CENG 2010 - Programming Language Concepts

Weeks 1-2: A Short Introduction to OCaml

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March 6 - March 13, 2023

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OCaml

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OCaml

General-purpose, strongly typed programming language

- successor of Caml Light (itself successor of Caml),
- part of the ML family (SML, F#, etc.)
- designed and implemented at Inria Rocquencourt by Xavier Leroy and others
- Some applications: symbolic computation and languages (IBM, Intel, Dassault Systèmes), static analysis (Microsoft, ENS), file synchronization (Unison), peer-to-peer (MLDonkey), finance (LexiFi, Jane Street Capital), teaching

The First Program

- `hello.ml`

```
let () = print_string "hello␣world!\n"
```

where

```
let () = ...
```

is the first entry of your program (like the “main” in C)

The First Program

- `hello.ml`

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  let () = print_string "hello␣world!\n"
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  where

  ```
  let () = ...
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  is the first entry of your program (like the “main” in C)

Compilation	`% ocamlopt -o hello hello.ml`
Execution	`% ./hello`
Output	`hello word!`

Variable Declarations

- introducing a global variable

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let x = e
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Java	OCaml
`final int x = 42;`	`let x = 42`

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Java	OCaml
`final int x = 42;`	`let x = 42`

- example:

```
let x = 1 + 2
let y = x * x

let () =
  print_int x;
  print_int y;
```

where semicolon (“;”) is the expression separator – sequencing

References

a variable to be assigned is called a reference; it is introduced with `ref`

```
let a = ref 1
let b = ref 2

let () =
  print_int !a;
  print_int !b;
  b := !a + 3;
  print_int !b;
```

Expressions and Statements

no distinction between expression/statement in the syntax : only expressions

usual constructs:

- conditional

```
let i = 1

let () =
  if i = 1 then print_int 1 else print_int 2
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  if i = 1 then print_int 1 else print_int 2
```

- for loop

```
let a = ref 1

let () =
  for ind = 1 to 5 do a := !a + ind done
```

Unit Type

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```
let () =
  if !a > 0 then a := 0
```

Unit Type

- expressions with no meaningful value (assignment, loop, ...) have type unit
- this type has a single value, written ()
- it is the type given to the else branch when it is omitted
  - correct

```
let () =
  if !a > 0 then a := 0
```

  - incorrect

```
let () =
  2 + (if !a > 0 then 1)
```

Local Variables

- in C or Java, the scope of a local variable extends to the bloc:

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  int x = 1;
  ...;
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let x = 12 in x * x
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let x = 12 in x * x
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- as for a local variable:
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  - type inferred
  - immutable
  - but scope limited to the expression following in

"`let in =`" Expression

- `let x = e1 in e2`

  is an expression

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- in an environment where x has the type and value of e1
- Example:

  ```
  let x = 1 in (let y = 2 in x + y) * (let z = 3 in x * z)
  ```

Example

Java	OCaml
`{`	
`  int x = 1;`	`let x = ref 1 in`
`  x = x + 1;`	`x := !x + 1;`
`  int y = x * x;`	`let y = !x * !x in`
`  System.out.print(y);`	`print_int y`
`}`	

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  OCaml version 4.14.0
  Enter #help;; for help.
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  # let y = 1 + 2;;
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  - : int = 3
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- ```
  # let y = 1 + 2;;
  ```
  ```
  val y : int = 3
  ```
- ```
  # y * y;;
  ```
  ```
  - : int = 9
  ```

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Syntax

- ```
  # let f x = x * x;;
  ```
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  val f : int → int = <fun>
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  ```

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# f 4 ;;
- : int = 16
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- versus:

Java	OCaml

`static int f(int x)`
`{`
`  return x * x;`
`}`
	`let f x = x * x`

Procedure

a procedure = a function whose result type is `unit`

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- ```
  # let x = ref 1
    let set v = x := v;;

  val x : int ref = {contents = 1}
  val set : int -> unit = <fun>
  ```
  ```

Procedure

a procedure = a function whose result type is `unit`

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  # set 3;;

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

  - : int = 3
  ```
  ```

Functions without Arguments

takes an argument of type `unit`

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- ```
  # let reset () = x := 0;;
  val reset : unit -> unit = <fun>
  ```
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  # let reset () = x := 0;;
  val reset : unit -> unit = <fun>
  ```
- ```
  # reset ();;
  - : unit = ()
  ```

Functions with Several Arguments

takes an argument of type `unit`

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takes an argument of type unit

