CMSC 330: Organization of Programming Languages

OCaml Imperative Programming

CMSC330 Spring 2024

So Far, Only Functional Programming

- We haven't given you any way so far to change something in memory
  - All you can do is create new values from old
- This makes programming easier since it supports mathematical (i.e., functional) reasoning
  - Don't care whether data is shared in memory
    - Aliasing is irrelevant
  - Calling a function f with the same argument always produces the same result
    - For all x and y, we have f x = f y when x = y

Imperative OCaml

- Sometimes it is useful for values to change
  - Call a function that returns an *incremented* counter
  - Store aggregations in *efficient* hash tables

- OCaml variables are *immutable*, but

- OCaml has references, fields, and arrays that are actually *mutable*
  - I.e., they can change

References

- **`'a ref`**: Pointer to a mutable value of type **`'a`**
- There are three basic operations on references:

  `ref` : **`'a -> 'a ref`**

  - Allocate a reference

  `!` : **`'a ref -> 'a`**

  - Read the value stored in reference

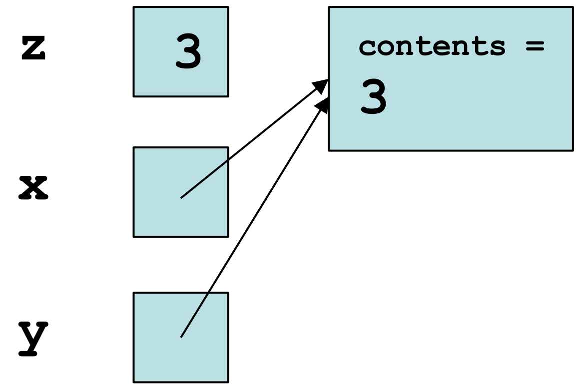
  `:=` : **`'a ref -> 'a -> unit`**

  Change the value stored in reference
- Binding variable **`x`** to a reference is immutable
  - The contents of the reference **`x`** points to may change

References Usage

Example:

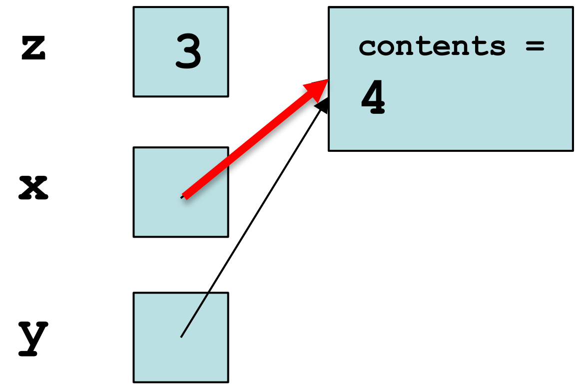
```
# let z = 3;;
  val z : int = 3

# let x = ref z;;
  val x : int ref = {contents = 3}

# let y = x;;
  val y : int ref = {contents = 3}
```



References Usage

Example:

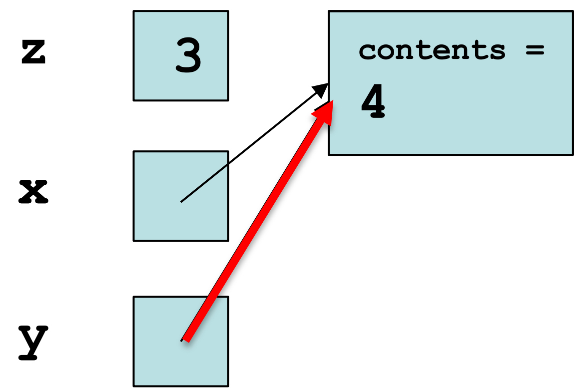
```
# let z = 3;;
  val z : int = 3

# let x = ref z;;
  val x : int ref = {contents = 3}

# let y = x;;
  val y : int ref = {contents = 3}

# x := 4;;
- : unit = ()
```



References Usage

Example:

