02157 Functional Programming

Lecture 3: Lists

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Overview

- Generation of lists
- Useful functions on lists
- Typical recursions on lists
- Programming as a modelling activity
  – Cash register
  – Map coloring

Range expressions (1)

A simple range expression $[b\ ..\ e]$, where $e \geq b$, generates the list:

$$[b; b+1; b+2; \ldots; b+n]$$

where n is chosen such that $b+n \leq e < b+n+1$.

Example

```
[ -3 .. 5 ];;
val it : int list = [-3; -2; -1; 0; 1; 2; 3; 4; 5]
```

```
[2.4 .. 3.0 ** 1.7];;
val it : float list = [2.4; 3.4; 4.4; 5.4; 6.4]
```

Note that `3.0 ** 1.7 = 6.47300784`.

The range expression generates the empty list when $e < b$:

```
[7 .. 4];;
val it : int list = []
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Range expressions (2)

The range expression $[b \mathrel{..} s \mathrel{..} e]$ generates either an ascending or a descending list:

$$[b \mathrel{..} s \mathrel{..} e] \;=\; [b; b+s; b+2s; \ldots; b+ns]$$

$$\text{where} \qquad \begin{cases} b+ns \le e < b+(n+1)s & \text{if } s>0 \\ b+ns \ge e > b+(n+1)s & \text{if } s<0 \end{cases}$$

depending on the sign of s.

Examples:

```
[6 .. -1 .. 2];;
val it : int list = [6; 5; 4; 3; 2]
```

and the float representation of $0, \pi/2, \pi, \frac{3}{2}\pi, 2\pi$ is generated by:

```
[0.0 .. System.Math.PI/2.0 .. 2.0*System.Math.PI];;
val it : float list =
  [0.0; 1.570796327; 3.141592654; 4.71238898; 6.283185307]
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```

Simple recursion on lists

We consider now three simple functions:

- append
- reverse
- isMember

whose declarations follow the structure of lists

```
let rec f ... xs ... =
    | []     -> v
    | x::xs -> .... f xs ...
```

using just two clauses.

Append

The infix operator @ (called ‘append’) joins two lists:

$$[x_1;x_2;\ldots;x_m] \;@\; [y_1;y_2;\ldots;y_n] \\ = [x_1;x_2;\ldots;x_m;y_1;y_2;\ldots;y_n]$$

Properties

$$\begin{aligned} [\,] \,@\, ys &= ys \\ [x_1;x_2;\ldots;x_m] \,@\, ys &= x_1::([x_2;\ldots;x_m] \,@\, ys) \end{aligned}$$

Declaration

```
let rec (@) xs ys =
  match xs with
  | []      -> ys
  | x::xs’ -> x::(xs’ @ ys);;
val (@) : ’a list -> ’a list -> ’a list
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Append: evaluation

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Evaluation

	`[1,2] @ [3,4]`	
$\rightsquigarrow$	`1::([2] @ [3,4])`	$(x \mapsto 1,\ xs' \mapsto [2],\ ys \mapsto [3,4])$
$\rightsquigarrow$	`1::(2::([] @ [3,4]))`	$(x \mapsto 2,\ xs' \mapsto [\,],\ ys \mapsto [3,4])$
$\rightsquigarrow$	`1::(2::[3,4])`	$(ys \mapsto [3,4])$
$\rightsquigarrow$	`1::[2,3,4]`	
$\rightsquigarrow$	`[1;2;3;4]`	

- Execution time is linear in the size of the first list

Append: evaluation

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  match xs with
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Evaluation

```
     [1,2] @ [3,4]
  ⇝  1::([2] @ [3,4])          (x ↦ 1, xs′ ↦ [2], ys ↦ [3,4])
  ⇝  1::(2::([] @ [3,4]))      (x ↦ 2, xs′ ↦ [], ys ↦ [3,4])
  ⇝  1::(2::[3,4])             (ys ↦ [3,4])
  ⇝  1::[2,3,4]
  ⇝  [1;2;3;4]
```

- Execution time is linear in the size of the first list

Append: polymorphic type

The answer from the system is:

```
> val (@) : 'a list -> 'a list -> 'a list
```

- `'a` is a *type variable*
- The type of `@` is *polymorphic* — it has many forms

`'a = int`: Appending integer lists

```
[1;2] @ [3;4];;
val it : int list = [1;2;3;4]
```

`'a = int list`: Appending lists of integer list

```
[[1];[2;3]] @ [[4]];;
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@ is a built-in function

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@ is a built-in function

Reverse $\texttt{rev}\,[x_1;x_2;\ldots;x_n] = [x_n;\ldots;x_2;x_1]$

```
let rec naive_rev = function
 | []    -> []
 | x::xs -> naive_rev xs @ [x];;
val naive_rev : 'a list -> 'a list
```

An evaluation:

```
    naive_rev[1;2;3]
⇝  naive_rev[2;3] @ [1]
⇝  (naive_rev[3] @ [2]) @ [1]
⇝  ((naive_rev[] @ [3]) @ [2]) @ [1]
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```

Takes $O(n^2)$ time — Built-in version (`List.rev`) is efficient $O(n)$

We consider efficiency later.

Reverse $\texttt{rev}\ [x_1; x_2; \ldots; x_n] = [x_n; \ldots; x_2; x_1]$

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$$
\begin{aligned}
& \texttt{isMember}\ x\ [y_1;y_2;\ldots;y_n] \\
= \;& (x = y_1) \lor (x = y_2) \lor \cdots \lor (x = y_n) \\
= \;& (x = y_1) \lor (\texttt{member}\ x\ [y_2,\ldots,y_n])
\end{aligned}
$$

Declaration

```
let rec isMember x = function
| []     -> false
| y::ys -> x=y || isMember x ys;;
val isMember : 'a -> 'a list -> bool when  'a : equality
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- `'a` is an equality type variable no function types
- `isMember (1,true) [(2,true); (1,false)]` ⇝ false
- `isMember [1;2;3]  [[1]; []; [1;2;3]]` ⇝ true

Membership — equality types

$$\begin{aligned} & \texttt{isMember}\, x\ [y_1;y_2;\ldots;y_n] \\ = \quad & (x = y_1) \lor (x = y_2) \lor \cdots \lor (x = y_n) \\ = \quad & (x = y_1) \lor (\texttt{member}\, x\ [y_2,\ldots,y_n]) \end{aligned}$$

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Match on results of recursive call

We consider declarations on the form:

```
let rec f ... xs ... =
    ....
    let pat(ȳ) = f xs
    e(ȳ)
```

Recall unzip and split from last week.

Example: sumProd

$$\texttt{sumProd}\,[x_0;x_1;\ldots;x_{n-1}] = (\,x_0 + x_1 + \ldots + x_{n-1}\,,\; x_0 * x_1 * \ldots * x_{n-1}\,)$$

The declaration is based on the recursion formula:

$$\texttt{sumProd}\,[x_0;x_1;\ldots;x_{n-1}] = (x_0 + \texttt{rSum}, x_0 * \texttt{rProd})$$

where $(\texttt{rSum},\texttt{rProd}) = \texttt{sumProd}\,[x_1;\ldots;x_{n-1}]$

This gives the declaration

```
let rec sumProd = function
    | []    -> (0,1)
    | x::rest ->
            let (rSum,rProd) = sumProd rest
            (x+rSum,x*rProd);;
val sumProd : int list -> int * int

sumProd [2;5];;
val it : int * int = (7, 10)
```

Example: `sumProd`

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Example: `split`

Declare an F# function `split` such that:

$$\texttt{split}\ [x_0;x_1;x_2;x_3;\ldots;x_{n-1}] = ([x_0;x_2;\ldots],[x_1;x_3;\ldots])$$

