Functional Programming in OCaml

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KAIST

Functional Programming?

- Programming = describing computation
- Programming language = language to describe computation
- How to describe computation?
  - Machine states and commands : imperative
  - Objects and methods : object-oriented
  - Values and functions : functional

Interacting with OCaml

- In a terminal, type `utop` to start the REFL (read-eval-print-loop)
- An expression with `;;` in the REFL tells you the resulting **value** and its **type**

```
$ utop
# 42;;
- : int = 42
# 1 + 1 (* this is a comment *);;
- : int = 2
```

- Use the OCaml compiler (`ocamlc`) to compile and execute programs

```
$ ocamlc -o hello hello.ml
$ ./hello
Hello, World!
```

Characteristics

- Statically-typed, strongly-typed language
  - Compile-time type checking and no type errors at run time (guaranteed)
  - Each value and expression has a type and no implicit type casting
- Garbage-collected language
  - The garbage collector automatically performs memory management
- Multi-paradigm language (but **some** are more preferred than **others**)
  - value / object, immutable / mutable, pure / side-effect

Values, Names, Expressions, and Definitions

Values

- OCaml is so called a “value-oriented” language
  - value: immutable, object: mutable
- The ultimate goal of OCaml programs: compute values
  - Programs **generate** new values using old values
  - **NOT changing** old objects to new object

Expressions

- The primary piece of OCaml
  - Imperative programs: built out of commands
  - Functional programs: built out of expressions
- The primary task of computation: to evaluate an expression to a value
- Example: true, `2+2`, `increment 21`, `x / 0`
- An expression evaluates to value, raises an exception, or never terminates

Arithmetic Expressions

- Arithmetic expressions evaluate to numbers
- OCaml has more or less all the usual arithmetic operators in other languages

```
# 1 + 2 - 3;;
- : int = 0
```

- Arithmetic operators on integers:

```
# 1 + 2     (* addition *)
# 1 - 2     (* subtraction *)
# 1 * 2     (* multiplication *)
# 1 / 2     (* division *)
# 1 mod 2   (* modulo *)
```

- Arithmetic operators on floating point numbers:

```
# 1.1 +. 2.1 (* addition *)
# 1.1 -. 2.1 (* subtraction *)
# 1.1 *. 2.1 (* multiplication *)
# 1.1 /. 2.1 (* division *)
```

Boolean Expressions

- Boolean expressions evaluate to boolean values
- OCaml has more or less all the usual boolean operators in other languages

```
# true;;
- : bool = true
# false;;
- : bool = false
# 1 + 1 > 2;;
- : bool = false
```

- Boolean operators

```
# x = y      (* equal *)
# x <> y     (* not equal *)
# x < y      (* less than *)
# x <= y     (* less than or equal *)
# x > y      (* larger than *)
# x >= y     (* larger than or equal *)
# x && y     (* logical and *)
# X || y     (* logical or *)
```

Character and String Expressions

- Character expressions evaluate to character values

```
# ‘a’;;
- : char = ‘a’
# ‘a’ = ‘a’;;
- : bool = true
```

- String expressions evaluate to string values (primitive values in OCaml)

```
# “hello”;;
- : string = “hello"

# “hello” = “hello”;;
- : bool = true

# “hello, “ ^ ”world!”;;
- : string = “hello, world!”
```

If Expressions

- If-then-else is an expression, not a statement as in imperative languages
- `if e1 then e2 else e3` evaluates to
  - e2 if e1 evaluates to true
  - e3 if e1 evaluates to false
  - e1 : bool, e2 : t, e3 : t, then the whole expression has type t
- Example:

```
# 4 + (if 1 > 2 then 1 else 2);;
- : int = 6
```

Definitions

- Definitions are not expressions (i.e., not evaluate to values)
- Definitions bind values to names

```
let x = 1 + 1
```

- An OCaml program is a sequence of definitions (no need for `main`)

```
let x = “Hello, World!”
let _ = print_endline x
```

Function Definitions

- Function definition

```
# let increment x = x + 1;;
val increment : int -> int = <fun>
# increment 0;;
- : int = 1
```