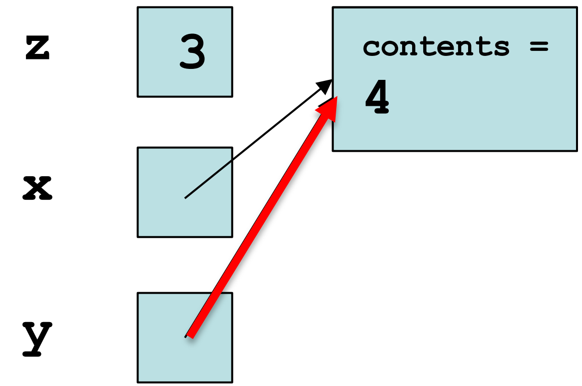
```
# let z = 3;;

# let x = ref z;;

# let y = x;;

# x := 4;;
# !y;;
- : int = 4
```



Aliasing

- Reconsider our example

```
let z = 3;;
let x = ref z;;
let y = x;;
x := 4;;
```



Here, variables **y** and **x** are aliases:

- In **let y = x**, variable **x** evaluates to a location, and **y** is bound to the same location
- So, changing the contents of that location will cause both **!x** and **!y** to change

Quiz 1: What is the value `w`?

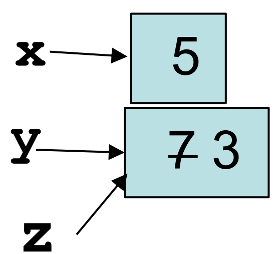
```
let x = ref 5 in
let y = ref 7 in
let z = y in
let _ = y := 3 in
let w = !y + !z in
w
```

A. 12
B. 6
C. 10
D. 8

Quiz 1: What is the value **w**?

```
let x = ref 5 in
let y = ref 7 in
let z = y in
let _ = y := 3 in
let w = !y + !z in
w
```

A. 12
B. 6
C. 10
D. 8



!y + !z = 3 + 3 = 6

Quiz 1a: What is the value **w**?

```
let x = ref 5 in
let y = ref 7 in
let z = !y in
let _ = y := 4 in
let w = !y + z in
w
```

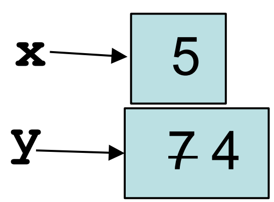
A. 12
B. 6
C. 9
D. 11

Quiz 1a: What is the value **w**?

```
let x = ref 5 in
let y = ref 7 in
let z = !y in
let _ = y := 4 in
let w = !y + z in
w
```

A. 12
B. 6
C. 9
D. 11

z=7



!y + z = 4 + 7 = 11

References: Syntax and Semantics

- Syntax: `ref` ***e***
- Evaluation
  - Evaluate ***e*** to a value ***v***
  - Allocate a new location ***loc*** in memory to hold ***v***
  - Store ***v*** in contents of memory at ***loc***
  - Return ***loc*** (which is itself a value)
- Type checking
  - (`ref` ***e***) : ***t*** `ref`
    - if ***e*** : ***t***

References: Syntax and Semantics

- Syntax: `e1 := e2`
- Evaluation
  - Evaluate `e2` to a value `v2`
  - Evaluate `e1` to a location `loc`
  - Store `v2` in contents of memory at `loc`
  - Return `()`
- Type checking
  - (`e1 := e2`) : `unit`
    - if `e1 : t ref` and `e2 : t`

References: Syntax and Semantics

- Syntax: `!e`
  - *This is not negation. Operator ! is like operator * in C*
- Evaluation
  - Evaluate `e` to a location `loc`
  - Return contents `v` of memory at `loc`
- Type checking
  - `!e : t`
    - if `e : t ref`

Sequences: Syntax and Semantics

- Syntax: `e1; e2`
  - `e1; e2` is the same as `let () = e1 in e2`
- Evaluation
  - Evaluate `e1` to a value `v1`
  - Evaluate `e2` to a value `v2`
  - Return `v2`
    - Throws away `v1` – so `e1` is useful only if it has *side effects*, e.g., if it modifies a reference's contents or accesses a file
- Type checking
  - `e1;e2 : t`
    - if `e1 : unit` and `e2 : t`

