_1 = e_2 \)

How do we prove them?

By using defining equations \( f(p) = t \)
A first, simple example

Remember:

\[
\begin{align*}
[] ++ ys &= ys \\
(x:xs) ++ ys &= x : (xs ++ ys)
\end{align*}
\]

Proof of \([1,2] ++ [] = [1] ++ [2]\\):

\[
\begin{align*}
1:2:[] ++ [] &= 1 : (2:[] ++ []) \\
&= 1 : 2 : ([] ++ []) \\
&= 1 : 2 : [] \\
&= 1 : ([] ++ 2:[]) \\
&= 1:[] ++ 2:[]
\end{align*}
\]

Observation: first used equations from left to right (ok),
then from right to left (strange!)
A more natural proof of \([1,2] \++ \[] = [1] \++ [2]\):

\[
1:2:[] \++ \[] \\
= 1 : (2:[] \++ \[]) \quad -- \text{by def of ++}
\]

\[
= 1 : 2 : ([] \++ []) \quad -- \text{by def of ++}
\]

\[
= 1 : 2 : [] \quad -- \text{by def of ++}
\]

\[
1:[] \++ 2:[] \\
= 1 : ([] \++ 2:[]) \quad -- \text{by def of ++}
\]

\[
= 1 : 2 : [] \quad -- \text{by def of ++}
\]

Proofs of \(e_1 = e_2\) are often better presented as two reductions to some expression \(e\):

\[
e_1 = \ldots = e
\]

\[
e_2 = \ldots = e
\]
Fact If an equation does not contain any variables, it can be proved by evaluating both sides separately and checking that the result is identical.

But how to prove equations with variables, for example associativity of ++:

\[(xs ++ ys) ++ zs = xs ++ (ys ++ zs)\]
Properties of recursive functions are proved by induction

Induction on natural numbers: see Diskrete Strukturen

Induction on lists: here and now
Structural induction on lists

To prove property $P(xs)$ for all finite lists $xs$

**Base case:** Prove $P([])$ and

**Induction step:** Prove $P(xs)$ implies $P(x:xs)$

This is called *structural induction* on $xs$.

It is a special case of induction on the length of $xs$. 
Example: associativity of ++

**Lemma** app_assoc: \((xs ++ ys) ++ zs = xs ++ (ys ++ zs)\)

**Proof** by structural induction on \(xs\)

Base case:
To show: \(([] ++ ys) ++ zs = [] ++ (ys ++ zs)\)

\[
\begin{align*}
(\[] ++ ys) ++ zs &= ys ++ zs \quad \text{-- by def of ++} \\
&= [] ++ (ys ++ zs) \quad \text{-- by def of ++}
\end{align*}
\]

Induction step:
To show: \(((x:xs) ++ ys) ++ zs = (x:xs) ++ (ys ++ zs)\)

\[
\begin{align*}
((x:xs) ++ ys) ++ zs &= (x : (xs ++ ys)) ++ zs \quad \text{-- by def of ++} \\
&= x : ((xs ++ ys) ++ zs) \quad \text{-- by def of ++} \\
&= x : (xs ++ (ys ++ zs)) \quad \text{-- by IH} \\
(x:xs) ++ (ys ++ zs) &= x : (xs ++ (ys ++ zs)) \quad \text{-- by def of ++}
\end{align*}
\]
Lemma $P(xs)$

Proof by structural induction on $xs$

Base case:
To show: $P([])$

Proof of $P([])$

Induction step:
To show: $P(x:xs)$

Proof of $P(x:xs)$ using IH $P(xs)$
Example: length of ++

Lemma length(xs ++ ys) = length xs + length ys

Proof by structural induction on xs

Base case:
To show: length ([] ++ ys) = length [] + length ys

length ([] ++ ys)
= length ys -- by def of ++
length [] + length ys
= 0 + length ys -- by def of length
= length ys

Induction step:
To show: length((x:xs)++ys) = length(x:xs) + length ys

length((x:xs) ++ ys)
= length(x : (xs ++ ys)) -- by def of ++
= 1 + length(xs ++ ys) -- by def of length
= 1 + length xs + length ys -- by IH
length(x:xs) + length ys
= 1 + length xs + length ys -- by def of length
Example: reverse of ++

Lemma \( \text{reverse}(xs ++ ys) = \text{reverse} \; ys \; ++ \; \text{reverse} \; xs \)

Proof by structural induction on \( xs \)

Base case:
To show: \( \text{reverse} \; ([] \; ++ \; ys) = \text{reverse} \; ys \; ++ \; \text{reverse} \; [] \)
\[
\begin{align*}
\text{reverse} \; ([] \; ++ \; ys) &= \text{reverse} \; ys \quad \text{-- by def of ++} \\
\text{reverse} \; ys \; ++ \; \text{reverse} \; [] &= \text{reverse} \; ys \; ++ \; [] \quad \text{-- by def of reverse} \\
&= \text{reverse} \; ys \quad \text{-- by Lemma app_Nil2}
\end{align*}
\]

Lemma app_Nil2: \( xs \; ++ \; [] = xs \)

Proof exercise
Induction step:

To show: \( \text{reverse}((x:xs)++ys) = \text{reverse}\ ys\ ++\ \text{reverse}(x:xs) \)

\[
\begin{align*}
\text{reverse}\((x:xs)++ys) & = \text{reverse}(x : (xs ++ ys)) \quad \text{-- by def of ++} \\
& = \text{reverse}(xs ++ ys) ++ [x] \quad \text{-- by def of reverse} \\
& = (\text{reverse} ys ++ \text{reverse} xs) ++ [x] \quad \text{-- by IH} \\
& = \text{reverse} ys ++ (\text{reverse} xs ++ [x]) \quad \text{-- by Lemma app_assoc} \\
\text{reverse} ys ++ \text{reverse}(x:xs) & = \text{reverse} ys ++ (\text{reverse} xs ++ [x]) \quad \text{-- by def of reverse}
\end{align*}
\]
Proof heuristic

• Try QuickCheck
• Try to evaluate both sides to common term
• Try induction
  • Base case: reduce both sides to a common term using function defs and lemmas
  • Induction step: reduce both sides to a common term using function defs, IH and lemmas
• If base case or induction step fails: conjecture, prove and use new lemmas
Two further tricks

- Proof by cases
- Generalization
Example: proof by cases

\[
\begin{align*}
\text{rem } x \; [] &= [] \\
\text{rem } x \; (y:ys) | x==y &= \text{rem } x \; ys \\
| \text{ otherwise } &= y : \text{rem } x \; ys
\end{align*}
\]

**Lemma** \(\text{rem } z \; (xs ++ ys) = \text{rem } z \; xs ++ \text{rem } z \; ys\)

**Proof** by structural induction on \(xs\)

Base case:

To show: \(\text{rem } z \; ([] ++ ys) = \text{rem } z \; [] ++ \text{rem } z \; ys\)

\[
\begin{align*}
\text{rem } z \; ([]) ++ \text{rem } z \; ys \\
= \text{rem } z \; ys & \quad \text{-- by def of ++} \\
\text{rem } z \; [] ++ \text{rem } z \; ys \\
= \text{rem } z \; ys & \quad \text{-- by def of rem and ++}
\end{align*}
\]
rem x [] = []
rem x (y:ys) | x==y = rem x ys
| otherwise = y : rem x ys

Induction step:
To show: rem z ((x:xs)++ys) = rem z (x:xs) ++ rem z ys
Proof by cases:

Case z == x:
rem z ((x:xs) ++ ys)
= rem z (xs ++ ys)       -- by def of ++ and rem
= rem z xs ++ rem z ys   -- by IH
rem z (x:xs) ++ rem z ys
= rem z xs ++ rem z ys   -- by def of rem

Case z /= x:
rem z ((x:xs) ++ ys)
= x : rem z (xs ++ ys)   -- by def of ++ and rem
= x : (rem z xs ++ rem z ys)  -- by IH
rem z (x:xs) ++ rem z ys
= x : (rem z xs ++ rem z ys)  -- by def of rem and ++
Proof by cases

Works just as well for if-then-else, for example

\[
\begin{align*}
\text{rem } x \; [] & = \; [] \\
\text{rem } x \; (y:ys) & = \begin{cases} 
\text{if } x == y \text{ then } \text{rem } x \; ys \\
\text{else } y : \text{rem } x \; ys
\end{cases}
\end{align*}
\]
Inefficiency of reverse

reverse [1,2,3]
= reverse [2,3] ++ [1]
= (reverse [3] ++ [2]) ++ [1]
= ((reverse [] ++ [3]) ++ [2]) ++ [1]
= (([] ++ [3]) ++ [2]) ++ [1]
= ([3] ++ [2]) ++ [1]
= (3 : ([] ++ [2])) ++ [1]
= [3,2] ++ [1]
= 3 : ([2] ++ [1])
= 3 : (2 : ([] ++ [1]))
= [3,2,1]
An improvement: itrev

\[
\begin{align*}
\text{itrev :: } & [a] \rightarrow [a] \rightarrow [a] \\
\text{itrev } [] & \text{ xs } = \text{ xs} \\
\text{itrev } (x:xs) & \text{ ys } = \text{ itrev } xs \ (x:ys) \\
\end{align*}
\]

\[
\begin{align*}
\text{itrev } [1,2,3] & \ [] \\
= & \text{ itrev } [2,3] \ [1] \\
= & \text{ itrev } [3] \ [2,1] \\
= & \text{ itrev } [] \ [3,2,1] \\
= & [3,2,1]
\end{align*}
\]
Lemma \textit{itrev} \( xs \ [\] = \textit{reverse} \ xs \)

Proof by structural induction on \( xs \)

Induction step fails:

To show: \( \textit{itrev} \ (x:xs) \ [\] = \textit{reverse} \ (x:xs) \)

\( \textit{itrev} \ (x:xs) \ [\] \)

\( = \textit{itrev} \ xs \ [x] \quad -- \text{by def of itrev} \)

\( \textit{reverse} \ (x:xs) \)

\( = \textit{reverse} \ xs \ ++ \ [x] \quad -- \text{by def of reverse} \)

Problem: IH not applicable because too specialized: \([\] \)
Lemma \textit{itrev} \(xs\) \(ys\) = \textit{reverse} \(xs\) ++ \(ys\)

Proof by structural induction on \(xs\)

Induction step:
To show: \textit{itrev} \((x:xs)\) \(ys\) = \textit{reverse} \((x:xs)\) ++ \(ys\)
\[
\begin{align*}
\textit{itrev} \,(x:xs)\,\,ys &= \textit{itrev} \,x\,s\,\,(x:ys) \quad -- \text{by def of itrev} \\
&= \text{reverse} \,x\,s\,++\,(x:ys) \quad -- \text{by IH} \\
\text{reverse} \,(x:xs)\,++\,ys &= (\text{reverse} \,x\,s\,++\,[x])\,++\,ys \quad -- \text{by def of reverse} \\
&= \text{reverse} \,x\,s\,++\,([x]\,++\,ys) \quad -- \text{by Lemma app_assoc} \\
&= \text{reverse} \,x\,s\,++\,(x:ys) \quad -- \text{by def of ++}
\end{align*}
\]

Note: IH is used with \(x:ys\) instead of \(ys\)
When using the IH, variables may be replaced by arbitrary expressions, only the induction variable must stay fixed.