- Recursive function definition using `let rec`:

```
# let rec fact n =
    if n = 0 then 1 else n * fact (n - 1)
val fact : int -> int = <fun>
```

```
# let rec pow x y =
  if y = 0 then 1 else x * pow x (y - 1)
val pow : int -> int -> int = <fun>
```

Anonymous Function

- Not all values have to have names

```
# 42;;
- : int = 42
```

- Anonymous function value (so called lambda)

```
# fun x -> x + 1;;
- : int -> int = <fun>
```

- The followings are semantically equivalent

```
let inc x = x + 1
let inc = fun x -> x + 1
```

Function Application

- Application-style: e0 e1 e2 … en
  where e0 is a function and e1 through en are the arguments

```
square (inc 5)
```

- Pipeline-style: “values are sent through the pipeline from left to right”

```
5 |> inc |> square
```

Polymorphic Functions

- Functions that take many types of values
- Example: the identity function

```
# let id x = x;;
id : ‘a -> ‘a = <fun>
```

- ‘a, ‘b, … are type variables that stand for unknown type

Partial Application

- A function that is partially applied to a subset of the arguments

```
# let add x y = x + y
val add : int -> int -> int = <fun>

# let add5 = add 5
val add5 : int -> int = <fun>

# add5 2;;
- : int = 7
```

Higher-order Functions

- **Functions** that take other **functions** as arguments or return **functions**
  - “Functional”!
  - because functions are first-class values like integers

```
# let add x y = x + y
val add : int -> int -> int = <fun>

# let add5 = add 5
val add5 : int -> int = <fun>

# let add_high f x = (f (x + 1)) + 2;;
val add_high : (int -> int) -> int -> int = <fun>

# add_high add5 10;;
- : int = 18

# add_high (fun x -> x + 5) 10;;
- : int = 18
```

Let-in Expressions

- Expressions with local name binding with `let`

```
# let x = 42 in x + 1
- : int = 43
```

- Let bindings are in effect only in the block of code in which they occur

```
let x = 42 in
  (* y is not meaningful here *)
  x
  +
  (let y = "3110" in
    (* y is meaningful here *)
    int_of_string y)
```

Pattern Matching

- A control structure for elegant case analysis (`match` … `with` …)

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

```
let rec fact n =
  match n with
  | 0 -> 1
  | _ -> n * fact (n - 1)
```

```
let rec fibo n =
  if n = 0 then 1
  else if n = 1 then 1
  else fibo(n-1) + fibo(n-2)
```

```
let rec fibo n =
  match n with
  | 0 | 1 -> 1
  | _ -> fibo(n - 1) + fibo(n - 2)
```

Pattern Matching with Function

- Simplified definitions with `function`

```
let rec fact = function
  | 0 -> 1
  | n -> n * fact (n - 1)
```

```
let rec fibo = function
  | 0 | 1 -> 1
  | n -> fibo(n - 1) + fibo(n - 2)
```

Data Types and Pattern Matching

Lists

- A sequence of values all of which have the same type

```
# [1; 2; 3];;
- : int list = [1; 2; 3]
# [true; false; false];;
- : bool list = [true; false; false]
# [[1;2;3];[4;5]];;
- : int list list = [[1;2;3];[4;5]];;
```

- In principle, there are only two ways to build a list: nil ([]) and cons (::)

```
# [] (* nil means the empty list*) ;;
- : ‘a list
# 1::[2; 3] (* cons prepends an elem to a list *);;
- : int list [1; 2; 3]
# 1::2::3::[] (* conceptually the same as above *);;
- : int list [1; 2; 3]
```

Pattern Matching with Lists

- Use pattern matching when doing a case analysis for lists
  - Remember that there are only two cases: nil and cons (head and tail)

```
(* compute the sum of an int list *)
let rec sum lst =
  match lst with
  | [] -> 0
  | h::t -> h + sum t
```

```
(* compute the length of a list *)
let rec length lst =
  match lst with
  | [] -> 0
  (* don't give a name to the head *)
  | _::t -> 1 + length t
```

