CMSC 330: Organization of Programming Languages

Functional Programming with OCaml

Background

- ML (Meta Language)
  - Univ. of Edinburgh, 1973
  - Part of a theorem proving system LCF
    - The Logic of Computable Functions
- Standard ML
  - Exemplar: SML/NJ (Standard ML of New Jersey)
    - Bell Labs and Princeton, 1990; later Yale, AT&T, U. Chicago
- OCaml (Objective CAML)
  - INRIA, 1996
    - French Nat'l Institute for Research in Computer Science
  - O is for "objective", meaning objects, which we'll ignore

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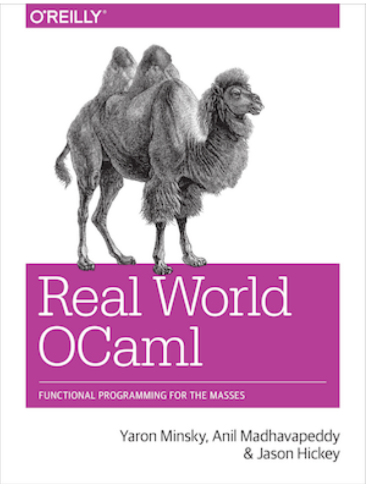
Dialects of ML

- MLs all have the same core ideas
  - But small and annoying syntactic differences
  - You should not buy a book with (just) ML in the title
    - Because it probably won't cover OCaml

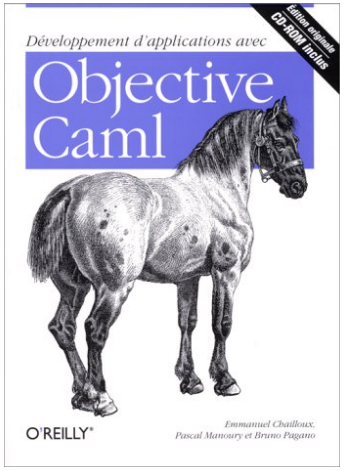
- Haskell is a functional language inspired by ML
  - Employs lazy, not eager, evaluation
  - More fancy types
  - But key ideas are the same
    - Learning OCaml a very useful step to learning Haskell

More Information on OCaml



- Book designed to introduce and advance understanding of Ocaml
  - Authors use OCaml in the real world
  - Introduces new libraries, tools
- Free HTML on-line
  - realworldocaml.org

More Information on OCaml language



- Translation available on the class webpage
  - *Developing Applications with Objective Caml*
- Webpage also has link to another book
  - *Introduction to the Objective Caml Programming Language*

Features of ML

- Higher-order functions
  - Functions can be parameters and return values
- "Mostly functional"
- Data types and pattern matching
  - Convenient for certain kinds of data structures
- Type inference
  - No need to write types in the source language
    - But the language is statically typed
  - Supports parametric polymorphism
    - *Generics* in Java, *templates* in C++
- Exceptions
- Garbage collection

Functional Languages

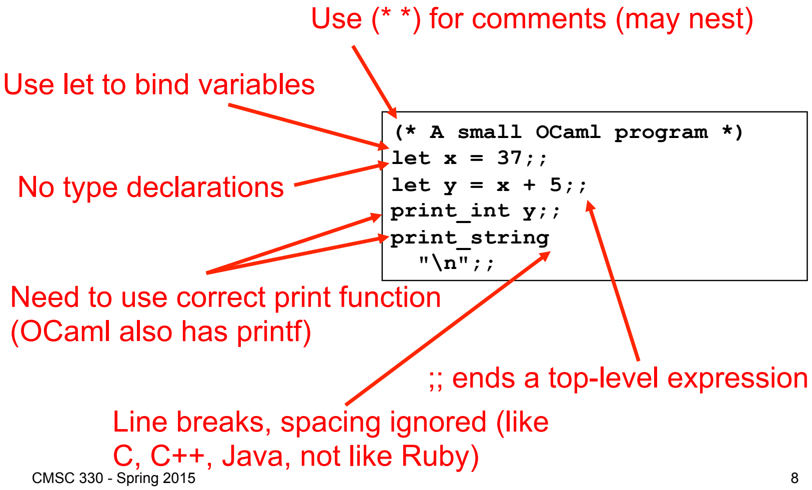
- In a pure functional language, every program is just an expression
  - no "effects" like (re)writing to variables

```
let add1 x = x + 1;;

let rec add (x,y) = if x=0 then y else add(x-1, add1(y));;

add(2,3) = add(1,add1(3)) = add(0,add1(add1(3)))
         = add1(add1(3)) = add1(3+1) = 3+1+1
         = 5
```

OCaml has this basic behavior, but has additional features to ease the programming process.