- ```
  # let f x y z = if x > 0 then y + x else z - x;;
  ```

  ```
  val f : int → int → int → int = <fun>
  ```
  ```

Functions with Several Arguments

takes an argument of type unit

- `# let f x y z = if x > 0 then y + x else z - x;;`

  `val f : int → int → int → int = <fun>`

- `# f 1 2 3;;`

  `- : int = 3`

Local Functions

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  - `# let sqr x = x * x in sqr 3 + sqr 4 = sqr 5;;`

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    # let sqr x = x * x in sqr 3 + sqr 4 = sqr 5;;
    ```
    ```
    - : bool = true
    ```
- function local to another function
  - ```
    # let pythagorean x y z =
        let sqr n = n * n in
        sqr x + sqr y = sqr z;;
    ```
    ```
    val pythagorean : int → int → int → bool = <fun>
    ```

Functions as First-Class Citizens

function = yet another expression, introduced with `fun`

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  # fun x → x+1
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  # fun x → x+1
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  # (fun x → x+1) 3;;
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  ```

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Functions as First-Class Citizens

function = yet another expression, introduced with `fun`

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

  # (fun x → x+1) 3;;
  - : int = 4
  ```

internally

```
let f x = x+1;;
```

is identical to

```
let f = fun x → x+1;;
```
```

Partial Application

```
fun x y → x*x + y*y
```

is the same as

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- ```
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- ```
  # let f x y = x*x + y*y;;
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- ```
  # let g = f 3;;
  val g : int → int = <fun>
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- ```
  # let g = f 3;;
  val g : int → int = <fun>
  ```
- ```
  # g 4;;
  - : int = 25
  ```
  ```

Partial Application (cont'd)

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- ```
  # let f x = let x2 = x * x in fun y → x2 + y * y;;
  val f : int → int → int = <fun>
  ```
  ```

Partial Application (cont'd)

- a partial application is a way to return a function
- but one can also return a function as the result of a computation
-
```
# let f x = let x2 = x * x in fun y → x2 + y * y;;
val f : int → int → int = <fun>
```
- a partial application of f computes x∗x only once

Example (Partial Application)

- ```
  # let count_from n = let r = ref (n-1) in fun () → incr r; !r;;
  ```

  ```
  val count_from : int → unit → int = <fun>
  ```
  ```

Example (Partial Application)

- ```
  # let count_from n = let r = ref (n-1) in fun () → incr r; !r;;
  val count_from : int → unit → int = <fun>

  # let c = count_from 0;;
  val c : unit → int = <fun>
  ```
  ```

Example (Partial Application)

- ```
  # let count_from n = let r = ref (n-1) in fun () → incr r; !r;;
  val count_from : int → unit → int = <fun>

  # let c = count_from 0;;
  val c : unit → int = <fun>
  ```

- ```
  # c ();;
  - : int = 0
  # c ();;
  - : int = 1
  ```

Higher-Order Functions

- functions that input and output functions

```
# let riemann (f: float → float) (a: int) (b: int) (n: int): float =
  let a = ref a in
  let s = ref 0.0 in
  let x = (b - !a)/n in
  a := !a + x;
  while !a ≤ b do
    s := !s +. (f (float !a) *. float x);
    a := !a + x
  done;
  !s;;

val riemann : (float → float) → int → int → int → float = <fun>
```

Recursive Functions

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  - tail calls are optimized
- Example:

```
let zero f =
  let rec lookup i = if f i = 0 then i else lookup (i+1)
  in lookup 0
```

Recursive Functions

- in OCaml, it is idiomatic to use recursive functions, for
  - a function call is cheap
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- Example:

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let zero f =
  let rec lookup i = if f i = 0 then i else lookup (i+1)
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- recursive code ⇒ clearer, simpler to justify

Polymorphism

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- ```
  # let f x = x;;
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  val f : $\alpha \rightarrow \alpha$ = <fun>
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Polymorphism

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- `# let f x = x;;`

  `val f : α → α = <fun>`

- `# f 3;;`

  `- : int = 3`

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- `# let f x = x;;`

  `val f :` $\alpha \to \alpha$ `= <fun>`

- `# f 3;;`

  `- : int = 3`

- `# f true;;`

  `- : bool = true`

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- `# let f x = x;;`

  `val f : α → α = <fun>`

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  `- : bool = true`

- `# f print_int;;`

  `- : int → unit = <fun>`

Polymorphism

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- polymorphic function = act over values with many different types
- ```
  # let f x = x;;
  val f : α → α = <fun>
  ```
- ```
  # f 3;;
  - : int = 3
  ```
- ```
  # f true;;
  - : bool = true
  ```
- ```
  # f print_int;;
  - : int → unit = <fun>
  ```
- ```
  # f (print_int 20; Printf.printf "\n");;
  20
  - : unit = ()
  ```
  ```