Justification: all variables are implicitly $\forall$-quantified, except for the induction variable.
Induction on the length of a list

\texttt{qsort :: Ord a => \[a\] -> \[a\]}
\texttt{qsort [] = []}
\texttt{qsort (x:xs) = qsort below ++ [x] ++ qsort above}
\hspace{1cm} where below = \[y | y \leftarrow xs, y \leq x\]
\hspace{1cm} above = \[z | y \leftarrow xs, x < z\]

\textbf{Lemma} \texttt{qsort xs} is sorted

\textbf{Proof} by induction on the length of the argument of \texttt{qsort}.

Induction step: In the call \texttt{qsort (x:xs)} we have \texttt{length below} \leq \texttt{length xs} < \texttt{length(x:xs)} (also for \texttt{above}).
Therefore \texttt{qsort below} and \texttt{qsort above} are sorted by IH.
By construction \texttt{below} contains only elements (\(\leq x\)).
Therefore \texttt{qsort below} contains only elements (\(\leq x\)) (proof!).
Analogously for \texttt{above} and (\(x<\)).
Therefore \texttt{qsort (x:xs)} is sorted.
Is that all? Or should we prove something else about sorting?

How about this sorting function?

```
superquicksort _ = []
```

Every element should occur as often in the output as in the input!
5.2 Definedness

Simplifying assumption, implicit so far:

No undefined values

Two kinds of undefinedness:

- `head []` raises exception
- `f x = f x + 1` does not terminate

Undefinedness can be handled, too.
But it complicates life
What is the problem?

Many familiar laws no longer hold unconditionally:

\[ x - x = 0 \]

is true only if \( x \) is a defined value.

Two examples:

- Not true: \( \text{head} [] - \text{head} [] = 0 \)
- From the nonterminating definition
  \[ f \ x = f \ x + 1 \]
  we could conclude that \( 0 = 1 \).
Termination of a function means termination for all inputs.

Restriction:

The proof methods in this chapter assume that all recursive definitions under consideration terminate.

Most Haskell functions we have seen so far terminate.
How to prove termination

Example

reverse [] = []
reverse (x:xs) = reverse xs ++ [x]

terminates because ++ terminates and with each recursive call of reverse, the length of the argument becomes smaller.

A function \( f :: T_1 \rightarrow T \) terminates if there is a measure function \( m :: T_1 \rightarrow \mathbb{N} \) such that

- for every defining equation \( f p = t \)
- and for every recursive call \( f r \) in \( t \): \( m p > m r \).

Note:

- All primitive recursive functions terminate.
- \( m \) can be defined in Haskell or mathematics.
- The conditions above can be refined to take special Haskell features into account, eg sequential pattern matching.
More generally: $f :: T_1 \to \ldots \to T_n \to T$ terminates if there is a measure function $m :: T_1 \to \ldots \to T_n \to \mathbb{N}$ such that

- for every defining equation $f \ p_1 \ldots \ p_n = t$
- and for every recursive call $f \ r_1 \ldots \ r_n$ in $t$: $m \ p_1 \ldots \ p_n > m \ r_1 \ldots \ r_n$.

Of course, all other functions that are called by $f$ must also terminate.
Haskell allows infinite values, in particular infinite lists.

Example: \([1, 1, 1, \ldots]\)

Infinite objects must be constructed by recursion:

\[
\text{ones} = 1 : \text{ones}
\]

Because we restrict to terminating definitions in this chapter, infinite values cannot arise.

Note:

- By termination of functions we really mean termination on \textit{finite} values.
- For example \texttt{reverse} terminates only on finite lists.

This is fine because we can only construct finite values anyway.
How can infinite values be useful?  
Because of “lazy evaluation”.  
More later.
If we use arithmetic equations like $x - x = 0$ unconditionally, we can “lose” exceptions:

$$\text{head } xs - \text{head } xs = 0$$

is only true if $xs \neq []$

In such cases, we can prove equations $e_1 = e_2$ that are only partially correct:

If $e_1$ and $e_2$ do not produce a runtime exception then they evaluate to the same value.
Summary

• In this chapter everything must terminate
• This avoids undefined and infinite values
• This simplifies proofs
6. Higher-Order Functions

Applying functions to all elements of a list: `map`

Filtering a list: `filter`
Recall [Pic is short for Picture]

alterH :: Pic -> Pic -> Int -> Pic
alterH pic1 pic2 1 = pic1
alterH pic1 pic2 n = beside pic1 (alterH pic2 pic1 (n-1))

alterV :: Pic -> Pic -> Int -> Pic
alterV pic1 pic2 1 = pic1
alterV pic1 pic2 n = above pic1 (alterV pic2 pic1 (n-1))

Very similar. Can we avoid duplication?

alt :: (Pic -> Pic -> Pic) -> Pic -> Pic -> Int -> Pic
alt f pic1 pic2 1 = pic1
alt f pic1 pic2 n = f pic1 (alt f pic2 pic1 (n-1))

alterH pic1 pic2 n = alt beside pic1 pic2 n
alterV pic1 pic2 n = alt above pic1 pic2 n
Higher-order functions:
Functions that take functions as arguments

... -> (...) -> ...

Higher-order functions capture patterns of computation
6.1 Applying functions to all elements of a list: \texttt{map}

Example

\begin{verbatim}
map even [1, 2, 3]  
= [False, True, False] 

map toLower "R2-D2"  
= "r2-d2" 

map reverse ["abc", "123"]  
= ["cba", "321"]
\end{verbatim}

What is the type of \texttt{map}?

\begin{verbatim}
map :: (\texttt{a} \to \texttt{b}) \to \texttt{[a]} \to \texttt{[b]}
\end{verbatim}
map: The mother of all higher-order functions

Predefined in Prelude.
Two possible definitions:

map f xs = [ f x | x <- xs ]

map f [] = []

map f (x:xs) = f x : map f xs
Evaluating map

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

\[
\begin{align*}
\text{map } \text{sqr} \; [1, \; -2] \\
= \; \text{map } \text{sqr} \; (1 \; : \; -2 \; : \; []) \\
= \; \text{sqr} \; 1 \; : \; \text{map } \text{sqr} \; (-2 \; : \; []) \\
= \; \text{sqr} \; 1 \; : \; \text{sqr} \; (-2) \; : \; (\text{map } \text{sqr} \; []) \\
= \; \text{sqr} \; 1 \; : \; \text{sqr} \; (-2) \; : \; [] \\
= \; 1 \; : \; 4 \; : \; [] \\
= \; [1, \; 4]
\end{align*}
\]
Some properties of map

length (map f xs) = length xs

map f (xs ++ ys) = map f xs ++ map f ys

map f (reverse xs) = reverse (map f xs)

Proofs by induction
QuickCheck and function variables

QuickCheck does not work automatically for properties of function variables

It needs to know how to generate and print functions.

Cheap alternative: replace function variable by specific function(s)

Example

prop_map_even :: [Int] -> [Int] -> Bool
prop_map_even xs ys =
    map even (xs ++ ys) = map even xs ++ map even ys
6.2 Filtering a list: filter

Example

filter even [1, 2, 3]  
= [2]

filter isAlpha "R2-D2"  
= "RD"

filter null [[]], [1,2], [[]]  
= [[]], [[]]

What is the type of filter?

\[
\text{filter} :: (a \rightarrow \text{Bool}) \rightarrow [a] \rightarrow [a]
\]
Predefined in Prelude.
Two possible definitions:

\[
\text{filter } p \ x s = [ x \mid x \leftarrow x s, p \ x ]
\]

\[
\text{filter } p \ [ ] = [ ]
\]

\[
\text{filter } p \ (x:xs) \mid p \ x = x : \text{filter } p \ x s \\
\mid \text{otherwise} = \text{filter } p \ x s
\]
Some properties of filter

True or false?

\( \text{filter } p \ (xs \ ++ \ ys) = \text{filter } p \ xs \ ++ \ \text{filter } p \ ys \)

\( \text{filter } p \ (\text{reverse } xs) = \text{reverse } (\text{filter } p \ xs) \)

\( \text{filter } p \ (\text{map } f \ xs) = \text{map } f \ (\text{filter } p \ xs) \)

Proofs by induction
6.3 Combining the elements of a list: foldr

Example

\[
\begin{align*}
\text{sum} \; [] & \; = \; 0 \\
\text{sum} \; (x:xs) & \; = \; x + \text{sum} \; xs \\
\text{sum} \; [x_1, \ldots, x_n] & \; = \; x_1 + \ldots + x_n + 0 \\
\text{concat} \; [] & \; = \; [] \\
\text{concat} \; (xs:xss) & \; = \; xs ++ \text{concat} \; xss \\
\text{concat} \; [xs_1, \ldots, xs_n] & \; = \; xs_1 ++ \ldots ++ xs_n ++ []
\end{align*}
\]
foldr

\[ \text{foldr} \ (\oplus) \ z \ [x_1, \ldots, x_n] = x_1 \oplus \ldots \oplus x_n \oplus z \]

Defined in Prelude:

\[
\text{foldr} :: (a \to a \to a) \to a \to [a] \to a \\
\text{foldr} \ f \ a \ [] = a \\
\text{foldr} \ f \ a \ (x:xs) = x \ 'f' \ \text{foldr} \ f \ a \ xs
\]

Applications:

\[ \text{sum} \ xs = \text{foldr} \ (+) \ 0 \ xs \]

\[ \text{concat} \ xss = \text{foldr} \ (+++) \ [] \ xss \]

What is the most general type of foldr?
foldr

foldr f a [] = a
foldr f a (x:xs) = x 'f' foldr f a xs

foldr f a replaces
(:) by f and
[] by a
Evaluating foldr

foldr \( f \ a \ [] \) = a
foldr \( f \ a \ (x:xs) \) = \( x \ 'f' \ foldr \ f \ a \ xs \)

foldr (+) 0 [1, -2]
= foldr (+) 0 (1 : -2 : [])
= 1 + foldr (+) 0 (-2 : [])
= 1 + -2 + (foldr (+) 0 [])
= 1 + -2 + 0
= -1
More applications of foldr

\[
\begin{align*}
\text{product } xs & = \text{foldr } (\times) 1 xs \\
\text{and } xs & = \text{foldr } (\&\&) \text{ True } xs \\
\text{or } xs & = \text{foldr } (\mid\mid) \text{ False } xs \\
\text{inSort } xs & = \text{foldr } \text{ins } [] xs
\end{align*}
\]
Quiz

What is

\[ \text{foldr (:) ys xs} \]

Example: \( \text{foldr (:) ys (1:2:3:[])} = 1:2:3:ys \)

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

Proof by induction on \( xs \) (Exercise!)
Defining functions via \texttt{foldr}

- means you have understood the art of higher-order functions
- allows you to apply properties of \texttt{foldr}

**Example**

If $f$ is associative and $a 'f' x = x$ then

\[
\text{foldr } f \ a \ (xs++ys) = \text{foldr } f \ a \ xs \ 'f' \ \text{foldr } f \ a \ ys.
\]

Proof by induction on $xs$. Induction step:

\[
\text{foldr } f \ a \ ((x:xs) ++ ys) = \text{foldr } f \ a \ (x : (xs++ys))
\]

\[
= x \ 'f' \ \text{foldr } f \ a \ (xs++ys)
\]

\[
= x \ 'f' \ (\text{foldr } f \ a \ xs \ 'f' \ \text{foldr } f \ a \ ys) \quad -- \text{by IH}
\]

\[
\text{foldr } f \ a \ (x:xs) \ 'f' \ \text{foldr } f \ a \ ys
\]

\[
= (x \ 'f' \ \text{foldr } f \ a \ xs) \ 'f' \ \text{foldr } f \ a \ ys
\]

\[
= x \ 'f' \ (\text{foldr } f \ a \ xs \ 'f' \ \text{foldr } f \ a \ ys) \quad -- \text{by assoc.}
\]

Therefore, if $g \ xs = \text{foldr } f \ a \ xs$,

then $g \ (xs ++ ys) = g \ xs \ 'f' \ g \ ys$.