- Less emphasis on data storage
- More emphasis on function evaluation

A Small OCaml Program - Things to Notice



```
(* A small OCaml program *)
let x = 37;;
let y = x + 5;;
print_int y;;
print_string
   "\n";;
```

Use (* *) for comments (may nest)

Use let to bind variables

No type declarations

Need to use correct print function (OCaml also has printf)

;; ends a top-level expression

Line breaks, spacing ignored (like C, C++, Java, not like Ruby)

Run, OCaml, Run

- OCaml programs can be compiled using ocamlc
  - Produces .cmo ("compiled object") and .cmi ("compiled interface") files
    - We'll talk about interface files later
  - By default, also links to produce executable a.out
    - Use -o to set output file name
    - Use -c to compile only to .cmo/.cmi and not to link
    - You'll be given a Makefile if you need to compile your files

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Run, OCaml, Run (cont.)

- Compiling and running the previous small program:

ocaml1.ml:

```
(* A small OCaml program *)
let x = 37;;
let y = x + 5;;
print_int y;;
print_string "\n";;
```

```
% ocamlc ocaml1.ml
% ./a.out
42
%
```

Run, OCaml, Run (cont.)

Expressions can also be typed and evaluated at the top-level:

```
# 3 + 4;;
- : int = 7

# let x = 37;;
val x : int = 37

# x;;
- : int = 37

# let y = 5;;
val y : int = 5

# let z = 5 + x;;
val z : int = 42

# print_int z;;
42- : unit = ()

# print_string "Colorless green ideas sleep furiously";;
Colorless green ideas sleep furiously- : unit = ()

# print_int  "Colorless green ideas sleep furiously";;
This expression has type string but is here used with type int
```

gives type and value of each expr

"-" = "the expression you just typed"

unit = "no interesting value" (like void)

Run, OCaml, Run (cont.)

- Files can be loaded at the top-level

```
% ocaml
        Objective Caml version 4.00.1

# #use "ocaml1.ml";;
val x : int = 37
val y : int = 42
42- : unit = ()

- : unit = ()
# x;;
- : int = 37
```

ocaml1.ml:

```
(* A small OCaml program *)
let x = 37;;
let y = x + 5;;
print_int y;;
print_string "\n";;
```

#use loads in a file one line at a time

A Note on ;;

- ;; ends an expression in the top-level of OCaml
  - Use it to say: “Give me the value of this expression”
  - Not used in the body of a function
  - Not needed after each function definition
    - Though for now it won’t hurt if used there
- There is also a single semi-colon ; in OCaml
  - But we won’t need it for now
  - It’s only useful when programming imperatively, i.e., with side effects
    - Which we won’t do for a while

Basic Types in OCaml

- Read *e* : *t* has “expression *e* has type *t*”

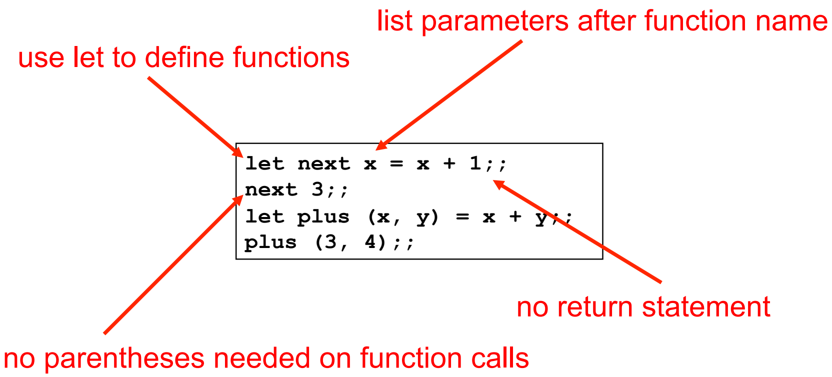
42 : int	true : bool
"hello" : string	'c' : char
3.14 : float	() : unit (* don’t care value *)

- OCaml has static types to help you avoid errors
  - Note: Sometimes the messages are a bit confusing

```
# 1 + true;;
This expression has type bool but is here used with
  type int
```