The declaration is

```
let rec split = function
    | []         -> ([],[])
    | [x]        -> ([x],[])
    | x::y::xs -> let (xs1,xs2) = split xs
                  in (x::xs1,y::xs2);;
```

Notice

- a convenient division into three cases, and
- the recursion formula

$$\texttt{split}\ [x_0;x_1;x_2;\ldots;x_{n-1}] = (x_0 :: \texttt{xs1}, x_1 :: \texttt{xs2})$$
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The problem

An electronic cash register contains a data register associating the name of the article and its price to each valid article code. A purchase comprises a sequence of items, where each item describes the purchase of one or several pieces of a specific article.

The task is to construct a program which makes a bill of a purchase. For each item the bill must contain the name of the article, the number of pieces, and the total price, and the bill must also contain the grand total of the entire purchase.

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Goal and approach

Goal: the main concepts of the problem formulation are traceable in the program.

Approach: to name the important concepts of the problem and associate types with the names.

- This model should facilitate discussions about whether it fits the problem formulation.

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Aim: A succinct, elegant program reflecting the model.

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An electronic cash register contains a data register associating the name of the article and its price to each valid article code. A purchase comprises a sequence of items, where each item describes the purchase of one or several pieces of a specific article.

The task is to construct a program which makes a bill of a purchase. For each item the bill must contain the name of the article, the number of pieces, and the total price, and the bill must also contain the grand total of the entire purchase.

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A Functional Model

- Name key concepts and give them a type

A signature for the cash register:

```
type articleCode = string
type articleName = string
type price       = int
type register    = (articleCode * (articleName*price)) list
type noPieces    = int
type item        = noPieces * articleCode
type purchase    = item list
type info        = noPieces * articleName * price
type infoseq     = info list
type bill        = infoseq * price

makeBill: register -> purchase -> bill
```

Is the model adequate?

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Example

The following declaration names a register:

```
let reg = [("a1",("cheese",25));
           ("a2",("herring",4));
           ("a3",("soft drink",5)) ];;
```

The following declaration names a purchase:

```
let pur = [(3,"a2"); (1,"a1")];;
```

A bill is computed as follows:

```
makeBill reg pur;;
val it : (int * string * int) list * int =
  ([(3, "herring", 12); (1, "cheese", 25)], 37)
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Functional decomposition (1)

Type: findArticle: articleCode → register → articleName * price

```
let rec findArticle ac = function
    | (ac’,adesc)::_ when ac=ac’ -> adesc
    | _::reg                     -> findArticle ac reg
    | _                          ->
          failwith(ac + " is an unknown article code");;
val findArticle : string -> (string * ’a) list -> ’a
```

Note that the specified type is an instance of the inferred type.

An article description is found as follows:

```
findArticle "a2" reg;;
val it : string * int = ("herring", 4)

findArticle "a5" reg;;
System.Exception: a5 is an unknown article code
   at FSI_0016.findArticle[a] ...
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Note: failwith is a built-in function that raises an exception

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Functional decomposition (2)

Type: makeBill: register → purchase → bill

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let rec makeBill reg = function
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    | (np,ac)::pur ->
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          let tprice         = np*aprice
          let (billtl,sumtl) = makeBill reg pur
          ((np,aname,tprice)::billtl, tprice+sumtl);;
```

The specified type is an instance of the inferred type:

```
val makeBill :
    (string * ('a * int)) list -> (int * string) list
                -> (int * 'a * int) list * int
```

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makeBill reg pur;;
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Patterns with guards: Three versions of `findArticle`

An if-then-else expression in

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- Easy to check whether it fits the problem.
- Conscious choice of variables (on the basis of the model) increases readability of the program.
- Standard recursions over lists solve the problem.

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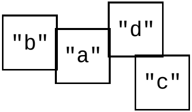
Example: Map Coloring.

A map should be colored so that neighbouring countries get different colors



The types for country and map are “straightforward”:

- `type country = string`

  Symbols: c, c1, c2, c′; Examples: "a", "b", . . .

- `type map=(country*country) list`

  Symbols: m; Example: val exMap = [("a","b"); ("c","d"); ("d","a")]

How many ways could above map be colored?

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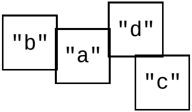

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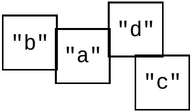

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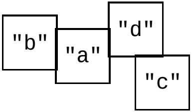

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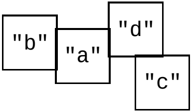

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Abstract models for color and coloring

- `type color = country list`

  Symbols: col; Example: ["c"; "a"]

- `type coloring = color list`

  Symbols: cols; Example: [["c"; "a"]; ["b"; "d"]]

Be conscious about symbols and examples

```
colMap:  map -> coloring
```

Meta symbol: Type		Definition	Sample value
c:	country	string	"a"
m:	map	(country*country) list	[("a","b"),("c","d"),("d","a")]
col:	color	country list	["a","c"]
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Figure: A Data model for map coloring problem

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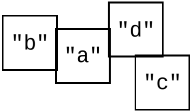
Algorithmic idea



Insert repeatedly countries in a coloring.

	country	old coloring	new coloring
1.	"a"	[]	[["a"]]
2.	"b"	[["a"]]	[["a"] ; ["b"]]
3.	"c"	[["a"] ; ["b"]]	[["a";"c"] ; ["b"]]
4.	"d"	[["a";"c"] ; ["b"]]	[["a";"c"] ; ["b";"d"]]

Figure: Algorithmic idea

Functional decomposition (I)

To make things easy

Are two countries neighbours?

areNb: map → country → country → bool

```
let areNb m c1 c2 = isMember (c1,c2) m || isMember (c2,c1) m;;
```

Can a color be extended?

canBeExtBy: map → color → country → bool

```
let rec canBeExtBy m col c =
  match  col with
  | []        -> true
  | c'::col' -> not (areNb m c' c) && canBeExtBy m col' c;;

canBeExtBy exMap ["c"] "a";;
val it : bool = true

canBeExtBy exMap ["a"; "c"] "b";;
val it : bool = false
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Combining functions make things easy

Extend a coloring by a country:

extColoring: map → coloring → country → coloring

```
Examples:
  extColoring exMap [] "a"        =  [["a"]]
  extColoring exMap [["b"]] "a"  =  [["b"] ; ["a"]]
  extColoring exMap [["c"]] "a"  =  [["a"; "c"]]
```

```
let rec extColoring m cols c =
    match cols with
    | []          -> [[c]]
    | col::cols’ -> if canBeExtBy m col c
                     then (c::col)::cols’
                     else col::extColoring m cols’ c;;
```

Function types, consistent use of symbols, and examples make program easy to comprehend

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Function types, consistent use of symbols, and examples make program easy to comprehend

Functional decomposition (II)

To color a neighbour relation:

- Get a list of countries from the neighbour relation.
- Color these countries

Get a list of countries without duplicates:

```
let addElem x ys = if isMember x ys then ys else x::ys;;

let rec countries = function
    | []           -> []
    | (c1,c2)::m -> addElem c1 (addElem c2 (countries m));;
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Color a country list:

```
let rec colCntrs m = function
    | []    -> []
    | c::cs -> extColoring m (colCntrs m cs) c;;
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    | c::cs -> extColoring m (colCntrs m cs) c;;
```

Functional composition (III)

The problem can now be solved by
combining well-understood pieces

Create a coloring from a neighbour relation:

colMap: map $\rightarrow$ coloring

```
let colMap m = colCntrs m (countries m);;

colMap exMap;;
val it : string list list = [["c"; "a"]; ["b"; "d"]]
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