Therefore $\text{sum } (xs++ys) = \text{sum } xs + \text{sum } ys$,

$\text{product } (xs++ys) = \text{product } xs \ast \text{product } ys,$...
6.4 Lambda expressions

Consider

\[ \text{squares } xs = \text{map } \lambda x \rightarrow x \times x \text{ where } \lambda x \rightarrow x \times x \]

Do we really need to define \( \text{sqr} \) explicitly? No!

\( \lambda x \rightarrow x \times x \)

is the anonymous function with

formal parameter \( x \) and result \( x \times x \)

In mathematics: \( x \mapsto x \times x \)

Evaluation:

\( (\lambda x \rightarrow x \times x) \rightarrow 3 = 3 \times 3 = 9 \)

Usage:

\[ \text{squares } xs = \text{map } (\lambda x \rightarrow x \times x) \text{ } xs \]
Terminology

\((\lambda x \rightarrow e_1) \; e_2\)

\(x\): formal parameter
\(e_1\): result
\(e_2\): actual parameter

Why “lambda”?

The logician Alonzo Church invented \textit{lambda calculus} in the 1930s

Logicians write \(\lambda x. \; e\) instead of \(\\lambda x \rightarrow e\)
Typing lambda expressions

Example

$$(\lambda x \rightarrow x > 0) :: \text{Int} \rightarrow \text{Bool}$$

because $x :: \text{Int}$ implies $x > 0 :: \text{Bool}$

The general rule:

$$(\lambda x \rightarrow e) :: T_1 \rightarrow T_2$$

if $x :: T_1$ implies $e :: T_2$$
Sections of infix operators

(+ 1) means (\x -> x + 1)
(2 *) means (\x -> 2 * x)
(2 ^) means (\x -> 2 ^ x)
(^ 2) means (\x -> x ^ 2)

etc

Example

squares xs = map (^ 2) xs
List comprehension

Just syntactic sugar for combinations of map

\[
\left[ f \ x \mid x \ <- \ xs \right] = \text{map} \ f \ xs
\]

filter

\[
\left[ x \mid x \ <- \ xs, \ p \ x \right] = \text{filter} \ p \ xs
\]

and concat

\[
\left[ f \ x \ y \mid x \ <- \ xs, \ y \ <- \ ys \right] = \text{concat} \ ( \quad )
\]
6.5 Extensionality

Two functions are equal if for all arguments they yield the same result.

\[ f, g :: T_1 \to T : \quad \forall a. \ f a = g a \quad \Rightarrow \quad f = g \]

\[ f, g :: T_1 \to T_2 \to T : \quad \forall a, b. \ f a b = g a b \quad \Rightarrow \quad f = g \]
6.6 Curried functions

A trick (re)invented by the logician Haskell Curry

Example

\[ f :: \text{Int} \rightarrow \text{Int} \rightarrow \text{Int} \quad f :: \text{Int} \rightarrow (\text{Int} \rightarrow \text{Int}) \]

\[ f \ x \ y = x+y \quad f \ x = \ x+y \]

Both mean the same:

\[ f \ a \ b \]
\[ = a + b \]
\[ (f \ a) \ b \]
\[ = (\ y \rightarrow a + y) \ b \]
\[ = a + b \]

The trick: any function of two arguments can be viewed as a function of the first argument that returns a function of the second argument.
In general

Every function is a function of one argument (which may return a function as a result)

\[ T_1 \rightarrow T_2 \rightarrow T \]

is just syntactic sugar for

\[ T_1 \rightarrow (T_2 \rightarrow T) \]

\[ f \ e_1 \ e_2 \]

is just syntactic sugar for

\[ (f \ e_1) \ e_2 \]

\[ :: T_2 \rightarrow T \]

Analogously for more arguments
-> is not associative:
\[ T_1 \rightarrow (T_2 \rightarrow T) \neq (T_1 \rightarrow T_2) \rightarrow T \]

Example

\begin{align*}
f &:: \text{Int} \rightarrow (\text{Int} \rightarrow \text{Int}) & g &:: (\text{Int} \rightarrow \text{Int}) \rightarrow \text{Int} \\
f \ x \ y &\ = \ x + y & g \ h &\ = \ h \ 0 + 1
\end{align*}

Application is not associative:
\[ (f \ e_1) \ e_2 \neq f \ (e_1 \ e_2) \]

Example

\begin{align*}
(f \ 3) \ 4 &\neq f \ (3 \ 4) & g \ (\text{id} \ \text{abs}) &\neq (g \ \text{id}) \ \text{abs}
\end{align*}
Quiz

head tail xs

Correct?
Partial application

Every function of $n$ parameters can be applied to less than $n$ arguments

Example
Instead of $\text{sum } xs = \text{foldr } (+) 0 \ xs$
just define $\text{sum } = \text{foldr } (+) 0$

In general:
If $f :: T_1 \rightarrow \ldots \rightarrow T_n \rightarrow T$
and $a_1 :: T_1, \ldots, a_m :: T_m$ and $m \leq n$
then $f \ a_1 \ldots \ a_m :: T_{m+1} \rightarrow \ldots \rightarrow T_n \rightarrow T$
6.7 More library functions

\( (\cdot) :: (b \rightarrow c) \rightarrow (a \rightarrow b) \rightarrow f \cdot g = \lambda x \rightarrow f (g \ x) \)

Example

\[ \text{head2} = \text{head} \cdot \text{tail} \]

\[ \text{head2} \ [1,2,3] \]
\[ = (\text{head} \cdot \text{tail}) \ [1,2,3] \]
\[ = (\lambda x \rightarrow \text{head} \ (\text{tail} \ x)) \ [1,2,3] \]
\[ = \text{head} \ (\text{tail} \ [1,2,3]) \]
\[ = \text{head} \ [2,3] \]
\[ = 2 \]
const :: a -> (b -> a)
const x = \_ -> x

curry :: ((a,b) -> c) -> (a -> b -> c)
curry f = \ x y -> f(x,y)

uncurry :: (a -> b -> c) -> ((a,b) -> c)
uncurry f = \(x,y) -> f x y
all :: (a -> Bool) -> [a] -> Bool
all p xs = and [p x | x <- xs]

Example
all (>1) [0, 1, 2]
= False

any :: (a -> Bool) -> [a] -> Bool
any p = or [p x | x <- xs]

Example
any (>1) [0, 1, 2]
= True
takeWhile :: (a -> Bool) -> [a] -> [a]
takeWhile p [] = []
takeWhile p (x:xs)
  | p x = x : takeWhile p xs
  | otherwise = []

Example

takeWhile (not . isSpace) "the end"
= "the"

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

Example

dropWhile (not . isSpace) "the end"
= " end"
6.8 Case study: Counting words

Input: A string, e.g. "never say never again"

Output: A string listing the words in alphabetical order, together with their frequency,
e.g. "again: 1\nnever: 2\nsay: 1\n"

Function putStr yields
again: 1
never: 2
say: 1

Design principle:

Solve problem in a sequence of small steps
transforming the input gradually into the output

Unix pipes!
Step 1: Break input into words

"never say never again"

function \[ \text{words} \]

\[ ["never", "say", "never", "again"] \]

Predefined in Prelude
Step 2: Sort words

function sort

["never", "say", "never", "again"]

["again", "never", "never", "say"]

Predefined in Data.List
Step 3: Group equal words together

```
function group
[["again"], ["never", "never"], ["say"]]
```

Predefined in Data.List
Step 4: Count each group

[["again"], ["never", "never"], ["say"]]

\[
\text{map}(\lambda ws \rightarrow (\text{head} \ ws, \text{length} \ ws))
\]

[(["again", 1]), (["never", 2]), (["say", 1])]
Step 5: Format each group

\[
\text{map (\((w, n) \rightarrow (w \: \text{++} \: "\: : \: " \: \text{++} \: \text{show } n)\))}
\]

\[
["again: 1", "never: 2", "say: 1"]
\]
Step 6: Combine the lines

```
["again: 1", "never: 2", "say: 1"]
```

Predefined in Prelude
The solution

countWords :: String -> String
countWords =
    unlines
    . map (\(w,n) -> w ++ ": " ++ show n)
    . map (\ws -> (head ws, length ws))
    . group
    . sort
    . words
Can we merge two consecutive maps?

\[
\text{map } f \ . \ \text{map } g = ???
\]
countWords :: String -> String
countWords =
  unlines
  . map (\ws -> head ws ++ ": " ++ show(length ws))
  . group
  . sort
  . words
Proving \( \text{map } f \ . \ \text{map } g = \text{map } (f \cdot g) \)

First we prove (why?)

\[
\text{map } f \ (\text{map } g \ xs) = \text{map } (f \cdot g) \ xs
\]

by induction on \( xs \):

- **Base case:**
  \[
  \text{map } f \ (\text{map } g \ []) = [] \\
  \text{map } (f \cdot g) \ [] = []
  \]

- **Induction step:**
  \[
  \text{map } f \ (\text{map } g \ (x:xs)) \\
  = f \ (g \ x) : \text{map } f \ (\text{map } g \ xs) \\
  = f \ (g \ x) : \text{map } (f \cdot g) \ xs \quad -- \ \text{by } \text{IH} \\
  \text{map } (f \cdot g) \ (x:xs) \\
  = f \ (g \ x) : \text{map } (f \cdot g) \ xs
  \]

\[
\implies (\text{map } f \ . \ \text{map } g) \ xs = \text{map } f \ (\text{map } g \ xs) = \text{map } (f \cdot g) \ xs
\]

\[
\implies (\text{map } f \ . \ \text{map } g) = \text{map } (f \cdot g) \quad \text{by \ extensionality}
\]
7. Type Classes
Remember: type classes enable overloading

**Example**

elem ::

elem x = any (== x)

where `Eq` is the class of all types with `==`
In general:

*Type classes are collections of types that implement some fixed set of functions*

Haskell type classes are analogous to Java interfaces: a set of function names with their types

**Example**

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

Note: the type of `==` outside the class context is

```haskell
Eq a => a -> a -> Bool
```
The general form of a class declaration:

class C a where
  f1 :: T1
  ...
  fn :: Tn

where the Ti may involve the type variable a
A type \( T \) is an instance of a class \( C \) if \( T \) supports all the functions of \( C \). Then we write \( C \ T \).

Example

Type \( \texttt{Int} \) is an instance of class \( \texttt{Eq} \), i.e., \( \texttt{Eq Int} \)

Therefore \( \texttt{elem :: Int -> [Int] -> Bool} \)

Warning Terminology clash:

Type \( T_1 \) is an instance of type \( T_2 \) if \( T_1 \) is the result of replacing type variables in \( T_2 \).
For example \( (\texttt{Bool},\texttt{Int}) \) is an instance of \( (\texttt{a},\texttt{b}) \).
The instance statement makes a type an instance of a class.