  - Watch for the underline as a hint to what went wrong
    - But not always reliable

Defining Functions



list parameters after function name

use let to define functions

```
let next x = x + 1;;
next 3;;
let plus (x, y) = x + y;;
plus (3, 4);;
```

no return statement

no parentheses needed on function calls

Local Let Bindings

- You can use let inside of functions for local vars

```
let area r =
  let pi = 3.14 in
  pi *. r *. r
```

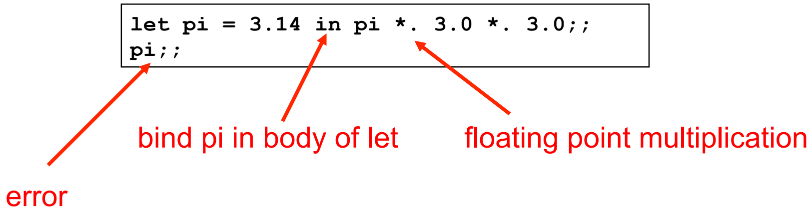
  - And you can use as many lets as you want

```
let area d =
  let pi = 3.14 in
  let r = d /. 2.0 in
  pi *. r *. r
```

  - Notice the use of in --- this is a local let

Semantics of Local Let

- `let x = e1 in e2` means
  - Evaluate `e1`
  - Evaluate `e2`, with `x` bound to result of evaluating `e1`
  - `x` is *not* visible outside of `e2`



```
let pi = 3.14 in pi *. 3.0 *. 3.0;;
pi;;
```

More on Local Lets

- Compare to similar usage in Java/C

```
let pi = 3.14 in
  pi *. 3.0 *. 3.0;;
pi;; (* unbound! *)
```

```
{
  float pi = 3.14;

  pi * 3.0 * 3.0;
}
pi; /* unbound! */
```

- In the top-level, omitting in means “from now on”:

  # let pi = 3.14;;

  (* pi is now bound in the rest of the top-level scope *)

Nested Local Lets

- Uses of let can be nested

```
let res =
  let area =
    let pi = 3.14 in
    let r = 3.0 in
    pi *. r *. r in
  area /. 2.0;;
```

```
float res;
{ float area;
  { float pi = 3.14
    float r = 3.0;
    area = pi * r * r;
  }
  res = area / 2.0;
}
```

Examples – Let (Local and Toplevel)

- x;;
  - (* Unbound value x *)
- let x = 1 in x + 1;;
  - (* 2 *)
- let x = x in x + 1;;
  - (* Unbound value x *)

Examples – Let (Local and Toplevel)

- let x = 1 in(x + 1 + x) ;;
  - (* 3 *)
- (let x = 1 in x + 1) ;; x;;
  - (* Unbound value x *)
- let x = 4 in(let x = x + 1 in x);;
  - (* 5 *)

Function Types

- In OCaml, `->` is the function type constructor
  - The type `t1 -> t2` is a function with argument or *domain* type `t1` and return or *range* type `t2`
- Examples
  - `let next x = x + 1 (* type int -> int *)`
  - `let fn x = (float_of_int x) *. 3.14`
    `(* type int -> float *)`
  - `print_string        (* type string -> unit *)`
- Type a function name at top level to get its type

Type Annotations

- The syntax `(e : t)` asserts that “`e` has type `t`”
  - This can be added anywhere you like

```
let (x : int) = 3
let z = (x : int) + 5
```

- Use to give functions parameter and return types

```
let fn (x:int):float =
       (float_of_int x) *. 3.14
```

  - Note special position for return type
  - Thus `let g x:int =` ... means `g` returns `int`
- Very useful for debugging, especially for more complicated types

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Lists in OCaml

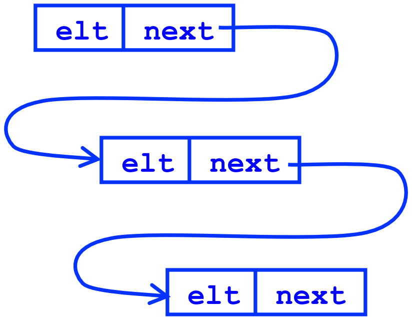
- The basic data structure in OCaml is the list
  - Lists are written as [*e1*; *e2*; ...; *en*]

    \# [1;2;3]
    \- : int list = [1;2;3]
  - Notice int list – lists must be *homogeneous*
  - The empty list is [ ]