Tuples

- An ordered collection of (possibly different types of) values
- A kind of *product* type: a Cartesian product of multiple sets

```
# (1, 2, 10);;
- : int * int * int = (1, 2, 10)

# (true, “Hello”);;
- : bool * string = (true, "Hello")

# (true, “Hello”, (1, 2));;
- : bool * string * (int * int) = (true, “Hello”, (1, 2))
```

Pattern Matching with Tuples

- Examples:

```
(* OK *)
let thrd t =
  match t with
  | (x, y, z) -> z

(* good *)
let thrd t =
  let (x, y, z) = t in z

(* better *)
let thrd t =
  let (_, _, z) = t in z

(* best *)
let thrd (_, _, z) = z
```

```
let logical_and x y =
  match (x, y) with
  | (true, true) -> true
  | (_, _) -> false

let logical_or x y =
  match (x, y) with
  | (true, _)
  | (_, true) -> true
  | (_, _) -> false
```

Records

- A composite of other types of data, each of which named
  - elements of a tuple: identified by position
  - elements of a record: identified by name

```
(* a record type definition *)
type student = { name: string; sid: int }
```

- Record expressions evaluate to record value

```
# let me = { name = “Kihong”; sid = 2020 };;
val me : student = {name = "Kihong"; sid = 2020}
```

- The dot expression gets a field from a record

```
# me.sid;;
- : int = 2020
```

Pattern Matching with Records

```
(* OK *)
let get_sid m =
  match m with
  | { name=n; sid=s } -> s

(* good *)
let get_sid m =
  match m with
  | { name=_; sid=s } -> s

(* better *)
let get_sid m =
  match s with
  | { sid } -> sid

(* best *)
let get_sid s = s.sid
```

Type Synonyms

- A new name for an already existing type
  - similar to `typedef` in C

```
type point = float * float
type vector = float list
type matrix = float list list
```

Options

- A value representing an optional value
  - A value with type t in some cases or nothing for the rest
  - Built by using Some and None

```
# Some 42;;
- : int option = Some 42

# None;;
- : ‘a option
```

```
let rec list_max lst =
  match lst with
  | []   -> None
  | h::t -> (match list_max t with
             | None -> Some h
             | Some m -> Some (max h m))
```

Pattern Matching with Options

- Example: a function that extracts an integer from an option value

```
let extract o =
  match o with
  | Some i  -> string_of_int i
  | None -> “”
```

Variants (1)

- A data type representing a value that is one of several possibilities
  - Similar to enum in C or Java but more powerful
  - A kind of *sum* type: union of multiple sets
  - Individual names of the values of a variant are called **constructors**

```
# type day = Sun | Mon | Tue | Wed | Thu | Fri | Sat;;
- type day = Sun | Mon | Tue | Wed | Thu | Fri | Sat

# let d = Tue;;
val d : day = Tue
```

Pattern Matching with Variants (1)

```
let int_of_day d =
  match d with
  | Sun -> 1
  | Mon -> 2
  | Tue -> 3
  | Wed -> 4
  | Thr -> 5
  | Fri -> 6
  | Sat -> 7

let good_day d =
  match m with
  | Sun | Sat -> true
  | _ -> false
```

Variants (2)

- Each constructor can have arguments
  - more than just enumerating finite set of elements (which is a special case: one value per a constructor)
  - carrying additional data

```
type shape =
  | Point  of point
  | Circle of point * float  (* center and radius *)
  | Rect   of point * point  (* lower-left and
                                upper-right corners *)

let rect1 = Rect (1.0, 5.7)
let circle1 = Circle ((0.6, 0.3), 50.5)
```

Pattern Matching with Variants (2)

```
type shape =
  | Point  of point
  | Circle of point * float  (* center and radius *)
  | Rect   of point * point  (* lower-eft and
                                upper-right corners *)

let area s =
  match s with
  | Point _ -> 0.0
  | Circle (_, r) -> pi *. (r ** 2.0)   (* ** means power *)
  | Rect ((x1, y1), (x2, y2)) ->
      let w = x2 -. x1 in
      let h = y2 -. y1 in
      w *. h
```