;; versus ;

- ;; 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

- ***e1; e2*** evaluates ***e1*** and then ***e2***, and returns ***e2***

```
let print_both (s, t) = print_string s; print_string t;
                        "Printed s and t"
```

  - notice no ; at end – it's a separator, not a terminator

Grouping Sequences

- If you're not sure about the scoping rules, use begin...end, or *parentheses*, to group together statements with semicolons

```
let x = ref 0
let f () =
  begin
    print_string "hello";
    x := !x + 1
  end
```

```
let x = ref 0
let f () =
  (
    print_string "hello";
    x := !x + 1
  )
```

Implement a Counter

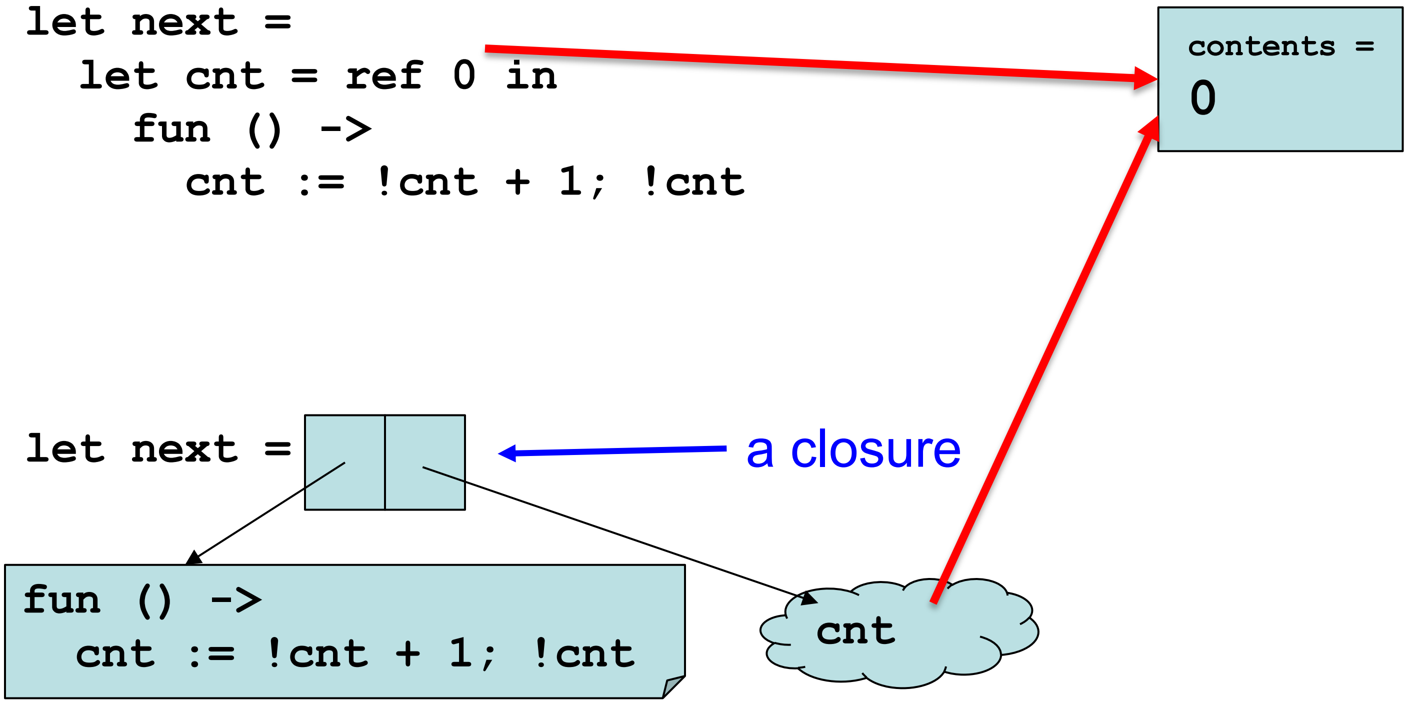
```
# let counter = ref 0 ;;
  val counter : int ref = { contents=0 }

# let next () =
      counter := !counter + 1; !counter ;;

val next : unit -> int = <fun>

 # next ();;
   - : int = 1

 # next ();;
   - : int = 2
```