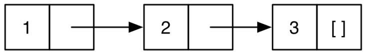
    \# [ ]
    \- : 'a list
  - The 'a means “a list containing anything”
    - We’ll see more about this later
  - Warning: Don’t use a comma instead of a semicolon
    - Means something different (we’ll see in a bit)

Consider a Linked List in C

```
struct list {
  int elt;
  struct list *next;
};
…
struct list *l;
…
i = 0;
while (l != NULL) {
  i++;
  l = l->next;
}
```

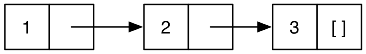


Lists in Ocaml are Linked



- [1;2;3] is represented above
  - A nonempty list is a pair (element, rest of list)
  - The element is the head of the list
  - The pointer is the tail or *rest* of the list
    - ...which is itself a list!
- Thus in math (i.e., inductively) a list is either
  - The empty list [ ]
  - Or a pair consisting of an element and a list
    - This recursive structure will come in handy shortly

Lists Are Linked (cont.)



- :: prepends an element to a list
  - h::t is the list with h as the element at the beginning and t as the “rest”
  - :: is called a constructor, because it builds a list
  - Although it’s not emphasized, :: does allocate memory
- Examples

3::[]	(* The list [3] *)
2::(3::[])	(* The list [2; 3] *)
1::(2::(3::[]))	(* The list [1; 2; 3] *)

More Examples

```
# let y = [1;2;3] ;;
val y : int list = [1; 2; 3]
# let x = 4::y ;;
val x : int list = [4; 1; 2; 3]
# let z = 5::y ;;
val z : int list = [5; 1; 2; 3]
```

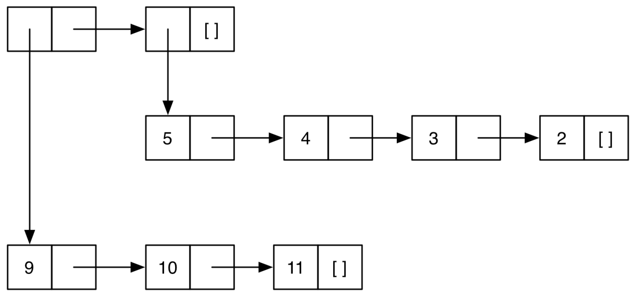
- *not* modifying existing lists, just creating new lists

```
# let w = [1;2]::y ;;
This expression has type int list but is here
  used with type int list list
```

- The left argument of :: is an element
- Can you construct a list y such that [1;2]::y makes sense?

Lists of Lists

- Lists can be nested arbitrarily
  - Example: `[ [9; 10; 11]; [5; 4; 3; 2] ]`
    - (Type `int list list`)



Digression: Shadowing

- If you bind the same variable twice, the most recent is in play
  - Looks like variable assignment, but it is not

- let x = [1; 2];;
- let y = 3::x;;
- let x = [3];; (* shadows x *)
- y;;
  - (* [3; 1; 2] *)
- x;;
  - (* [3] *)

Practice

- What is the type of
  - [1;2;3] `int list`
  - [[[ ]; [ ]; [1.3;2.4]]] `float list list list`
  - let func x = x::(0::[ ]) `int -> int list`

Pattern Matching

- To pull lists apart, use the match construct

  `match e with p1 -> e1 | … | pn -> en`
- ***p1***...***pn*** are *patterns* made up of [ ], ::, constants, and *pattern variables*
- **`match`** finds the first ***pk*** that matches the shape of ***e***
  - Then ***ek*** is evaluated and returned
  - During evaluation of ***pk***, pattern variables in pk are bound to the corresponding parts of ***e***
- An underscore _ is a wildcard pattern
  - Matches anything
  - Does not add any bindings
  - Useful when you want to know something matches, but don't care what its value is