Example

instance Eq Bool where
  True == True   = True
  False == False = True
  _    == _     = False
Instances can be constrained:

**Example**

```haskell
instance Eq a => Eq [a] where
    []      == []      = True
    (x:xs) == (y:ys) = x == y && xs == ys
    _       == _       = False
```

Possibly with multiple constraints:

**Example**

```haskell
instance (Eq a, Eq b) => Eq (a,b) where
    (x1,y1) == (x2,y2) = x1 == x2 && y1 == y2
```
The general form of the instance statement:

```
instance (context) => C T where
  definitions

T is a type
context is a list of assumptions C; T;
definitions are definitions of the functions of class C
```
Example

class Eq a => Ord a where
  (<=), (<) :: a -> a -> Bool

Class Ord inherits all the operations of class Eq

Because Bool is already an instance of Eq, we can now make it an instance of Ord:

instance Ord Bool where
  b1 <= b2 = not b1 || b2
  b1 < b2 = b1 <= b2 && not(b1 == b2)
From the Prelude: Eq, Ord, Show

class Eq a where
    (==), (/=) :: a -> a -> Bool
    -- default definition:
    x /= y = not(x==y)

class Eq a => Ord a where
    (<=), (<), (>=), (>) :: a -> a -> Bool
    -- default definitions:
    x < y = x <= y && x /= y
    x > y = y < x
    x >= y = y <= x

class Show a where
    show :: a -> String
8. Algebraic data Types

Data by example

The general case

Case study: boolean formulas

Case study: boolean formulas

Case study: boolean formulas

Case study: boolean formulas

Case study: boolean formulas

Case study: boolean formulas

Case study: boolean formulas

Case study: boolean formulas

Case study: boolean formulas

Case study: boolean formulas

Case study: boolean formulas

Structural induction
So far: no really new types, just compositions of existing types

Example: type String = [Char]

Now: data defines new types

Introduction by example: From enumerated types to recursive and polymorphic types
8.1 data by example
From the Prelude:

```haskell
data Bool = False | True

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

(&&) :: Bool -> Bool -> Bool
False && q = False
True && q = q

(||) :: Bool -> Bool -> Bool
False || q = q
True || q = True
```
instance Eq Bool where
    True  == True   = True
    False == False  = True
    _      == _     = False

instance Show Bool where
    show True       = "True"
    show False      = "False"

Better: let Haskell write the code for you:

data Bool = False | True
            deriving (Eq, Show)

deriving supports many more classes: Ord, Read, ...
Warning
Do not forget to make your data types instances of Show.
Otherwise Haskell cannot even print values of your type.

Warning
QuickCheck does not automatically work for data types.
You have to write your own test data generator. Later.
```haskell
data Season = Spring | Summer | Autumn | Winter
             deriving (Eq, Show)

next :: Season -> Season
next Spring = Summer
next Summer = Autumn
next Autumn = Winter
next Winter = Spring
```
type Radius = Float
type Width   = Float
type Height = Float

data Shape = Circle Radius | Rect Width Height
deriving (Eq, Show)

Some values of type Shape:  Circle 1.0
                          Rect 0.9 1.1
                          Circle (-2.0)

area :: Shape -> Float
area (Circle r) = pi * r^2
area (Rect w h) = w * h
**Maybe**

From the Prelude:

```haskell
data Maybe a = Nothing | Just a
    deriving (Eq, Show)
```

Some values of type Maybe:
- Nothing :: Maybe a
- Just True :: Maybe Bool
- Just "?" :: Maybe String

```haskell
lookup :: Eq a => a -> [(a,b)] -> Maybe b
lookup key [] =
lookup key ((x,y):xys)
    | key == x =
    | otherwise =
```
Natural numbers:

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

Some values of type Nat:
- Zero
- Suc Zero
- Suc (Suc Zero)
- ...

```
add :: Nat -> Nat -> Nat
add Zero n = n
add (Suc m) n = ...
```

```
mul :: Nat -> Nat -> Nat
mul Zero n = Zero
mul (Suc m) n = ...
```
Lists

From the Prelude:

```haskell
data [a] = [] | (:) a [a]
    deriving Eq
```

The result of deriving `Eq`:

```haskell
instance Eq a => Eq [a] where
    [] == [] = True
    (x:xs) == (y:ys) = x == y && xs == ys
    _ == _ = False
```

Defined explicitly:

```haskell
instance Show a => Show [a] where
    show xs = "[" ++ concat cs ++ "]"
    where cs = Data.List.intersperse ", " (map show xs)
```
data Tree a = Empty | Node a (Tree a) (Tree a)
deriving (Eq, Show)

Some trees:
    Empty
    Node 1 Empty Empty
    Node 1 (Node 2 Empty Empty) Empty
    Node 1 Empty (Node 2 Empty Empty)
    Node 1 (Node 2 Empty Empty) (Node 3 Empty Empty)
    :
find :: Ord a => a -> Tree a -> Bool
find _ Empty = False
find x (Node a l r)
  | x < a = find x l
  | a < x = find x r
  | otherwise = True
insert :: Ord a => a -> Tree a -> Tree a
insert x Empty = Node x Empty Empty
insert x (Node a l r)
    | x < a = Node a (insert x l) r
    | a < x = Node a l (insert x r)
    | otherwise = Node a l r

Example

insert 6 (Node 5 Empty (Node 7 Empty Empty))
= Node 5 Empty (insert 6 (Node 7 Empty Empty))
= Node 5 Empty (Node 7 (insert 6 Empty) Empty)
= Node 5 Empty (Node 7 (Node 6 Empty Empty) Empty)
import Control.Monad
import Test.QuickCheck

-- for QuickCheck: test data generator for Trees
instance Arbitrary a => Arbitrary (Tree a) where
  arbitrary = sized tree
    where
      tree 0 = return Empty
      tree n | n > 0 =
        oneof [return Empty,
               liftM3 Node arbitrary (tree (n `div` 2))
               (tree (n `div` 2))]

QuickCheck for Tree
prop_find_insert :: Int -> Int -> Tree Int -> Bool
prop_find_insert x y t =
    find x (insert y t) == ???

(Int not optimal for QuickCheck)
Edit distance (see Thompson)

Problem: how to get from one word to another, with a *minimal* number of “edits”.

Example: from "fish" to "chips"

Applications: DNA Analysis, Unix diff command
data Edit = Change Char
  | Copy
  | Delete
  | Insert Char

deriving (Eq, Show)

transform :: String -> String -> [Edit]

transform [] ys = map Insert ys
transform xs [] = replicate (length xs) Delete
transform (x:xs) (y:ys)
  | x == y = Copy : transform xs ys
  | otherwise = best [Change y : transform xs ys,
                      Delete : transform xs (y:ys),
                      Insert y : transform (x:xs) ys]
best :: [[Edit]] -> [Edit]
best [x] = x
best (x:xs)
  | cost x <= cost b = x
  | otherwise = b
  where b = best xs

cost :: [Edit] -> Int
cost = length . filter (/=Copy)
Example: What is the edit distance from "trittin" to "tarantino"?

transform "trittin" "tarantino" = ?

Complexity of transform: time $O(\quad )$

The edit distance problem can be solved in time $O(mn)$ with dynamic programming
8.2 The general case

data $T \ a_1 \ ... \ a_p =$
$\ \ \ \ C_1 \ t_{11} \ ... \ t_{1k_1} \ |
\ \ \ \ :$
$\ \ \ \ C_n \ t_{n1} \ ... \ t_{nk_n}$

defines the *constructors*

$\ \ \ \ C_1 :: \ t_{11} \to \ ... \ t_{1k_1} \to T \ a_1 \ ... \ a_p$
$\ \ \ \ :$
$\ \ \ \ C_n :: \ t_{n1} \to \ ... \ t_{nk_n} \to T \ a_1 \ ... \ a_p$
Constructors are functions too!

Constructors can be used just like other functions

Example

map Just [1, 2, 3] = [Just 1, Just 2, Just 3]

But constructors can also occur in patterns!
Patterns are expressions that consist only of constructors and variables (which must not occur twice):

A *pattern* can be

- a variable (incl. `_`)
- a literal like `1`, `'a'`, "xyz", ... 
- a tuple `(p₁, ..., pₙ)` where each `pᵢ` is a pattern
- a constructor pattern `C p₁ ... pₙ` where
  - `C` is a data constructor (incl. True, False, [] and (:))
  - and each `pᵢ` is a pattern
8.3 Case study: boolean formulas

type Name = String

data Form = F | T |
| Var Name |
| Not Form |
| And Form Form |
| Or Form Form |
deriving Eq

Example: Or (Var "p") (Not(Var "p"))

More readable: symbolic infix constructors, must start with :
data Form = F | T | Var Name |
| Not Form |
| Form :&: Form |
| Form :|: Form |
deriving Eq

Now: Var "p" :|: Not(Var "p"
Pretty printing

par :: String -> String
par s = "(" ++ s ++ ")"

instance Show Form where
  show F = "F"
  show T = "T"
  show (Var x) = x
  show (Not p) = par("~" ++ show p)
  show (p :&: q) = par(show p ++ " & " ++ show q)
  show (p :+: q) = par(show p ++ " | " ++ show q)

> Var "p" :&: Not(Var "p")
(p & (~p))
Syntax versus meaning

Form is the *syntax* of boolean formulas, not their meaning:

\( \text{Not(Not T)} \) and \( T \) mean the same but are different:

\[
\text{Not(Not T)} \neq T
\]

What is the meaning of a Form?

Its value!?

But what is the value of \( \text{Var "p"} \)?
-- Wertebelegung

type Valuation = [(Name,Bool)]

eval :: Valuation -> Form -> Bool
eval _ F = False
eval _ T = True
eval v (Var x) = the(lookup x v) where the(Just b) = b
eval v (Not p) = not(eval v p)
eval v (p :&: q) = eval v p && eval v q
eval v (p :|: q) = eval v p || eval v q

> eval ["a",False), ("b",False)]
   (Not(Var "a") :&: Not(Var "b"))
True
All valuations for a given list of variable names:

vals :: [Name] -> [Valuation]
vals [] = [[]]
vals (x:xs) = [(x,False):v | v <- vals xs] ++
               [(x,True):v | v <- vals xs]

vals "b"
= [("b",False):v | v <- vals []] ++
   [("b",True):v | v <- vals []]
= [(["b",False]), ["b",True]]

vals "a","b"
= [("a",False):v | v <- vals "b"] ++
   [("a",True):v | v <- vals "b"]
= [(["a",False]), (["b",False]), (["a",False]), (["b",True]) ++
   [[("a",True), ("b",False)], ["a",True, ("b",True)]]
Does vals construct all valuations?

```haskell
prop_vals1 xs =
    length(vals xs) == 2 ^ length xs

prop_vals2 xs =
    distinct (vals xs)

distinct :: Eq a => [a] -> Bool
distinct [] = True
distinct (x:xs) = not(elem x xs) && distinct xs
```

Demo
Restrict size of test cases:

\[
\text{prop\_vals1'} \; xs = \\
\quad \text{length } xs \leq 10 \implies \\
\quad \text{length(vals } xs) = 2 ^ \text{length } xs
\]

\[
\text{prop\_vals2'} \; xs = \\
\quad \text{length } xs \leq 10 \implies \text{distinct (vals } xs)
\]

Demo
Satisfiable and tautology

satisfiable :: Form -> Bool
satisfiable p = or [eval v p | v <- vals(vars p)]

tautology :: Form -> Bool
tautology = not . satisfiable . Not

vars :: Form -> [Name]
vars F = []
vars T = []
vars (Var x) = [x]
vars (Not p) = vars p
vars (p &: q) = nub (vars p ++ vars q)
vars (p :+: q) = nub (vars p ++ vars q)
p0 :: Form
p0 = (Var "a" :&: Var "b") :+: 
    (Not (Var "a") :&: Not (Var "b") )