Polymorphism (cont'd)

- OCaml always infers the most general type

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```
# let compose f g = fun x → f (g x);;
val compose : (α → β) → (γ → α) → γ → β = <fun>
```

Table of Contents

Arrays

- ```
  # let a = Array.make 10 0;;
  ```
  ```
  val a : int array = [|0; 0; 0; 0; 0; 0; 0; 0; 0; 0|]
  ```
  necessarily initialized
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  # let a = [| 1; 2; 3; 4 |];;
  # a.(1);;
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  ```
  - : int = 2
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  - : int = 2
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- ```
  # a.(1) ← 5;;
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  ```
  - : unit = ()
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  ```
  - : unit = ()
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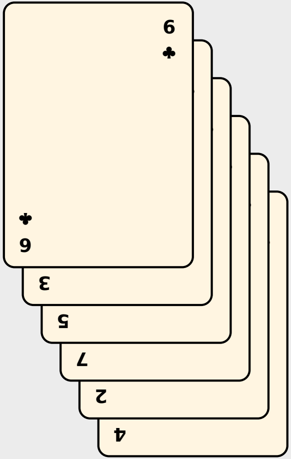
- ```
  # a;;
  ```
  ```
  - : int array = [|1; 5; 3; 4|]
  ```

Example

Java	OCaml
`int[] a = new int[42];`	`let a = Array.make 42 0`
`a[17]`	`a.(17)`
`a[7] = 3;`	`a.(7) <- 3`
`a.length`	`Array.length a`

Example (Insertion Sort)



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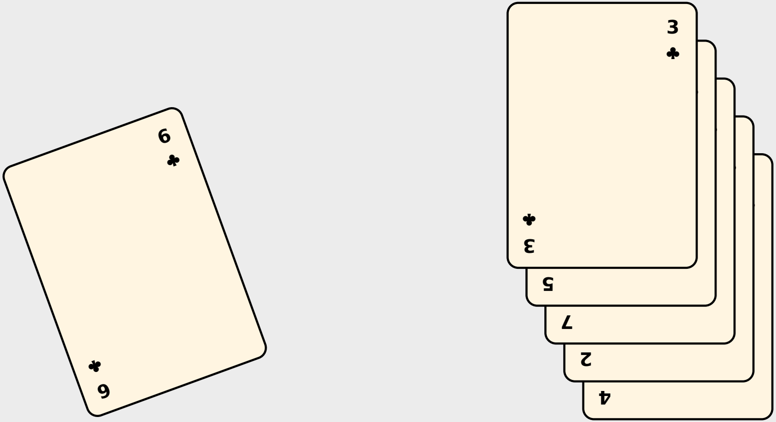

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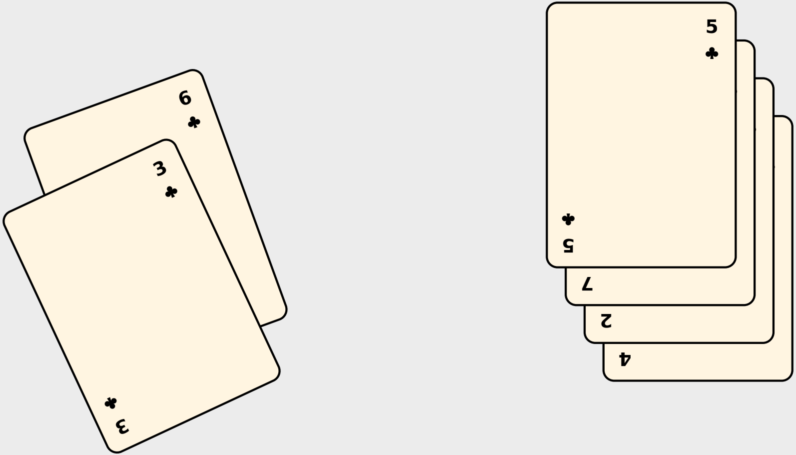