Pattern Matching Example

- Match syntax
  - `match e with p1 -> e1 | ... | pn -> en`
- Code 1

  -
    ```
    let is_empty l = match l with
             [] -> true
           | (h::t) -> false
    ```
- Outputs
  - `is_empty []    (* evaluates to true  *)`
  - `is_empty [1]   (* evaluates to false *)`
  - `is_empty [1;2] (* evaluates to false *)`

Pattern Matching Example (cont.)

- Code 2
  - `let hd l = match l with (h::t) -> h`
- Outputs
  - `hd [1;2;3] (* evaluates to 1 *)`
  - `hd [1;2]   (* evaluates to 1 *)`
  - `hd [1]     (* evaluates to 1 *)`
  - `hd []      (* Exception: Match failure *)`

Pattern Matching Example (cont.)

- Code 3
  - `let tl l = match l with (h::t) -> t`
- Outputs
  - `tl [1;2;3] (* evaluates to [2;3] *)`
  - `tl [1;2]   (* evaluates to [2] *)`
  - `tl [1]     (* evaluates to [ ] *)`
  - `tl []      (* Exception: Match failure *)`

Pattern Matching – Wildcards

- An underscore _ is a wildcard pattern
  - Matches anything
  - Doesn't add any bindings
  - Useful when you want to know something matches
    - But don't care what its value is
- In previous examples
  - Many values of `h` or `t` ignored
  - Can replace with wildcard _
  - Code behavior is identical

Pattern Matching – Wildcards (cont.)

- Code using _
  - `let is_empty l = match l with`
    `[] -> true      | (_::_) -> false`
  - `let hd l = match l with (h::_) -> h`
  - `let tl l = match l with (_::t) -> t`
- Outputs
  - `is_empty[1](* evaluates to false *)`
  - `is_empty[ ](* evaluates to true  *)`
  - `hd [1;2;3] (* evaluates to 1     *)`
  - `tl [1;2;3] (* evaluates to [2;3] *)`
  - `hd [1]     (* evaluates to 1     *)`
  - `tl [1]     (* evaluates to [ ]   *)`

Missing Cases

- Exceptions for inputs that don't match any pattern
  - OCaml will warn you about non-exhaustive matches
- Example:

```
# let hd l = match l with (h::_) -> h;;
Warning: this pattern-matching is not exhaustive.
Here is an example of a value that is not matched:
[]

# hd [];;
Exception: Match_failure ("", 1, 11).
```

More Examples

- `let f l =`
  `match l with (h1::(h2::_)) -> h1 + h2`
  - `f [1;2;3]`
  - `(* evaluates to 3 *)`
- `let g l =`
  `match l with [h1; h2] -> h1 + h2`
  - `g [1; 2]`
  - `(* evaluates to 3 *)`
  - `g [1; 2; 3]`
  - `(* error!  no pattern matches *)`

Pattern Matching – An Abbreviation

- **let f *p* = *e***, where *p* is a pattern
  - is shorthand for **let f x = match x with *p* -> *e***
- Examples
  - `let hd (h::_) = h`
  - `let tl (_::t) = t`
  - `let f (x::y::_) = x + y`
  - `let g [x; y] = x + y`
- Useful if there's only one acceptable input

Pattern Matching Lists of Lists

- You can do pattern matching on these as well

- Examples
  - `let addFirsts ((x::_) :: (y::_) :: _) = x + y`
    - `addFirsts [ [1; 2; 3]; [4; 5]; [7; 8; 9] ] = 5`

  - `let addFirstSecond ((x::_)::(_::y::_)::_) = x + y`
    - `addFirstSecond [ [1; 2; 3]; [4; 5]; [7; 8; 9] ] = 6`

- Note: You probably won't do this much or at all
  - You'll mostly write recursive functions over lists
  - We'll see that soon

OCaml Functions Take One Argument

- Recall this example

```
let plus (x, y) = x + y;;
plus (3, 4);;
```

  - It looks like you're passing in two arguments
- Actually, you're passing in a tuple instead