> vals (vars p0)
[[("a",False),("b",False)], [("a",False),("b",True)], 
 [("a",True), ("b",False)], [("a",True), ("b",True )]]

> [ eval v p0 | v <- vals (vars p0) ]
[True, False, False, True]

> satisfiable p0
True
Simplifying a formula: Not inside?

```haskell
isSimple :: Form -> Bool
isSimple (Not p)   =  not (isOp p)
  where
    isOp (Not p)   =  True
    isOp (p :&: q) =  True
    isOp (p :+: q) =  True
    isOp p         =  False
isSimple (p :&: q) =  isSimple p && isSimple q
isSimple (p :+: q) =  isSimple p && isSimple q
isSimple p         =  True
```
Simplifying a formula: Not inside!

simplify :: Form -> Form
simplify (Not p) = pushNot (simplify p)

where
    pushNot (Not p) = p
    pushNot (p &: q) = pushNot p :|: pushNot q
    pushNot (p :| q) = pushNot p &: pushNot q
    pushNot p = Not p

simplify (p &: q) = simplify q &: simplify q
simplify (p :| q) = simplify p :| simplify q
simplify p = p
-- for QuickCheck: test data generator for Form
instance Arbitrary Form where
  arbitrary = sized prop
    where
    prop 0  =
      oneof [return F,
              return T,
              liftM Var arbitrary]
    prop n | n > 0 =
      oneof
        [return F,
         return T,
         liftM Var arbitrary,
         liftM Not (prop (n-1)),
         liftM2 (:&:) (prop(n `div` 2)) (prop(n `div` 2)),
         liftM2 (:|:) (prop(n `div` 2)) (prop(n `div` 2))]
prop_simplify p = isSimple(simplify p)
8.4 Structural induction
Structural induction for Tree

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

To prove property $P(t)$ for all finite $t :: Tree a$

Base case: Prove $P(\text{Empty})$ and

Induction step: Prove $P(\text{Node } x \ t1 \ t2)$
assuming the induction hypotheses $P(t1)$ and $P(t2)$.  
($x$, $t1$ and $t2$ are new variables)
Example

flat :: Tree a -> [a]
flat Empty = []
flat (Node x t1 t2) =
    flat t1 ++ [x] ++ flat t2

mapTree :: (a -> b) -> Tree a -> Tree b
mapTree f Empty = Empty
mapTree f (Node x t1 t2) =
    Node (f x) (mapTree f t1) (mapTree f t2)
Lemma \( \text{flat} (\text{mapTree} f t) = \text{map} f (\text{flat} t) \)

Proof by structural induction on \( t \)

Induction step:

IH1: \( \text{flat} (\text{mapTree} f t1) = \text{map} f (\text{flat} t1) \)

IH2: \( \text{flat} (\text{mapTree} f t2) = \text{map} f (\text{flat} t2) \)

To show: \( \text{flat} (\text{mapTree} f (\text{Node} x t1 t2)) = \text{map} f (\text{flat} (\text{Node} x t1 t2)) \)

\[
\text{flat} (\text{mapTree} f (\text{Node} x t1 t2)) \\
= \text{flat} (\text{Node} (f x) (\text{mapTree} f t1) (\text{mapTree} f t2)) \\
= \text{flat} (\text{mapTree} f t1) ++ [f x] ++ \text{flat} (\text{mapTree} f t2) \\
= \text{map} f (\text{flat} t1) ++ [f x] ++ \text{map} f (\text{flat} t2) \\
\quad \quad \quad \quad \quad \quad \quad \quad \quad -- \text{by IH1 and IH2} \\
\text{map} f (\text{flat} (\text{Node} x t1 t2)) \\
= \text{map} f (\text{flat} t1 ++ [x] ++ \text{flat} t2) \\
= \text{map} f (\text{flat} t1) ++ [f x] ++ \text{map} f (\text{flat} t2) \\
\quad \quad \quad \quad \quad \quad \quad \quad \quad -- \text{by lemma distributivity of map over ++} \\
\]

Note: Base case and -- by def of ... omitted
The general (regular) case

data T a = ...

Assumption: T is a regular data type:

Each constructor $C_i$ of T must have a type

$t_1 \rightarrow \ldots \rightarrow t_{n_i} \rightarrow T \ a$

such that each $t_j$ is either $T \ a$ or does not contain $T$

To prove property $P(t)$ for all finite $t :: T \ a$:

prove for each constructor $C_i$ that $P(C_i \ x_1 \ldots x_{n_i})$

assuming the induction hypotheses $P(x_j)$ for all $j$ s.t. $t_j = T \ a$

Example of non-regular type: data T = C [T]
9. I/O

File I/O
Network I/O
• So far, only batch programs: given the full input at the beginning, the full output is produced at the end
• Now, interactive programs: read input and write output while the program is running
The problem

- Haskell programs are pure mathematical functions:
  Haskell programs have no side effects

- Reading and writing are side effects:
  Interactive programs have side effects
Most languages allow functions to perform I/O without reflecting it in their type.

Assume that Haskell were to provide an input function

\[
\text{inputInt} :: \text{Int}
\]

Now all functions potentially perform side effects.

Now we can no longer reason about Haskell like in mathematics:

\[
\begin{align*}
\text{inputInt} - \text{inputInt} &= 0 \\
\text{inputInt} + \text{inputInt} &= 2*\text{inputInt} \\
\end{align*}
\]

... are no longer true.
The pure solution

Haskell distinguishes expressions without side effects from expressions with side effects (actions) by their type:

\[ \text{IO} \ a \]

is the type of (I/O) actions that return a value of type \( a \).

Example

- \text{Char}: the type of pure expressions that return a Char
- \text{IO Char}: the type of actions that return a Char
- \text{IO ()}: the type of actions that return no result value
• Type () is the type of empty tuples (no fields).
• The only value of type () is (), the empty tuple.
• Therefore IO () is the type of actions that return the dummy value ()
  (because every action must return some value)
Basic actions

- **getChar :: IO Char**
  
  Reads a Char from standard input,
  echoes it to standard output,
  and returns it as the result

- **putChar :: Char -> IO ()**
  
  Writes a Char to standard output,
  and returns no result

- **return :: a -> IO a**
  
  Performs no action,
  just returns the given value as a result
Sequencing: do

A sequence of actions can be combined into a single action with the keyword **do**

**Example**

```haskell
get2 :: IO (Char,Char)
get2 = do x <- getChar
          -- result is named x
          getChar
          -- result is ignored
          y <- getChar
          return (x,y)
```
General format (observe layout!):

do  \ a_1
   
   : 

   \ a_n

where each \ a_i \ can be one of

- an action
  Effect: execute action

- \ x <- \ action
  Effect: execute \ action :: IO \ a, give result the name \ x :: a

- let \ x = expr
  Effect: give \ expr \ the name \ x
  Lazy: \ expr \ is only evaluated when \ x \ is needed!
Derived primitives

Write a string to standard output:

```haskell
putStrLn :: IO ()
putStrLn cs = putStr (cs ++ '
')
```

Write a line to standard output:

```haskell
putStrLn :: IO ()
putStrLn cs = putStr (cs ++ '\n')
```
Read a line from standard input:

```haskell
getLine :: IO String
getLine = do x <- getChar
               if x == '\n' then
                 return []
               else
                 do xs <- getLine
                     return (x:xs)
```

Actions are normal Haskell values and can be combined as usual, for example with if-then-else.
Prompt for a string and display its length:

```haskell
strLen :: IO ()
strLen = do
    putStr "Enter a string: "
    xs <- getLine
    putStr "The string has "
    putStr (show (length xs))
    putStrLn " characters"

> strLen

Enter a string: abc
The string has 3 characters
How to read other types

Input string and convert

Useful class:

class Read a where
  read :: String -> a

Most predefined types are in class Read.

Example:

gGetInt :: IO Integer
getInt = do xs <- getLine
  return (read xs)
Case study

The game of Hangman
in file hangman.hs
main :: IO ()
main = do putStrLn "Input secret word: "
        word <- getWord ""
        clear_screen
        guess word
        main
guess :: String -> IO ()
guess word = loop "" "" gallows where
  loop :: String -> String -> [String] -> IO()
  loop guessed missed gals =
    do let word’ =
        map (\x -> if x ‘elem‘ guessed
        then x else ’-‘)
            word

    writeAt (1,1)
        (head gals ++ "\n" ++ "Word: " ++ word’ ++
        "\nMissed: " ++ missed ++ "\n")
    if length gals == 1
    then putStrLn ("YOU ARE DEAD: " ++ word)
    else if word’ == word then putStrLn "YOU WIN!"
    else do c <- getChar
         let ok = c ‘elem‘ word
         loop (if ok then c:guessed else guessed)
             (if ok then missed else missed++[c])
             (if ok then gals else tail gals)
Once IO, always IO

You cannot add I/O to a function without giving it an IO type.

For example

\[
\begin{align*}
\text{sq} & : \text{Int} \rightarrow \text{Int} & \text{cube} & : \text{Int} \rightarrow \text{Int} \\
\text{sq} \ x & = x \times x & \text{cube} \ x & = x \times \text{sq} \ x
\end{align*}
\]

Let us try to make \text{sq} print out some message:

\[
\text{sq} \ x = \text{do} \ \text{putStr}("I am in sq!") \\
\text{\hspace{1cm} return}(x \times x)
\]

What is the type of \text{sq} now? \text{Int} \rightarrow \text{IO} \ \text{Int}

And this is what happens to \text{cube}:

\[
\text{cube} \ x = \text{do} \ x2 \gets \text{sq} \ x \\
\text{\hspace{1cm} return}(x \times x2)
\]
Haskell is a pure functional language
Functions that have side effects must show this in their type
I/O is a side effect
Separate I/O from processing to reduce I/O creep:

```haskell
class :: IO ()
main = do s <- getLine
        let r = process s
        putStrLn r
        main