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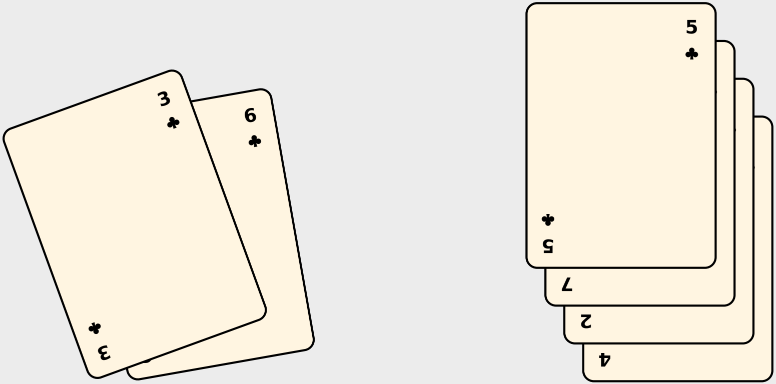

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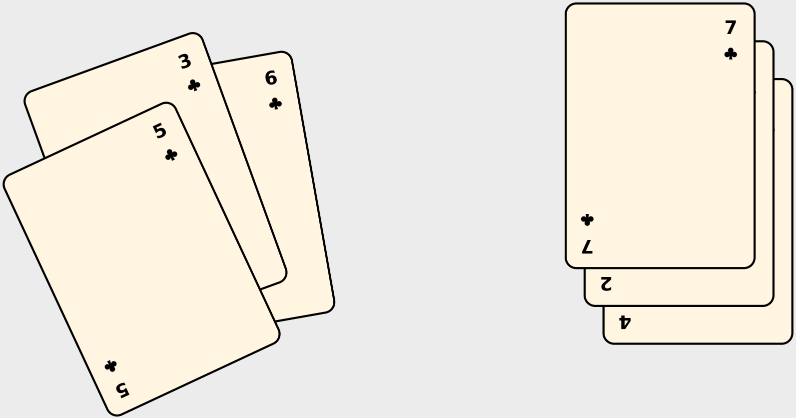

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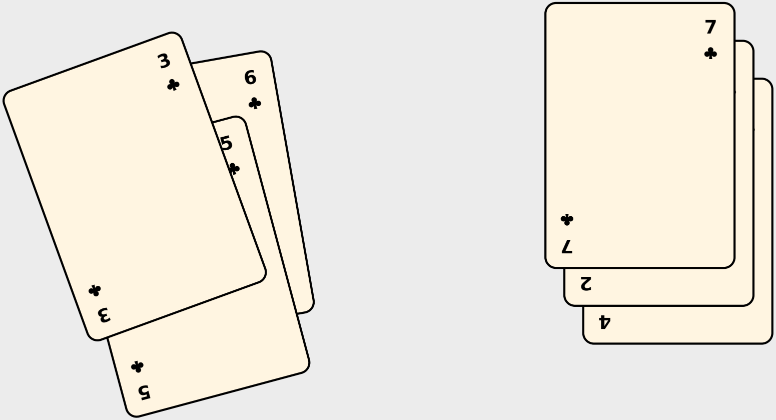

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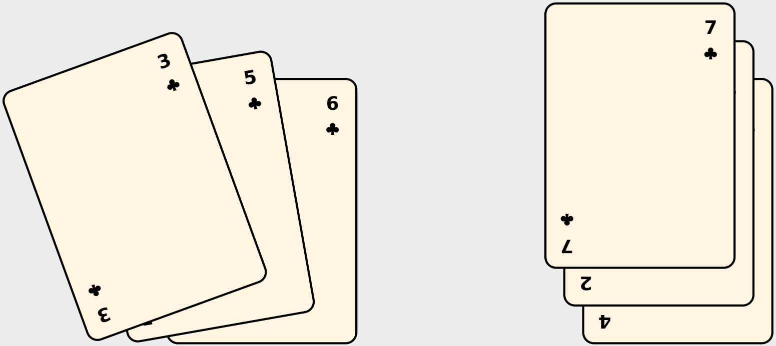

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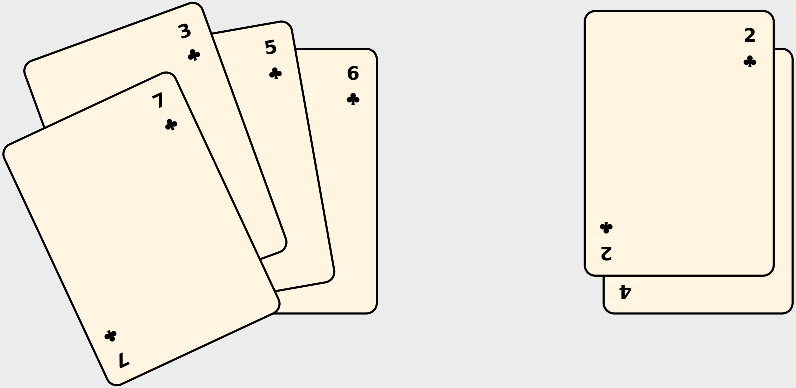

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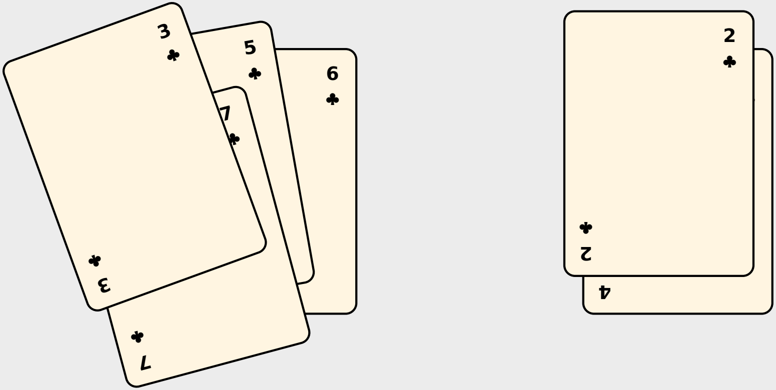

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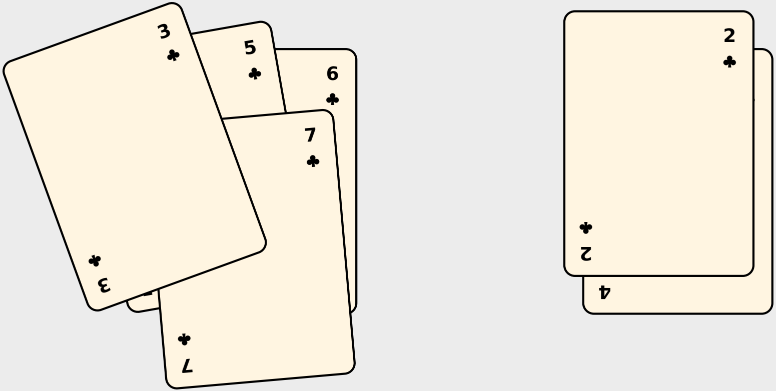