Hide the Reference

```
# let next =
    let counter = ref 0 in
    fun () ->
      counter := !counter + 1; !counter ;;

val next : unit -> int = <fun>

# next ();;
   - : int = 1

# next ();;
   - : int = 2
```

Hide the Reference, Visualized

```
let next =
  let cnt = ref 0 in
    fun () ->
      cnt := !cnt + 1; !cnt
```



Quiz 2: What is wrong with the counter?

```
let next =
      fun () ->
        let counter = ref 0 in
        counter := !counter + 1;
        !counter
```

A. It returns a boolean, not an integer
B. It returns the same integer every time
C. It returns a reference to an integer instead of an integer
D. Nothing is wrong

Quiz 2: What is wrong with the counter?

```
let next =
      fun () ->
        let counter = ref 0 in
        counter := !counter + 1;
        !counter
```

A. It returns a boolean, not an integer
B. It returns the same integer every time
C. It returns a reference to an integer instead of an integer
D. Nothing is wrong

The Trade-Off Of Side Effects

- Side effects are necessary
  - That's usually why we run software! We want something to happen that we can observe
- They also make reasoning harder
  - Order of evaluation now matters
  - No referential transparency
    - Calling the same function with the same arguments may produce different results
  - Aliasing may result in hard-to-understand bugs
    - If we call a function with refs r1 and r2, it might do strange things if r1 and r2 are aliases

Order of Evaluation

- Consider this example

```
let y = ref 1;;
let f _ z = z+1;;   (* ignores first arg *)
let w = f (y:=2) !y;;
w;;
```

- What is **w** if **f**'s arguments are evaluated left to right?
  - **3**
- What if they are evaluated right to left?
  - **2**

OCaml Order of Evaluation

- In OCaml, the order of evaluation is unspecified
  - This means that the language doesn't take a stand, and different implementations may do different things
- On my Mac, OCaml evaluates right to left
  - True for the bytecode interpreter and x86 native code
  - Run the previous example and see for yourself!
- Strive to make your programs produce the same answer regardless of evaluation order

Order of Evaluation

List items are evaluated in right to left order

```
let f () = Printf.printf ″F\t";;
let g () = Printf.printf ″G\t";;
[f (); g ()]
    G   F - : unit list = [(); ()]
```

`g ()` is called before `f ()`

Quiz 3: Will **`w`**'s value differ

If evaluation order is left to right, rather than right to left?

```
let y   =  ref 1 in
let f z =  z := !z+1; !z in
let w   =  (f y) + (f y) in
w
```

A. True
B. False

Quiz 3: Will **`w`**'s value differ

If evaluation order is left to right, rather than right to left?

```
let y   =  ref 1 in
let f z =  z := !z+1; !z in
let w   =  (f y) + (f y) in
w
```

A. True
B. False

Quiz 4: Will **`w`**'s value differ

If evaluation order is left to right, rather than right to left?

```
let y   =  ref 1 in
let f z =  z := !z+1; !z in
let w   =  (f y) + !y in
w
```

A. True
B. False

Quiz 4: Will **`w`**'s value differ

If evaluation order is left to right, rather than right to left?

```
let y   =  ref 1 in
let f z =  z := !z+1; !z in
let w   =  (f y) + !y in
w
```

A. True
B. False

left to right: 4

right to left: 3

Quiz 5: Which `f` is not referentially transparent?