process :: String -> String
process s = ...
```
9.1 File I/O
The simple way

- **type FilePath = String**
- **readFile :: FilePath -> IO String**
  
  Reads file contents *lazily*, only as much as is needed
- **writeFile :: FilePath -> String -> IO ()**
  
  Writes whole file
- **appendFile :: FilePath -> String -> IO ()**
  
  Appends string to file
import System.IO
data Handle

Opaque type, implementation dependent

Haskell defines operations to read and write characters from and to files, represented by values of type Handle. Each value of this type is a handle: a record used by the Haskell run-time system to manage I/O with file system objects.
Files and handles

- `data IOMode = ReadMode | WriteMode | AppendMode | ReadWriteMode`
- `openFile :: FilePath -> IOMode -> IO Handle`
  Creates handle to file and opens file
- `hClose :: Handle -> IO ()`
  Closes file
By convention
all IO actions that take a handle argument begin with $h$
In ReadMode

- `hGetChar :: Handle -> IO Char`
- `hGetLine :: Handle -> IO String`
- `hGetContents :: Handle -> IO String`

Reads the whole file *lazily*
In WriteMode

- `hPutChar :: Handle -> Char -> IO ()`
- `hPutStr :: Handle -> String -> IO ()`
- `hPutStrLn :: Handle -> String -> IO ()`
- `hPrint :: Show a => Handle -> a -> IO ()`
stdin and stdout

- stdin :: Handle
  stdout :: Handle

- getChar = hGetChar stdin
  putChar = hPutChar stdout
There is much more in the Standard IO Library
(including exception handling for IO actions)
Example (interactive cp: icp.hs)

main :: IO()
main =
    do fromH <- readOpenFile "Copy from: " ReadMode
toH <- readOpenFile "Copy to: " WriteMode
    contents <- hGetContents fromH
    hPutStr toH contents
    hClose fromH
    hClose toH

readOpenFile :: String -> IOMode -> IO Handle
readOpenFile prompt mode =
    do putStrLn prompt
       name <- getLine
       handle <- openFile name mode
       return handle
Executing \texttt{xyz.hs}

If \texttt{xyz.hs} contains a definition of \texttt{main}:

- \texttt{runhaskell \ xyz}
  
  or

- \texttt{ghc \ xyz} \ \leadsto \ executable \ file \ \texttt{xyz}
9.2 Network I/O
import Network
• data Socket

• data PortId = PortNumber PortNumber | ...

• data PortNumber
  instance Num PortNumber
  ⇒ PortNumber 9000 :: PortId
Server functions

- `listenOn :: PortId -> IO Socket`
  Create server side socket for specific port

- `accept :: Socket -> IO (Handle, ..., ...)`
  \[\Rightarrow\] can read/write from/to socket via handle

- `sClose :: Socket -> IO ()`
  Close socket
Initialization for Windows

\[
\text{withSocketsDo} :: \text{IO } a \rightarrow \text{IO } a
\]

Standard use pattern:

\[
\text{main} = \text{withSocketsDo } \& \text{ do } ...
\]

Does nothing under Unix
Example (pingPong.hs)

main :: IO ()
main = withSocketsDo $ do
  sock <- listenOn $ PortNumber 9000
  (h, _, _) <- accept sock
  hSetBuffering h LineBuffering
  loop h
  sClose sock

loop :: Handle -> IO ()
loop h = do
  input <- hGetLine h
  if take 4 input == "quit"
  then do hPutStrLn h "goodbye!"
         hClose h
  else do hPutStrLn h ("got " ++ input)
         loop h
Client functions

- type HostName = String
  For example "haskell.org" or "192.168.0.1"

- connectTo :: HostName -> PortId -> IO Handle
  Connect to specific port of specific host
Example (wGet.hs)

main :: IO()
main = withSocketsDo $ do
    putStrLn "Host?"
    host <- getLine
    h <- connectTo host (PortNumber 80)
    hSetBuffering h LineBuffering
    putStrLn "Resource?"
    res <- getLine
    hPutStrLn h ("GET " ++ res ++ " HTTP/1.0\n")
    s <- hGetContents h
    putStrLn s
For more detail see

http://hackage.haskell.org/package/network/docs/
Network.html

http://hackage.haskell.org/package/network/docs/
Network-Socket.html
10. Modules and Abstract Data Types

- Modules
- Modules
- Modules
- Modules
- Modules
- Modules
- Modules
- Modules
- Modules
- Abstract Data Types
- Abstract Data Types
- Abstract Data Types
- Abstract Data Types
- Abstract Data Types
- Abstract Data Types
10.1 Modules

Module = collection of type, function, class etc definitions

Purposes:
- Grouping
- Interfaces
- Division of labour
- Name space management: \texttt{M.f} vs \texttt{f}
- Information hiding

GHC: one module per file
Recommendation: module \texttt{M} in file \texttt{M.hs}
module M where  -- M must start with capital letter

↑

All definitions must start in this column

• Exports everything defined in M (at the top level)

Selective export:

module M (T, f, ...) where

• Exports only T, f, ...
Exporting data types

module M (T) where
data T = ...

- Exports only T, but not its constructors

module M (T(C,D,...)) where
data T = ...

- Exports T and its constructors C, D, ...

module M (T(..)) where
data T = ...

- Exports T and all of its constructors

Not permitted: module M (T,C,D) where (why?)

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Exporting modules

By default, modules do not export names from imported modules

```haskell
module B where
import A
...
⇒ B does not export f
```

Unless the names are mentioned in the export list

```haskell
module B (f) where
import A
...
```

Or the whole module is exported

```haskell
module B (module A) where
import A
...
```
By default, everything that is exported is imported

module B where
import A
...
⇒ B imports f and g

Unless an import list is specified

module B where
import A (f)
...
⇒ B imports only f

Or specific names are hidden

module B where
import A hiding (g)
...
import A
import B
import C
... f ...

Where does f come from??

Clearer: qualified names

... A.f ...

Can be enforced:

import qualified A

⇒ must always write A.f
Renaming modules

```haskell
import TotallyAwesomeModule

... TotallyAwesomeModule.f ...

Painful

More readable:

import qualified TotallyAwesomeModule as TAM

... TAM.f ...
```
For the full description of the module system see the Haskell report.
Abstract Data Types do not expose their internal representation

Why? Example: sets implemented as lists without duplicates

- Could create illegal value: \([1, 1]\)
- Could distinguish what should be indistinguishable: \([1, 2] /= [2, 1]\)
- Cannot easily change representation later
Example: Sets

module Set where
-- sets are represented as lists w/o duplicates
type Set a = [a]
empty :: Set a
empty = []
insert :: a -> Set a -> Set a
insert x xs = ...
isin :: a -> Set a -> Set a
isin x xs = ...
size :: Set a -> Integer
size xs = ...

Exposes everything
Allows nonsense like Set.size [1,1]
Better

module Set (Set, empty, insert, isin, size) where

-- Interface
empty  :: Set a
insert :: Eq a => a -> Set a -> Set a
isin   :: Eq a => a -> Set a -> Bool
size   :: Set a -> Int

-- Implementation

type Set a = [a]

...

- Explicit export list/interface
- But representation still not hidden
  Does not help: hiding the type name Set
Hiding the representation

module Set (Set, empty, insert, isin, size) where

-- Interface
...

-- Implementation
data Set a = S [a]

empty = S []
insert x (S xs) = S(if elem x xs then xs else x:xs)
isin x (S xs) = elem x xs
size (S xs) = length xs

Cannot construct values of type Set outside of module Set because S is not exported

Test.hs:3:11: Not in scope: data constructor ‘S’
Uniform naming convention: $S \leadsto \text{Set}$

module Set (Set, empty, insert, isin, size) where
-- Interface
...
-- Implementation
data Set a = Set [a]

empty = Set []
insert x (Set xs) = Set(if elem x xs then xs else x:xs)
isin x (Set xs) = elem x xs
size (Set xs) = length xs

Which Set is exported?
Slightly more efficient: newtype

module Set (Set, empty, insert, isin, size) where
  -- Interface
  ...
  -- Implementation
  newtype Set a = Set [a]

  empty = Set []
  insert x (Set xs) = Set(if elem x xs then xs else x:xs)
  isin x (Set xs) = elem x xs
  size (Set xs) = length xs
Data representation can be hidden by wrapping data up in a constructor that is not exported
What if Set is already a data type?

module SetByTree (Set, empty, insert, isin, size) where

-- Interface
empty  :: Set a
insert :: Ord a => a -> Set a -> Set a
isin   :: Ord a => a -> Set a -> Bool
size   :: Set a -> Integer

-- Implementation
type Set a = Tree a
data Tree a = Empty | Node a (Tree a) (Tree a)

No need for newtype:
The representation of Tree is hidden
as long as its constructors are hidden
Beware of ==

module SetByTree (Set, empty, insert, isin, size) where
...
type Set a = Tree a
data Tree a = Empty | Node a (Tree a) (Tree a)
  deriving (Eq)
...

Class instances are automatically exported and cannot be hidden

Client module:

import SetByTree
...
  insert 2 (insert 1 empty) ==
    insert 1 (insert 2 empty)
  ...

Result is probably False — representation is partly exposed!
The proper treatment of \texttt{==}

Some alternatives:

- Do not make \texttt{Tree} an instance of \texttt{Eq}

- Hide representation:

  -- do not export constructor \texttt{Set}:
  
  \begin{verbatim}
  newtype Set a = Set (Tree a)
  data Tree a = Empty \mid Node a (Tree a) (Tree a)
  deriving (Eq)
  \end{verbatim}

- Define the right \texttt{==} on \texttt{Tree}:

  \begin{verbatim}
  instance Eq a \Rightarrow Eq (Tree a) where
  t1 == t2 = \texttt{elems t1 == elems t2}
  where
  \texttt{elems Empty} = []
  \texttt{elems (Node x t1 t2)} = \texttt{elems t1 ++ [x] ++ elems t2}
  \end{verbatim}
Similar for all class instances, not just Eq
10.3 Correctness

Why is module Set a correct implementation of (finite) sets?

Because empty simulates \{\}\n
and insert _ _ simulates \{\_\} \cup \_ 

and isin _ _ simulates \_ \in \_ 

and size _ simulates |\_|

Each concrete operation on the implementation type of lists
simulates its abstract counterpart on sets

NB: We relate Haskell to mathematics
For uniformity we write \{a\} for the type of finite sets over type a
From lists to sets

Each list \([x_1, \ldots, x_n]\) represents the set \(\{x_1, \ldots, x_n\}\).

**Abstraction function** \(\alpha :: [a] \rightarrow \{a\}\)

\[
\alpha[x_1, \ldots, x_n] = \{x_1, \ldots, x_n\}
\]

In Haskell style:

\[
\alpha \texttt{[]} = {}
\]

\[
\alpha \texttt{(x:xs)} = \{x\} \cup \alpha \texttt{xs}
\]

What does it mean that “lists simulate (implement) sets”:

\[
\alpha \texttt{(concrete operation)} = \text{abstract operation}
\]

\[
\alpha \texttt{empty} = {}
\]

\[
\alpha \texttt{(insert x xs)} = \{x\} \cup \alpha \texttt{xs}
\]

\[
\texttt{isin x xs} = x \in \alpha \texttt{xs}
\]

\[
\texttt{size xs} = |\alpha \texttt{xs}|
\]
For the mathematically enclined:

\[ \alpha \text{ must be a homomorphism} \]
Implementation I: lists with duplicates

empty = []
insert x xs = x : xs
isin x xs = elem x xs
size xs = length(nub xs)

The simulation requirements:

\[ \alpha \text{ empty} = \{\} \]

\[ \alpha (\text{insert x xs}) = \{x\} \cup \alpha \text{ xs} \]

\[ \text{isin x xs} = x \in \alpha \text{ xs} \]

\[ \text{size xs} = |\alpha \text{ xs}| \]

Two proofs immediate, two need lemmas proved by induction
Implementation II: lists without duplicates

empty = []
insert x xs = if elem x xs then xs else x:xs
isin x xs = elem x xs
size xs = length xs

The simulation requirements:
\[ \alpha \text{ empty} = {} \]
\[ \alpha \text{ (insert x xs)} = \{x\} \cup \alpha \text{ xs} \]
\[ \text{isin x xs} = x \in \alpha \text{ xs} \]
\[ \text{size xs} = |\alpha \text{ xs}| \]

Needs \textit{invariant} that \( xs \) contains no duplicates

\textbf{invar} :: [a] \rightarrow \text{Bool}
\textbf{invar} [] = True
\textbf{invar} (x:xs) = \text{not}(\text{elem} x xs) \&\& \text{invar} xs
Implementation II: lists without duplicates

empty = []
insert x xs = if elem x xs then xs else x:xs
isin x xs = elem x xs
size xs = length xs

Revised simulation requirements:

\[ \alpha \text{ empty} = \{\} \]
\[ \text{invar } xs \implies \alpha (\text{insert } x \text{ xs}) = \{x\} \cup \alpha \text{ xs} \]
\[ \text{invar } xs \implies \text{isin } x \text{ xs} = x \in \alpha \text{ xs} \]
\[ \text{invar } xs \implies \text{size } xs = |\alpha \text{ xs}| \]

Proofs omitted. Anything else?
invar must be invariant!

In an imperative context:

If \textit{invar} is true before an operation, it must also be true after the operation.

In a functional context:

If \textit{invar} is true for the arguments of an operation, it must also be true for the result of the operation.

\textit{invar} is \textit{preserved} by every operation:

\textit{invar empty}

\textit{invar xs} \implies \textit{invar (insert x xs)}

Proofs do not even need induction.
Let $C$ and $A$ be two modules that have the same interface: a type $T$ and a set of functions $F$

To prove that $C$ is a correct implementation of $A$ define

an abstraction function $\alpha :: C.T \to A.T$

and an invariant $\text{invar} :: C.T \to \text{Bool}$

and prove for each $f \in F$:

- $\text{invar}$ is invariant:

$$\text{invar} x_1 \land \cdots \land \text{invar} x_n \implies \text{invar} (C.f \, x_1 \, \ldots \, x_n)$$

(where $\text{invar}$ is True on types other than $C.T$)

- $C.f$ simulates $A.f$:

$$\text{invar} x_1 \land \cdots \land \text{invar} x_n \implies \alpha(C.f \, x_1 \, \ldots \, x_n) = A.f \left(\alpha x_1\right) \ldots \left(\alpha x_n\right)$$

(where $\alpha$ is the identity on types other than $C.T$)
11. Case Study: Two Efficient Algorithms
This lecture covers two classic efficient algorithms in functional style on the blackboard:

**Huffman Coding**
See the Haskell book by Thompson for a detailed exposition.

**Skew Heaps**
See the original paper for an imperative presentation and the derivation of the amortized complexity:


The source files are on the web page.
12. Lazy evaluation

Applications of lazy evaluation
Infinite lists
Introduction

So far, we have not looked at the details of how Haskell expressions are evaluated. The evaluation strategy is called

\textit{lzy evaluation} (,,verzögerte Auswertung’’)

Advantages:

\begin{itemize}
  \item Avoids unnecessary evaluations
  \item Terminates as often as possible
  \item Supports infinite lists
  \item Increases modularity
\end{itemize}

Therefore Haskell is called a \textit{lazy functional language}. Haskell is the only mainstream lazy functional language.
Evaluating expressions

Expressions are evaluated (reduced) by successively applying definitions until no further reduction is possible.

Example:

\[ sq :: \text{Integer} \to \text{Integer} \]
\[ sq \ n \ = \ n \times n \]

One evaluation:

\[ sq(3+4) = sq\ 7 = 7 \times 7 = 49 \]

Another evaluation:

\[ sq(3+4) = (3+4) \times (3+4) = 7 \times (3+4) = 7 \times 7 = 49 \]
**Theorem**
Any two terminating evaluations of the same Haskell expression lead to the same final result.

This is not the case in languages with side effects:

**Example**
Let \( n \) have value 0 initially.

Two evaluations:

\[
\begin{align*}
n + (n := 1) & = 0 + (n := 1) = 0 + 1 = 1 \\
n + (n := 1) & = n + 1 = 1 + 1 = 2
\end{align*}
\]
Reduction strategies

An expression may have many reducible subexpressions:

\[ \text{sq} (3+4) \]

Terminology: *redex* = reducible expression

Two common reduction strategies:

**Innermost reduction**  Always reduce an innermost redex.
Corresponds to *call by value*:
Arguments are evaluated before they are substituted into the function body
\[ \text{sq} (3+4) = \text{sq} 7 = 7 \times 7 \]

**Outermost reduction**  Always reduce an outermost redex.
Corresponds to *call by name*:
The unevaluated arguments are substituted into the function body
\[ \text{sq} (3+4) = (3+4) \times (3+4) \]
Comparison: termination

Definition:
\(\text{loop} = \text{tail loop}\)

Innermost reduction:
\[
\text{fst}(1,\text{loop}) = \text{fst}(1,\text{tail loop}) \\
= \text{fst}(1,\text{tail(tail loop)}) \\
= \ldots
\]

Outermost reduction:
\[
\text{fst}(1,\text{loop}) = 1
\]

**Theorem** If expression \(e\) has a terminating reduction sequence, then outermost reduction of \(e\) also terminates.

Outermost reduction terminates as often as possible
Why is this useful?

**Example**

Can build your own control constructs:

```haskell
switch :: Int -> a -> a -> a
switch n x y
   | n > 0     = x
   | otherwise = y

fac :: Int -> Int
fac n = switch n (n * fac(n-1)) 1
```
Comparison: Number of steps

Innermost reduction:

\[ \text{sq}(3+4) = \text{sq} 7 = 7 \times 7 = 49 \]

Outermost reduction:

\[ \text{sq}(3+4) = (3+4) \times (3+4) = 7 \times (3+4) = 7 \times 7 = 49 \]

More outermost than innermost steps!
How can outermost reduction be improved?
Sharing!
$$\text{sq}(3+4) = \bullet \times \bullet = \bullet \times \bullet = 49$$

3+4

7

The expression $3+4$ is only evaluated \textit{once}!

Lazy evaluation $:\equiv$ outermost reduction + sharing

\textbf{Theorem}

Lazy evaluation never needs more steps than innermost reduction.
The principles of lazy evaluation:

- Arguments of functions are evaluated only if needed to continue the evaluation of the function.
- Arguments are not necessarily evaluated fully, but only far enough to evaluate the function. (Remember \texttt{fst (1,loop)})
- Each argument is evaluated at most once (sharing!)
Example

\[
f :: [\text{Int}] \rightarrow [\text{Int}] \rightarrow \text{Int}
f [] \quad \text{ys} \quad = \quad 0 \\
f (x:xs) [] \quad = \quad 0 \\
f (x:xs) \ (y:ys) \quad = \quad x+y
\]

Lazy evaluation:

\[
f \ [1..3] \ [7..9] \quad -- \text{does f.1 match?} \\
= \quad f \ (1 : \ [2..3]) \ [7..9] \quad -- \text{does f.2 match?} \\
= \quad f \ (1 : \ [2..3]) \ (7 : \ [8..9]) \quad -- \text{does f.3 match?} \\
= \quad 1+7 \\
= \quad 8
\]
Guards

Example

\[
f(m, n, p) \mid m \geq n \land m \geq p = m \\
\mid n \geq m \land n \geq p = n \\
\mid \text{otherwise} \quad = p
\]

Lazy evaluation:
\[
f(2+3) \ (4-1) \ (3+9)
\]
\[
? \quad 2+3 \geq 4-1 \land 2+3 \geq 3+9
\]
\[
? \quad = \quad 5 \geq 3 \land 5 \geq 3+9
\]
\[
? \quad = \quad \text{True} \land 5 \geq 3+9
\]
\[
? \quad = \quad 5 \geq 3+9
\]
\[
? \quad = \quad 5 \geq 12
\]
\[
? \quad = \quad \text{False}
\]
\[
? \quad 3 \geq 5 \land 3 \geq 12
\]
\[
? \quad = \quad \text{False} \land \quad 3 \geq 12
\]
\[
? \quad = \quad \text{False}
\]
\[
? \quad \text{otherwise} \quad = \quad \text{True}
\]
\[
= \quad 12
\]
Same principle: definitions in where clauses are only evaluated when needed and only as much as needed.
Haskell never reduces inside a lambda

Example: $\lambda x \rightarrow \text{False} \&\& x$ cannot be reduced

Reasons:
- Functions are black boxes
- All you can do with a function is apply it

Example:
$$(\lambda x \rightarrow \text{False} \&\& x) \text{True} = \text{False} \&\& \text{True} = \text{False}$$
Built-in functions

Arithmetic operators and other built-in functions evaluate their arguments first

Example

3 * 5 is a redex
0 * head(...) is not a redex
Predefined functions from Prelude

They behave like their Haskell definition:

\( (\&\&) :: \text{Bool} \rightarrow \text{Bool} \rightarrow \text{Bool} \)

\begin{align*}
\text{True} \ &\& y & = & y \\
\text{False} \ &\& y & = & \text{False}
\end{align*}
Lazy evaluation evaluates an expression only when needed and only as much as needed.

("Call by need")
12.1 Applications of lazy evaluation
Minimum of a list

\[
\text{min} = \text{head} \cdot \text{inSort}
\]

\[
\text{inSort} :: \text{Ord } a \Rightarrow \text{[a]} \to \text{[a]}
\]
\[
\text{inSort} \; [] = []
\]
\[
\text{inSort} \; (x:xs) = \text{ins } x \; (\text{inSort } xs)
\]

\[
\text{ins} :: \text{Ord } a \Rightarrow a \to \text{[a]} \to \text{[a]}
\]
\[
\text{ins} \; x \; [] = [x]
\]
\[
\text{ins} \; x \; (y:ys) \mid x \leq y = x : y : ys
\]
\[
\quad \mid \text{otherwise} = y : \text{ins } x \; ys
\]

\[
\Rightarrow \text{inSort } [6,1,7,5]
\]
\[
= \text{ins } 6 \; (\text{ins } 1 \; (\text{ins } 7 \; (\text{ins } 5 \; [])))
\]
\[
\text{min } [6,1,7,5] = \text{head}(\text{insSort } [6,1,7,5])
\]
\[
= \text{head}(\text{ins } 6 (\text{ins } 1 (\text{ins } 7 (\text{ins } 5 []))))
\]
\[
= \text{head}(\text{ins } 6 (\text{ins } 1 (\text{ins } 7 (5 : []))))
\]
\[
= \text{head}(\text{ins } 6 (\text{ins } 1 (5 : \text{ins } 7 [])))
\]
\[
= \text{head}(\text{ins } 6 (1 : 5 : \text{ins } 7 []))
\]
\[
= \text{head}(1 : \text{ins } 6 (5 : \text{ins } 7 []))
\]
\[
= 1
\]

Lazy evaluation needs only linear time
although \text{insSort} is quadratic
because the sorted list is never constructed completely

Warning: this depends on the exact algorithm and does not work so nicely with all sorting functions!
Maximum of a list

\[ \text{max} = \text{last} \cdot \text{inSort} \]

Complexity?
12.2 Infinite lists
Example
A recursive definition
ones :: [Int]
ones = 1 : ones
that defines an infinite list of 1s:
ones

=

1 : ones

=

1 : 1 : ones

=

...

What GHCi has to say about it:

> ones

[1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,
Haskell lists can be finite or infinite
Printing an infinite list does not terminate

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But Haskell can compute with infinite lists, thanks to lazy evaluation:

\[
> \text{head ones}
\]

1

Remember:

Lazy evaluation evaluates an expression only as much as needed

Outermost reduction: \( \text{head ones} = \text{head (1 : ones)} = 1 \)

Innermost reduction:  
\[
\text{head ones} \\
= \text{head (1 : ones)} \\
= \text{head (1 : 1 : ones)} \\
= \ldots
\]
Haskell lists are never actually infinite but only potentially infinite

Lazy evaluation computes as much of the infinite list as needed

This is how partially evaluated lists are represented internally:

1 : 2 : 3 : code pointer to compute rest

In general: finite prefix followed by code pointer
Why (potentially) infinite lists?

- They come for free with lazy evaluation
- They increase modularity:
  - list producer does not need to know how much of the list the consumer wants
Example: The sieve of Eratosthenes

1. Create the list 2, 3, 4, \ldots
2. Output the first value $p$ in the list as a prime.
3. Delete all multiples of $p$ from the list
4. Goto step 2

$$2 \ 3 \ 4 \ 5 \ 6 \ 7 \ 8 \ 9 \ 10 \ 11 \ 12 \ \ldots$$
$$2 \ 3 \ 5 \ 7 \ 11 \ \ldots$$
In Haskell:

primes :: [Int]
primes = sieve [2..]

sieve :: [Int] -> [Int]
sieve (p:xs) = p : sieve [x | x <- xs, x ‘mod’ p /= 0]

Lazy evaluation:

primes = sieve [2..] = sieve (2:[3..])
= 2 : sieve [x | x <- [3..], x ‘mod’ 2 /= 0]
= 2 : sieve [x | x <- 3:[4..], x ‘mod’ 2 /= 0]
= 2 : sieve (3 : [x | x <- [4..], x ‘mod’ 2 /= 0])
= 2 : 3 : sieve [x | x <- [x|x <- [4..], x ‘mod’ 2 /= 0],
                 x ‘mod’ 3 /= 0]
= ...
The first 10 primes:

> take 10 primes
[2, 3, 5, 7, 11, 13, 17, 19, 23, 29]

The primes between 100 and 150:

> takeWhile (<150) (dropWhile (<100) primes)
[101, 103, 107, 109, 113, 127, 131, 137, 139, 149]

All twin primes:

> [(p,q) | (p,q) <- zip primes (tail primes), p+2==q]
[(3,5), (5,7), (11,13), (17,19), (29,31), (41,43), (59,61), (71,73)]
Primality test?

> 101 ‘elem‘ primes
True

> 102 ‘elem‘ primes
nontermination

prime n = n == head (dropWhile (<n) primes)
Sharing!

There is only one copy of primes

Every time part of primes needs to be evaluated
  Example: when computing \texttt{take 5 primes}
primes is (invisibly!) updated to remember the evaluated part
  Example: \texttt{primes = 2 : 3 : 5 : 7 : 11 : sieve ...}
The next uses of primes are faster:
  Example: now \texttt{primes !! 2} needs only 3 steps

Nothing special, just the automatic result of sharing
The list of Fibonacci numbers

Idea: 0 1 1 2 ...
     + 0 1 1 ...
     = 0 1 2 3 ...

From Prelude: zipWith
Example: zipWith f [a1, a2, ...] [b1, b2, ...]
         = [f a1 b1, f a2 b2, ...]

fibs :: [Integer]
fibs = 0 : 1 : zipWith (+) fibs (tail fibs)

How about
fibs = 0 : 1 : [x+y | x <- fibs, y <- tail fibs]
Hamming numbers

Definition

\[ H = \{1\} \cup \{2 \cdot h \mid h \in H\} \cup \{3 \cdot h \mid h \in H\} \cup \{5 \cdot h \mid h \in H\} \]

(Due to Richard Hamming, Turing award winner 1968)

Problem: list \( H \) in increasing order: 1, 2, 3, 4, 5, 6, 8, 9, \ldots

\[
\text{hams :: [Int]} \\