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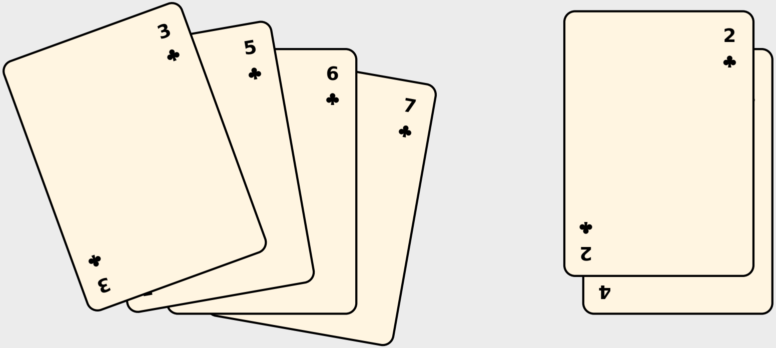

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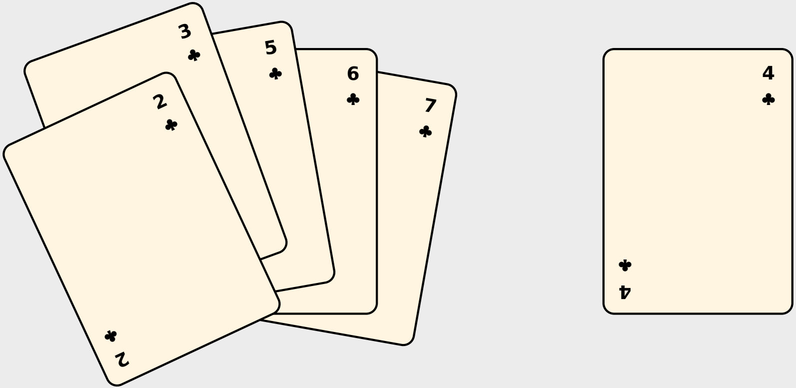

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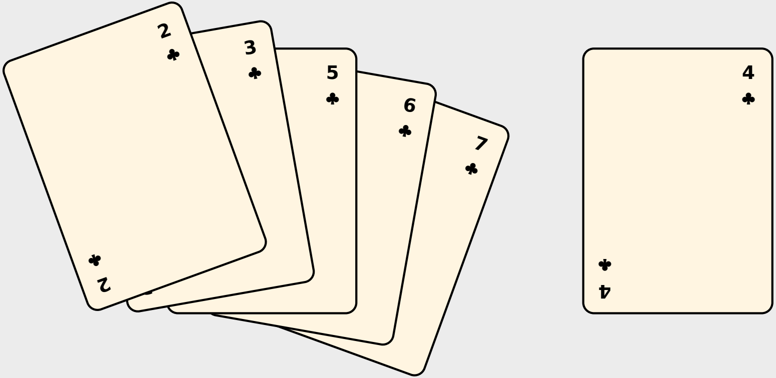

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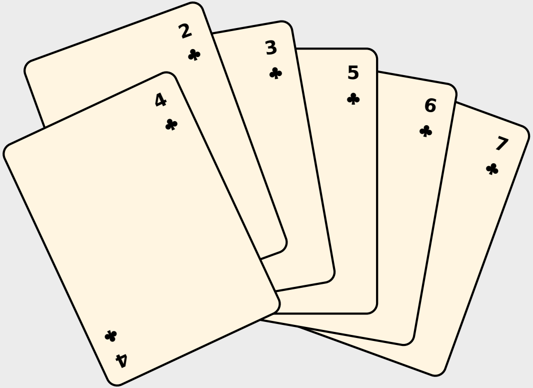

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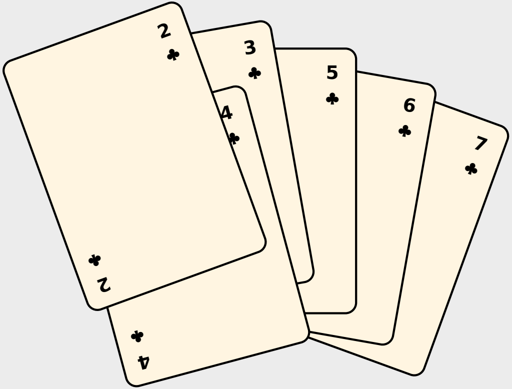

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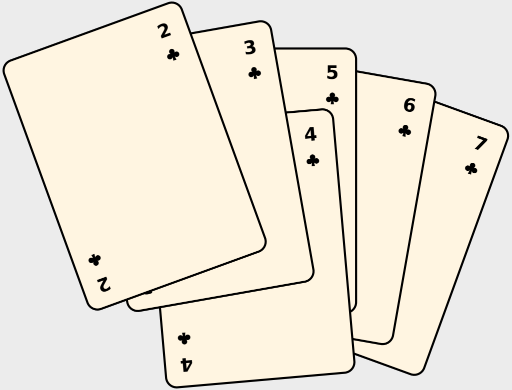

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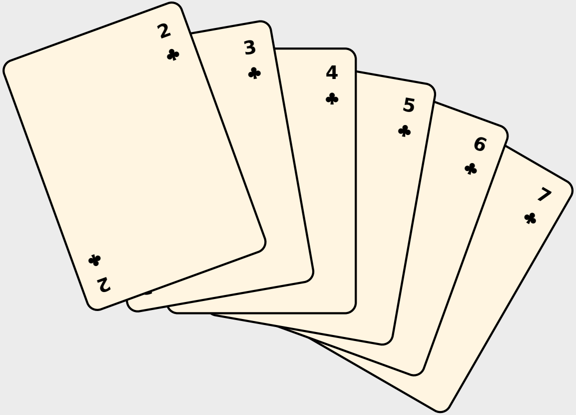

Example (Insertion Sort – iterative insertion)