Variants (3)

- Recursive variants are also possible
  - Variants mentioning their own name inside their own body

```
type intlist = Nil | Cons of int * intlist

let lst3 = Cons (3, Nil)                (* conceptually, 3::[] *)
let lst123 = Cons (1, Cons (2, lst3)) (* conceptually, [1; 2;,3] *)
```

Unit

- A value and a type that mean nothing
  - Similar to void in C and Java

```
# ();;
- : unit = ()
```

- Mostly used for side-effect only expressions such as print

```
# print_endline;;
- : string -> unit = <fun>
# print_endline “Hi”;;
Hi
- : unit = ()
```

Exceptions

- Conventional exception mechanism similar to other languages
- A new type of exception is defined with `exception`

```
exception Division_by_zero
exception Failure of string

let rec div x y =
  if y = 0 then raise Division_by_zero
  else x / y
```

Pattern Matching with Exceptions

- Pattern matching for exceptions with `try`
  - Try to evaluate an expression and handle each exception if raised

```
let r =
  try div x y with
  | Division_by_zero -> 0
  | Not_implemented -> -1
```

- Pattern matching for exceptions with `match`

```
let r =
  match div x y with
  | n -> string_of_int n
  | Division_by_zero -> “Division_by_zero”
  | Not_implemented -> “Not_implement”
```

Modules

Module

- A set of definitions of types, values, and exceptions
  - Similar to class in Java and C++ (except objects)

```
module ListStack = struct
  type ‘a stack = ‘a list
  exception Empty

  let empty = []
  let is_empty s = (s = [])
  let push x s = x :: s
  let peek = function
    | [] -> raise Empty
    | x::_ -> x
  let pop = function
    | [] -> raise Empty
    | _::xs -> xs
end
```

Module Type

- A set of declarations of types, values, and exceptions
  - Similar to interface in Java

```
(* all capital by convection *)
module type STACK = sig
  type ‘a stack
  exception Empty
  val empty : ‘a stack
  val is_empty : ‘a stack -> bool
  val push : ‘a -> ‘a stack -> ‘a stack
  val peek : ‘a stack -> ‘a
  val pop : ‘a stack -> ‘a stack
end

module ListStack : STACK = struct
  (* the rest is the same as before *)
end
```

Functors

- A function from modules to modules
  - Similar to template (C++) and generic (Java)

```
module type X = sig
  val x : int
end

module IncX (M: X) = struct
  let x = M.x + 1
end

module A = struct let x = 0 end
(* A.x is 0 *)

module B = IncX(A)
(* B.x is 1 *)
```

Libraries

OCaml Standard Libraries

- A collection of many useful modules
- Data structures, algorithms, system calls, etc
- http://caml.inria.fr/pub/docs/manual-ocaml/libref
- Also, an awesome reference for OCaml programming
  - https://github.com/ocaml/ocaml/tree/trunk/stdlib