```
let plus t = match t with
    (x, y) -> x + y;;
plus (3, 4);;
```

  - And using pattern matching to extract its contents

Tuples

- Constructed using (*e1*, ..., *en*)
- Deconstructed using pattern matching
  - **Patterns involve parens and commas, e.g., (p1,p2, …)**
- Tuples are like C structs
  - But without field labels
  - Allocated on the heap
- Tuples can be heterogenous
  - Unlike lists, which must be homogenous
  - `(1, ["string1"; "string2"])` is a valid tuple

Examples With Tuples

- `let plusThree (x, y, z) = x + y + z`
  `let addOne (x, y, z) = (x+1, y+1, z+1)`
  - `plusThree (addOne (3, 4, 5))   (* returns 15 *)`

- `let sum ((a, b), c) = (a+c, b+c)`
  - `sum ((1, 2), 3) = (4, 5)`

- `let plusFirstTwo (x::y::_, a) = (x + a, y + a)`
  - `plusFirstTwo ([1; 2; 3], 4) = (5, 6)`

- `let tls (_::xs, _::ys) = (xs, ys)`
  - `tls ([1; 2; 3], [4; 5; 6; 7]) = ([2; 3], [5; 6; 7])`

- Remember, semicolon for lists, comma for tuples
  - `[1, 2] = [(1, 2)] = a list of size one`
  - `(1; 2) = Warning: This expression should have type unit`

Another Example

- `let f l = match l with x::(_::y) -> (x,y)`
- What is `f [1;2;3;4]`?

  Possibilities:
  `([1],[3])`
  `(1,3)`
  `(1,[3])`
  `(1,4)`
  `(1,[3;4])`

List And Tuple Types

- Tuple types use `*` to separate components

- Examples
  - `(1, 2) :`
  - `(1, "string", 3.5) :`
  - `(1, ["a"; "b"], 'c') :`
  - `[(1,2)] :`
  - `[(1, 2); (3, 4)] :`
  - `[(1,2); (1,2,3)] :`

List And Tuple Types

- Tuple types use `*` to separate components

- Examples
  - `(1, 2) : int * int`
  - `(1, "string", 3.5) : int * string * float`
  - `(1, ["a"; "b"], 'c') : int * string list * char`
  - `[(1,2)] : (int * int) list`
  - `[(1, 2); (3, 4)] : (int * int) list`
  - `[(1,2); (1,2,3)] :` *`error`*
    - Because the first list element has type int * int, but the second has type int * int * int – list elements must all be of the same type

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Polymorphic Types

- Some functions we saw require specific list types
  - `let plusFirstTwo (x::y::_, a) = (x + a, y + a)`
  - `plusFirstTwo : int list * int -> (int * int)`
- But other functions work for any list
  - `let hd (h::_) = h`
  - `hd [1; 2; 3]        (* returns 1 *)`
  - `hd ["a"; "b"; "c"] (* returns "a" *)`
- OCaml gives such functions polymorphic types
  - `hd : 'a list -> 'a`
  - this says the function takes a list of any element type `'a`, and returns something of that type

Examples Of Polymorphic Types

- `let tl (_::t) = t`
  - `tl : 'a list -> 'a list`
- `let swap (x, y) = (y, x)`
  - `swap : 'a * 'b -> 'b * 'a`
- `let tls (_::xs, _::ys) = (xs, ys)`
  - `tls : 'a list * 'b list -> 'a list * 'b list`
- `let eq (x,y) = x = y`
  - `eq : 'a * ’a -> bool`

Tuples Are A Fixed Size

- This OCaml definition
  - `# let foo x = match x with`

```
  (a, b) -> a + b
| (a, b, c) -> a + b + c;;
```

- Would yield this error message
  - This pattern matches values of type 'a * 'b * 'c but is here used to match values of type 'd * 'e
- Tuples of different size have different types
  - Thus never more than one match case with tuples

Conditionals

- Use if...then...else like C/Java/Ruby
  - But no parentheses, no elsif, and no end

```
if grade >= 90 then
  print_string "You got an A"
else if grade >= 80 then
  print_string "You got a B"
else if grade >= 70 then
  print_string "You got a C"
else
  print_string "You’re not doing so well"
```

Conditionals (cont.)

- In OCaml, conditionals return a result
  - The value of whichever branch is true/false
  - Like ? : in C, C++, and Java

```
# if 7 > 42 then "hello" else “goodbye";;
- : string = "goodbye"
# let x = if true then 3 else 4;;
x : int = 3
# if false then 3 else 3.0;;
This expression has type float but is
 here used with type int
```

The Factorial Function

- Using conditionals & functions
  - Can you write fact, the factorial function?