```
let insertion_sort a =
  let swap i j =
    let t = a.(i) in a.(i) ← a.(j); a.(j) ← t
  in
  for i = 1 to Array.length a - 1 do
  (* insert element a[i] in a[0..i−1] *)
    let j = ref (i-1) in
    while !j ≥ 0 && a.(!j) > a.(!j+1) do
      swap !j (!j + 1); decr j
    done
  done
```

Example (Insertion Sort – recursive insertion)

```
let insertion_sort a =
  let swap i j =
    let t = a.(i) in a.(i) ← a.(j); a.(j) ← t
  in
  for i = 1 to Array.length a - 1 do
  (* insert element a[i] in a[0..i−1] *)
    let rec insert j =
      if j ≥ 0 && a.(j) > a.(j+1) then
      begin swap j (j+1); insert (j-1) end
    in
    insert (i-1)
  done
```

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Algebraic Data Types (Memory Representation)

- algebraic data type = union of several constructors

```
type formula =
  | True
  | False
  | And of formula * formula

# True;;

- : formula = True

# And (True, False);;

- : formula = And (True, False)
```

Pattern Matching (Algebraic Data Types)

- pattern matching generalizes to algebraic data types

```
# let rec eval = function
  | True          → true
  | False         → false
  | And (f1, f2) → eval f1 && eval f2;;

val eval : formula → bool = <fun>
```

Pattern Matching (Algebraic Data Types)

- pattern matching generalizes to algebraic data types

```
# let rec eval = function
  | True          → true
  | False         → false
  | And (f1, f2) → eval f1 && eval f2;;

val eval : formula → bool = <fun>
```

- patterns can be omitted or grouped:

```
let rec eval = function
  | True                                  → true
  | False                                 → false
  | And (False, _) | And (_, False) → false
  | And (f1, f2)                          → eval f1 && eval f2;;
```

Example (Positive Integers)

```
type pos =
  | XI: pos → pos
  | XO: pos → pos
  | XH: pos

let rec pos2Int (p: pos): int =
  match p with
    | XI k → 2 ∗ pos2Int k + 1
    | XO k → 2 ∗ pos2Int k
    | XH   → 1

let rec int2PosH (n: int) (m: int): pos =
  if n ≥ 1 && m ≥ 2 then int2PosH (n-1) (m-2)
  else if n ≥ 1 && m = 1 then XO (int2PosH (n-1) (n-1))
  else if n ≥ 1 && m = 0 then XI (int2PosH (n-1) (n-1))
  else XH

let int2Pos (i: int): pos =
  if i < 1 then failwith "input␣a␣non-negative␣integer"
  else int2PosH i (i+1)
```

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Lists

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  val l : int list = [1; 2; 3]
  ```
  ```

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-
```
# let l = 1 :: 2 :: 3 :: [];;
val l : int list = [1; 2; 3]
```
- shorter syntax
```
# let l = [1; 2; 3];;
```

Pattern Matching (Lists)

pattern matching = case analysis on a list

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- ```
  # let rec sum l =
      match l with
        | []     → 0
        | x :: r → x + sum r;;

  val sum : int list → int = <fun>

  # sum [1;2;3];;

  - : int = 6
  ```
  ```

Pattern Matching (Lists)

pattern matching = case analysis on a list

- ```
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  val sum : int list → int = <fun>

  # sum [1;2;3];;

  - : int = 6
  ```

- shorter notation for a function performing pattern matching on its argument

  ```
  let rec sum = function
    | []     → 0
    | x :: r → x + sum r;;
  ```
  ```

Lists (Memory Representation)

- OCaml lists = identical to lists in C or Java

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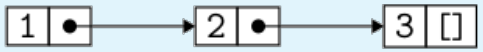
- OCaml lists = identical to lists in C or Java
- the list [1; 2; 3] is represented as



Example (List Operations)

```
let rec myConcat (l1: α list)
                 (l2: α list): α list =
  match l1 with
    | []    → l2
    | x::xs → x :: myConcat xs l2

let rec myReverse (l: α list): α list =
  match l with
    | []    → []
    | x::xs → myConcat (myReverse xs) [x]
```

```
let rec myMap (f: α → β) (l: α list): β list =
  match l with
    | []    → []
    | x::xs → f x :: myMap f xs

let rec myFoldr (f: α → β → β)
                (u: β) (l: α list): β =
  match l with
    | []    → u
    | x::xs → f x (myFoldr f u xs)
```

Table of Contents

Tuples

- usual notation:

```
# (1,2,3);;

- : int * int * int = (1, 2, 3)
```

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val v : int * bool * string * char = (1, true, "hello", 'a')
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Tuples

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```
# (1,2,3);;

- : int * int * int = (1, 2, 3)


# let v = (1, true, "hello", 'a');;

val v : int * bool * string * char = (1, true, "hello", 'a')
```

- access to components

```
# let (a,b,c,d) = v;;

val a : int = 1
val b : bool = true
val c : string = "hello"
val d : char = 'a'
```

Tuples (cont'd)

- beneficial when it comes to returning several values:

```
# let rec division n m =
    if n < m then (0, n)
    else let (q,r) = division (n - m) m in (q + 1, r);;

val division : int → int → int * int = <fun>
```

Tuples (cont'd)

- beneficial when it comes to returning several values:

```
# let rec division n m =
    if n < m then (0, n)
    else let (q,r) = division (n - m) m in (q + 1, r);;

val division : int → int → int * int = <fun>
```

- function taking a tuple as argument

```
# let f (x,y) = x + y;;

val f : int * int → int = <fun>

# f (1,2);;

- : int = 3
```

Example (Currification)

```
let myCurry (f: (α∗β) → γ): (α → β → γ) =
  fun (x: α) → fun (y: β) → f (x, y)

let addP (t: (int∗int)): int = fst t + snd t

let myUnCurry (f: α → β → γ): ((α∗β) → γ) =
  fun (x: (α∗β)) → f (fst x) (snd x)

let add (x: int) (y: int): int = x + y
```

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Records

- `type complex = { re : float; im : float }`

Records

- `type complex = { re : float; im : float }`
- allocation and initialization are simultaneous:

```
# let x = { re = 1.0; im = -1.0 };;
val x : complex = {re = 1.; im = -1.}
# x.im;;
- : float = -1.
```

Mutable Fields

```
type person = { name : string; mutable age : int }
# let p = { name = "Martin"; age = 23 };;
val p : person = {name = "Martin"; age = 23}
# p.age ← p.age + 1;;
- : unit = ()
# p.age;;
- : int = 24
```

Example

<table>
<tr><th>Java</th><th>OCaml</th></tr>
<tr><td><pre>class T
{
  final int v;
  boolean b;

  T(int v, boolean b)
  {
    this.v = v;
    this.b = b;
  }
}

T r = new T(42, true);
r.b = false;
r.v</pre></td><td><pre>type t =
{
  v: int;
  mutable b: bool;
}

let r = { v = 42; b = true }
r.b ← false
r.v</pre></td></tr>
</table>

References

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- `ref`, `!` and `:=` are syntactic sugar

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- `type ‘a ref = { mutable contents : ‘a }`

- `ref`, `!` and `:=` are syntactic sugar
- only arrays and mutable fields can be mutated

Example (Rationals)

```
type rat =
{
  num  : int;
  denom: pos;
}

let rat2String (r: rat): string =
  string_of_int (r.num) ^ "/" ^ string_of_int (pos2Int (r.denom))

let printRat (r: rat): unit =
  printf "%s\n" (rat2String r)

let ratEq (r1: rat) (r2: rat): bool =
  r1.num * (pos2Int r2.denom) = r2.num * (pos2Int r1.denom)
```

Table of Contents

OOP Classes

- class = collection of attributes (data) and methods

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- class = collection of attributes (data) and methods
- example:

```
class dice = object
  val max = 6
  val mutable faceValue = 0

  method roll =
    Random.self_init();
    faceValue ← (Random.full_int max) + 1

  method set_faceValue v =
    faceValue ← v

  method get_faceValue =
    faceValue
end
```

Example (inheritance)

```
class rectangle (w: int) (h: int) = object (s)
  val mutable x = 0
  val mutable y = 0

  method get_x = x
  method set_x v = x ← v

  method get_y = y
  method set_y v = y ← v

  method area = w ∗ h
end

class square (w: int) = object (s)
  inherit rectangle w w as r

  method is_contained (px, py) =
    x ≤ px && px ≤ x + w &&
    y ≤ py && py ≤ y + w

end
```

Example (ad-hoc polymorphism)

```
class virtual shape (name: string) = object (s)
  val virtual mutable x: int
  val virtual mutable y: int
  method virtual area: int

  method describe =
    "shape␣is␣" ^name ^ "␣at␣" ^ "(" ^ string_of_int x ^ "," ^ string_of_int y ^ ")" ^
    "␣with␣the␣area␣=␣" ^  string_of_int (s#area)
end
```

Example (ad-hoc polymorphism (cont'd))

```
class rectangle (w: int) (h: int) = object
  inherit shape "rectangle" as r

  val mutable x = 0
  val mutable y = 0

  method get_x = x
  method set_x v = x ← v

  method get_y = y
  method set_y v = y ← v

  method area = w ∗ h
end
```

Example (ad-hoc polymorphism (cont'd))

```
class square (w: int) = object
  inherit shape "square" as r

  val mutable x = 0
  val mutable y = 0

  method get_x = x
  method set_x v = x ← v

  method get_y = y
  method set_y v = y ← v

  method area = w ∗ w
end
```

Thanks! & Questions?