Arg	Parsing of command line arguments.
Array	
ArrayLabels	Array operations
Bigarray	Large, multi-dimensional, numerical arrays.
Bool	Boolean values.
Buffer	Extensible buffers.
Bytes	Byte sequence operations.
BytesLabels	Byte sequence operations.
Callback	Registering OCaml values with the C runtime.
CamlinternalFormat	
CamlinternalFormatBasics	
CamlinternalLazy	Run-time support for lazy values.
CamlinternalMod	Run-time support for recursive modules.
CamlinternalOO	Run-time support for objects and classes.
Char	Character operations.
Complex	Complex numbers.
Condition	Condition variables to synchronize between threads.
Digest	MD5 message digest.
Dynlink	Dynamic loading of .cmo, .cma and .cmxs files.
Ephemeron	Ephemerons and weak hash table
Event	First-class synchronous communication.
Filename	Operations on file names.
Float	Floating-point arithmetic
Format	Pretty-printing.
Fun	Function manipulation.
Gc	Memory management control and statistics; finalised values.
Genlex	A generic lexical analyzer.
Hashtbl	Hash tables and hash functions.
Int	Integer values.
Int32	32-bit integers.
Int64	64-bit integers.
Lazy	Deferred computations.
Lexing	The run-time library for lexers generated by `ocamllex`.
List	List operations.
ListLabels	
Map	Association tables over ordered types.
Marshal	Marshaling of data structures.
MoreLabels	Extra labeled libraries.
Mutex	Locks for mutual exclusion.
Nativeint	Processor-native integers.
Obj	Operations on internal representations of values.
Ocaml_operators	Precedence level and associativity of operators
Oo	Operations on objects
Option	Option values.
Parsing	The run-time library for parsers generated by `ocamlyacc`.
Pervasives	
Printexc	Facilities for printing exceptions and inspecting current call stack.
Printf	Formatted output functions.
Queue	First-in first-out queues.
Random	Pseudo-random number generators (PRNG).
Result	Result values.
Scanf	Formatted input functions.
Seq	Functional Iterators
Set	Sets over ordered types.
Spacetime	Profiling of a program's space behaviour over time.
Stack	Last-in first-out stacks.
StdLabels	Standard labeled libraries.
Stdlib	The OCaml Standard library.
Str	Regular expressions and high-level string processing
Stream	Streams and parsers.
String	String operations.
StringLabels	String operations.
Sys	System interface.
Thread	Lightweight threads for Posix `1003.1c` and Win32.
ThreadUnix	Thread-compatible system calls.
Uchar	Unicode characters.
Unit	Unit values.
Unix	Interface to the Unix system.
UnixLabels	Interface to the Unix system.
Weak	Arrays of weak pointers and hash sets of weak pointers.

Stdlib

- The `Stdlib` module is automatically opened
  - Specifying module name (`Stdlib`) is not needed
- A lot of basic operations over the built-in types (numbers, booleans, strings, I/O channels, etc)
  - http://caml.inria.fr/pub/docs/manual-ocaml/libref/Stdlib.html

List (1)

- The List module has a number of utility functions for lists
  - http://caml.inria.fr/pub/docs/manual-ocaml/libref/List.html
- Builders: constructing a new list

```
(* val cons : 'a -> 'a list -> 'a list *)
let lst = [1;2;3]
let x = List.cons 1 lst
let y = 1::lst (* simpler form *)

(* val append : 'a list -> 'a list -> 'a list
let z = List.append x y
let w = x @ y (* simpler form *)
```

List (2)

- Iterators: iterating over lists

```
(* val iter : ('a -> unit) -> 'a list -> unit *)
let l = [1;2;3]
let _ = List.iter print_int lst

(* val map : ('a -> 'b) -> 'a list -> 'b list *)
let str_lst = List.map string_of_int lst
(* str_lst = ["1"; "2"; "3"] *)

(* val fold_left : ('a -> 'b -> 'a) -> 'a -> 'b list -> 'a *)
let sum = List.fold_left (+) 0 lst
let sum_of_squre = List.fold_left (fun acc x -> acc + x * x) 0 lst
```

List (3)

- Searching

```
(* find_opt : ('a -> bool) -> 'a list -> 'a option *)
let one = List.find_opt (fun x -> x > 1) lst

(* filter : ('a -> bool) -> 'a list -> 'a list *)
let larger_than_one = List.filter (fun x -> x > 1) lst
```

- All together with pipelining

```
let r = (* define r by doing the following *)
  1::lst                          (* prepend 1 to lst *)
  |> List.map (fun x -> x * x)    (* apply square for all the elems *)
  |> List.filter (fun x -> x > 1) (* get all the elems larger than 1 *)
  |> List.fold_left ( + ) 0       (* compute the sum of all the elems *)
```

Set (1)

- The set data structure and functions
  - http://caml.inria.fr/pub/docs/manual-ocaml/libref/Set.html
- The `Set.Make` functor constructs implementations for any type
  - The argument module must have a type `t` and a `compare` function

```
module IntPairs = struct
  type t = int * int
  (* a total ordering function with type t -> t -> int is required *)
  (* compare x y is -1 if x < y, 0 if x = y, 1 otherwise *)
  let compare (x0, y0) (x1, y1) =
    match compare x0 x1 with  (* this compare is a builtin function *)
    | 0 -> compare y0 y1
    | c -> c
end
module PairSet = Set.Make(IntPairs)
```