```
let rec fact n =
  if n = 0 then
     1
  else
     n * fact (n-1);;
```

- Notice no return statements
  - This is pretty much how it needs to be written

Let Rec

- The rec part means "define a recursive function"
- Let vs. let rec
  - let *x* = *e1* in *e2*   *x* in scope within *e2*
  - let rec *x* = *e1* in *e2*   *x* in scope within *e2* **and** *e1*
- Why use let rec?
  - If you used let instead of let rec to define fact

```
let fact n =
  if n = 0 then 1
  else n * fact (n-1);;
```

Fact is not bound here!

Let – More Examples

- let f n = 10;;
  let f n = if n = 0 then 1 else n * f (n – 1);;
  - f 0;; (* 1 *)
  - f 1;; (* 10 *)
- let f x = … f … in … f …
  - (* Unbound value f *)
- let rec f x = … f … in … f …
  - (* Bound value f *)

Recursion = Looping

- Recursion is essentially the only way to iterate
  - (The only way we're going to talk about)
- Another example

```
let rec print_up_to (n, m) =
  print_int n; print_string "\n";
  if n < m then print_up_to (n + 1, m)
```

Lists and Recursion

- Lists have a recursive structure
  - And so most functions over lists will be recursive

```
let rec length l = match l with
    [] -> 0
  | (_::t) -> 1 + (length t)
```

  - This is just like an inductive definition
    - *The length of the empty list is zero*
    - *The length of a nonempty list is 1 plus the length of the tail*
  - Type of length?

More Examples

- `sum l (* sum of elts in l *)`

```
let rec sum l = match l with
    [] -> 0
  | (x::xs) -> x + (sum xs)
```

- `negate l (* negate elements in list *)`

```
 let rec negate l = match l with
    [] -> []
  | (x::xs) -> (-x) :: (negate xs)
```

- `last l  (* last element of l *)`

```
let rec last l = match l with
    [x] -> x
  | (x::xs) -> last xs
```

More Examples (cont.)

```
(* return a list containing all the elements in the
  list l followed by all the elements in list m *)
```

- `append (l, m)`

```
let rec append (l, m) = match l with
    [] -> m
  | (x::xs) -> x::(append (xs, m))
```

- `rev l  (* reverse list; hint: use append *)`

```
let rec rev l = match l with
    [] -> []
  | (x::xs) -> append ((rev xs), [x])
```

- **rev** takes $O(n^2)$ time. Can you do better?

More Examples (cont)

- `flattenPairs l  (* ('a * 'a) list -> 'a list *)`

```
let rec flattenPairs l = match l with
  [] -> []
 | ((a, b)::t) -> a :: b :: (flattenPairs t)
```

- `take (n, l) (* return first n elts of l *)`

```
let rec take (n, l) =
  if n = 0 then []
  else match l with
      [] -> []
   | (x::xs) -> x :: (take (n-1, xs))
```

A Clever Version of Reverse

```
let rec rev_helper (l, a) = match l with
    [] -> a
  | (x::xs) -> rev_helper (xs, (x::a))
let rev l = rev_helper (l, [])
```

- Let’s give it a try

```
rev [1; 2; 3] →
rev_helper ([1;2;3], []) →
rev_helper ([2;3], [1]) →
rev_helper ([3], [2;1]) →
rev_helper ([], [3;2;1]) →
[3;2;1]
```

Tail recursion

- Whenever a function ends with a recursive call, it is called tail recursive
  - It’s “tail” is recursive
- Tail recursive functions can be implemented without requiring a stack frame for each call
  - No intermediate variables need to be saved, so the compiler overwrites them
- Typical pattern is to use an “accumulator” to build up the result, and return it in the base case

Tail recursion pattern (1 argument)

```
let func x =
  let rec helper (arg,acc) =
    if (base case) then acc
    else
      let arg’ = (argument to recursive call)
      let acc’ = (updated accumulator)
      helper (arg’,acc’) in in (* end of helper fun *)
  helper x (initial val of accumulator)
;;
```

Tail recursion pattern with fact

```
let fact x =
  let rec helper (arg,acc) =
    if arg = 0 then acc
    else
      let arg’ = arg – 1 in
      let acc’ = acc * arg in
      helper (arg’,acc’) in (* end of helper fun *)
  helper x 1
;;
```

Tail recursion pattern with rev

```
let rev x =
  let rec helper (arg,acc) =
    match arg with [] -> acc
    | h::t ->
      let arg’ = t in
      let acc’ = h::acc in
      helper (arg’,acc’) in (* end of helper fun *)
  helper x []
;;
```

Can generalize to more than one argument, and multiple cases for each recursive call

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Working With Lists

- Several of these examples have the same flavor
  - Walk through the list and do something to every element
  - Walk through the list and keep track of something

- Recall the following example code from Ruby:

```
a = [1,2,3,4,5]
b = a.collect { |x| -x }
```

  - Here we passed a code block into the collect method
  - Wouldn’t it be nice to do the same in OCaml?