\text{hams = 1 : merge [2*h | h <- hams]} \\
\quad \text{(merge [3*h | h <- hams]} \\
\quad \quad \text{[5*h | h <- hams])}
\]

\[
\text{merge (x:xs) (y:ys)} \\
\quad \mid x < y \quad = \quad x : \text{merge xs (y:ys)} \\
\quad \mid x > y \quad = \quad y : \text{merge (x:xs) ys} \\
\quad \mid \text{otherwise} \quad = \quad x : \text{merge xs ys}
\]
Game tree

data Tree p v = Tree p v [Tree p v]

Separates move computation and valuation from move selection

Laziness:

- The game tree is computed incrementally, as much as is needed
- No part of the game tree is computed twice
- Supports infinitely broad and deep trees (useful??)

gameTree :: (p -> [p]) -> (p -> v) -> p -> Tree p v

gameTree next val = tree where
  tree p = Tree p (val p) (map tree (next p))

chessTree = gameTree ...
minimax :: Ord v => Int -> Bool -> Tree p v -> v
minimax d player1 (Tree p v ts) =
  if d == 0 || null ts then v
  else let vs = map (minimax (d-1) (not player1)) ts
       in if player1 then maximum vs else minimum vs

> minimax 3 True chessTree
Generates chessTree up to level 3

> minimax 4 True chessTree
Needs to search 4 levels, but only level 4 needs to be generated
13. Complexity and Optimization

Time complexity analysis
Time complexity analysis
Time complexity analysis
Time complexity analysis
Time complexity analysis
Time complexity analysis
Time complexity analysis
Time complexity analysis
Time complexity analysis
Time complexity analysis

Optimizing functional programs
Optimizing functional programs
Optimizing functional programs
Optimizing functional programs
How to analyze and improve the time (and space) complexity of functional programs

Based largely on Richard Bird’s book *Introduction to Functional Programming using Haskell*.

Assumption in this section:

Reduction strategy is innermost (call by value, cbv)

- Analysis much easier
- Most languages follow cbv
- Number of lazy evaluation steps ≤ number of cbv steps
  \[ \Rightarrow \quad O\text{-analysis under cbv also correct for Haskell but can be too pessimistic} \]
13.1 Time complexity analysis

Basic assumption:

One reduction step takes one time unit

(No guards on the left-hand side of an equation, if-then-else on the right-hand side instead)

Justification:

The implementation does not copy data structures but works with pointers and sharing

Example: \texttt{length \_ : xs} = \texttt{length xs} + 1
Reduce \texttt{length [1,2,3]}

Compare: \texttt{id []} = []
\texttt{id (x:xs)} = x : id xs
Reduce \texttt{id [e1,e2]}
Copies list but shares elements.
\[ T_f(n) = \text{number of steps required for the evaluation of } f \]
when applied to an argument of size \( n \)
in the worst case

What is “size”?  
- Number of bits. Too low level.  
- Better: specific measure based on the argument type of \( f \)  
- Measure may differ from function to function.  
- Frequent measure for functions on lists: the length of the list

We use this measure unless stated otherwise
Sufficient if \( f \) does not compute with the elements of the list
Not sufficient for function \( \ldots \)
How to calculate (not mechanically!) $T_f(n)$:

1. From the equations for $f$ derive equations for $T_f$
2. If the equations for $T_f$ are recursive, solve them
Example

\[
\begin{align*}
[] ++ ys &= ys \\
(x:xs) ++ ys &= x : (xs ++ ys)
\end{align*}
\]

\[
\begin{align*}
T_{++}(0, n) &= O(1) \\
T_{++}(m + 1, n) &= T_{++}(m, n) + O(1)
\end{align*}
\]

\[\implies T_{++}(m, n) = O(m)\]

Note: (++) creates copy of first argument

Principle:

Every constructor of an algebraic data type takes time \( O(1) \).

A constant amount of space needs to be allocated.
Example

reverse [] = []
reverse (x:xs) = reverse xs ++ [x]

\[
T_{reverse}(0) = O(1)
\]
\[
T_{reverse}(n + 1) = T_{reverse}(n) + T_{++}(n, 1)
\]

\[\Rightarrow T_{++}(n) = O(n^2)\]

Observation:

Complexity analysis may need functional properties of the algorithm
The worst case time complexity of an expression $e$:

Sum up all $T_f(n_1, ..., n_k)$

where $f\; e_1 \ldots e_n$ is a function call in $e$
and $n_i$ is the size of $e_i$

(assumption: no higher-order functions)

Note: examples so far equally correct with $\Theta(.)$ instead of $O(.)$, both for cbv and lazy evaluation. (Why?)

Consider $\text{min}\; xs = \text{head}(\text{sort}\; xs)$

$$T_{\text{min}}(n) = T_{\text{sort}}(n) + T_{\text{head}}(n)$$

For cbv also a lower bound, but not for lazy evaluation.

Complexity analysis is *compositional* under cbv
13.2 Optimizing functional programs

*Premature optimization is the root of all evil*

*Don Knuth*

But we are in week $n - 1$ now ;-

The ideal of program optimization:

1. Write (possibly) inefficient but correct code
2. Optimize your code *and prove equivalence to correct version*
Tail recursion / Endrekursion

The definition of a function $f$ is tail recursive / endrekursiv if every recursive call is in “end position”,
$\equiv$ it is the last function call before leaving $f$,
$\equiv$ nothing happens afterwards
$\equiv$ no call of $f$ is nested in another function call

Example

$$
\text{length } [] = 0 \\
\text{length } (x:xs) = \text{length } xs + 1
$$

$$
\text{length2 } [] n = n \\
\text{length2 } (x:xs) n = \text{length2 } xs (n+1)
$$
length [] = 0
length (x:xs) = length xs + 1

length2 [] n = n
length2 (x:xs) n = length2 xs (n+1)

Compare executions:

length [a, b, c]
= length [b, c] + 1
= (length [c] + 1) + 1
= ((length [] + 1) + 1) + 1
= ((0 + 1) + 1) + 1
= 3

length2 [a, b, c] 0
= length2 [b, c] 1
= length2 [c] 2
= length2 [] 3
= 3
**Fact**  Tail recursive definitions can be compiled into loops. Not just in functional languages.

No (additional) stack space is needed to execute tail recursive functions

**Example**

```
length2 [] n = n
length2 (x:xs) n = length2 xs (n+1)
```

⇝

```
loop: if null xs then return n
  xs := tail xs
  n := n+1
  goto loop
```
What does tail recursive mean for

\[ f \ x = \text{if } b \text{ then } e_1 \text{ else } e_2 \]

• \( f \) does not occur in \( b \)
• if \( f \) occurs in \( e_i \) then only at the outside: \( e_i = f \ldots \)

Tail recursive example:

\[ f \ x = \text{if } x > 0 \text{ then } f(x-1) \text{ else } f(x+1) \]

Similar for guards and case \( e \) of:

• \( f \) does not occur in \( e \)
• if \( f \) occurs in any branch then only at the outside: \( f \ldots \)
Accumulating parameters

An accumulating parameter is a parameter where intermediate results are accumulated.

Purpose:

- tail recursion
- replace (++) by (:)

\[
\text{length2 } [] \quad n = n \\
\text{length2 } (x:xs) \quad n = \text{length2 } xs \quad (n+1)
\]

\[
\text{length’ } xs = \text{length2 } xs \quad 0
\]

Correctness:

**Lemma** \( \text{length2 } xs \quad n = \text{length } xs + n \)

\(\implies\) \(\text{length’ } xs = \text{length } xs\)
Tupling of results

Typical application:

Avoid multiple traversals of the same data structure

average :: [Float] -> Float
average xs = (sum xs) / (length xs)

Requires two traversals of the argument list.
Avoid intermediate data structures

Typical example: \( \text{map } g \ . \ \text{map } f = \text{map } (g \ . \ f) \)

Another example: \( \text{sum } [n..m] \)
Precompute large data structures

search :: String -> String -> Bool
search text s = table_search (hash_table text) (hash s,s)

bsearch = search bible

> map bsearch ["Moses", "Goethe"]

Better:

search text = let ht = hash_table text
               in \s -> table_search ht (hash s,s)

Strong hint for compiler
Not everything that is good for cbv is good for lazy evaluation

Problem: lazy evaluation may leave many expressions unevaluated until the end, which requires more space

Space is time because it requires garbage collection — not counted by number of reductions!
14. Case Study: Parsing
See one of

- blackboard
- source files on the web page
- Chapter 8 of Hutton’s *Programming in Haskell*
- Section 17.5 in Thompson’s Haskell book (3rd edition)