Set (2)

- Builders

```
(* type elt is the type of the set element *)

(* val empty : t *)
let emptyset = PairSet.empty

(* val add : elt -> t -> t *)
let x = PairSet.add (1,2) emptyset

(* val singleton : elt -> t *)
let y = PairSet.singleton (1,2)

(* val remove : elt -> t -> t *)
let z = PairSet.remove (1,2) y

(* set operators with type t -> t -> t *)
let u = PairSet.union x y
let i = PairSet.inter x y
let d = PairSet.diff x y
```

Set (3)

- Iterators

```
(* val fold : (elt -> 'a -> 'a) -> t -> 'a -> 'a *)
let sum_left = PairSet.fold (fun (i, _) s -> i + s) x 0

(* val iter : (elt -> unit) t -> t *)
let _ = PairSet.iter (fun i, _) -> print_int i) x

(* val map : (elt -> elt) -> t *)
let double = PairSet.map (fun (i, j) -> (2 * i, 2 * j)) x
```

- Searching

```
(* val mem : elt -> t -> bool *)
let membership = PairSet.mem (1, 2) x

(* val filter : (elt -> bool) -> t -> t *)
let big_left = PairSet.filter (fun (i, j) -> i > j) x
```

Map (1)

- The map data structure (kay-value pairs) and functions
  - http://caml.inria.fr/pub/docs/manual-ocaml/libref/Map.html
- The `Map.Make` functor constructs implementations for any type of key
  - The argument module must have a type `t` and a `compare` function

```
module IntPairs = struct
  type t = int * int
  (* a total ordering function with type t -> t -> int is required *)
  (* compare x y is -1 if x < y, 0 if x = y, 1 otherwise *)
  let compare (x0, y0) (x1, y1) =
    match compare x0 x1 with  (* this compare is a builtin function *)
    | 0 -> compare y0 y1
    | c -> c
end
module PairMap = Map.Make(IntPairs)
```

Map (2)

- Builders

```
(* type key is the type of the map keys *)
(* type ‘a t is the type of maps is from type key to type ‘a *)

(* val empty : ’a t *)
let emptymap = PairMap.empty

(* val add : key -> ‘a -> bool *)
let x = PairMap.add (1,2) “one-two” emptymap

(* val singleton : key -> ‘a -> ’a t *)
let y = PairMap.singleton (1,2) “one-two”

(* val remove : key -> ’a t -> ’a t *)
let z = PairMap.remove (1,2) y
```

Map (3)

- Iterators

```
(* val fold : (key -> ‘a -> ‘b -> ‘b) -> ’a t -> ‘b -> ‘b *)
let sum = PairMap.fold (fun (i, j) _ s -> (i + j) x 0

(* val iter : (elt -> unit) t -> t *)
let _ = PairMap.iter (fun (i, _) -> print_int i) x

(* val map : ('a -> ‘b) -> 'a t -> ‘b t *)
let double = PairMap.map (fun str -> String.length str) x
```

- Searching

```
(* val mem : key -> ’a t -> bool *)
let membership = PairMap.mem (1, 2) x

(* val filter : (key -> ‘a -> bool) -> ‘a t -> ‘a t *)
let big_left = PairMap.filter (fun (i, j) _ -> i > j) x
```

Get Into The Wild Adventure

Reference: Books and Tutorials

- Real World OCaml: http://dev.realworldocaml.org
- Functional Programming in OCaml: https://www.cs.cornell.edu/courses/cs3110/2019sp/textbook
- OCaml tutorials: https://ocaml.org/learn/tutorials/

Reference: Real World OCaml Code

- Learn more from real-world OCaml code!
  - OCaml compiler: https://github.com/ocaml/ocaml
  - Sparrow: https://github.com/prosyslab/sparrow
  - Infer: https://github.com/facebook/infer
  - OCamlgraph: https://github.com/backtracking/ocamlgraph