I.e., not the case that `f x = f y` for all `x = y`

```
A. let f z =
     let y = ref z in
     y := !y + z;
     !y
```

```
B. let f =
     let y = ref 0 in
     fun z ->
      y := !y + z; !y
```

```
C. let f z =
     let y = z in
     y+z
```

```
D. let f z = z+1
```

Quiz 5: Which `f` is not referentially transparent?

I.e., not the case that `f x = f y` for all `x = y`

```
A. let f z =
     let y = ref z in
     y := !y + z;
     !y
```

```
B. let f =
     let y = ref 0 in
     fun z ->
      y := !y + z; !y
```

```
C. let f z =
     let y = z in
     y+z
```

```
D. let f z = z+1
```

This is basically the `counter` function

Structural vs. Physical Equality

- Structural comparison: = and <>
- Physical comparison: == and !=
- let x = [1;2;3];; let y = [1;2;3];;
  - (x = y) (* true *) (x <> y) (* false *)
  - (x == y) (* false *) (x != y) (* true *)
- Mostly you want to use = and <>
  - E.g., the = operator is used for pattern matching
- But = is a problem with cyclic data structures

Equality of `refs` themselves

- Refs are compared structurally by their contents, physically by their addresses
  - ref 1 = ref 1 (* true *)
  - ref 1 <> ref 2 (* true *)
  - ref 1 != ref 1 (* true *)
  - let x = ref 1 in x == x (* true *)

Mutable fields

- Fields of a record type can be declared as mutable:

```
# type point = {x:int; y:int; mutable c:string};;
type point = { x : int; y : int; mutable c : string; }

# let p = {x=0; y=0; c="red"};;
   val p : point = {x = 0; y = 0; c = "red"}

# p.c <- “white”;;
- : unit = ()

# p;;
  p : point = {x = 0; y = 0; c = ”white"}

# p.x <- 3;;
  Error: The record field x is not mutable
```

Implementing Refs

- Ref cells are essentially syntactic sugar:

```
type 'a ref = { mutable contents: 'a }
let ref x = { contents = x }
let (!) r = r.contents
let (:=) r newval = r.contents <- newval
```

- ref type is declared in **Pervasives**
- ref functions are compiled to equivalents of above

Arrays

- **Arrays** generalize ref cells from a single mutable value to a sequence of mutable values

```
# let v = [|0.; 1.|];;
      val v : float array = [|0.; 1.|]

# v.(0) <- 5.;;
      - : unit = ()

# v;;
      - : float array = [|5.; 1.|]
```

Quiz 6: What does this evaluate to?

```
let x = [| 0; 1 |] in
let w = x in
x.(0) <- 1;
x == w
```

A. ()
B. true
C. false
D. *Type error*

Quiz 6: What does this evaluate to?

```
let x = [| 0; 1 |] in
let w = x in
x.(0) <- 1;
x == w
```

A. ()
B. **true** – they point to the same array
C. false
D. *Type error*

Control structures

- Traditional loop structures are useful with imperative features:

```
while e1 do e2 done
for x = e1 to e2 do e3 done
for x = e1 downto e2 do e3 done
```

```
for i = 1 to 5  do
  Printf.printf "%d " i
done;;
1 2 3 4 5,
```

Hash Table

- **Hashtbl Module**

```
let h = Hashtbl.create 1331;
Hashtbl.add h "alice" 100;;
Hashtbl.add h "bob" 200;;
Hashtbl.iter (Printf.printf "(%s,%d)\n")  h;;
```

```
(alice,100)
(bob,200)
```

List.assoc as Map

- An *association list is an* easy implementation of a map (aka dictionary)

```
let d = [("alice", 100); ("bob", 200);
         ("cathy", 300)]. (* (string * int) list *)
# List.assoc "alice" d;;
      - : int = 100

List.assoc "frank" d;;
  Exception: Not_found.
```

Build a Map Using Functions

```
let empty v = fun _-> 0;;
let update m k v = fun s->if k=s then v else m s

let m = empty 0;;
let m = update m "foo" 100;;
let m = update m "bar" 200;;
let m = update m "baz" 300;;

m "foo";; (* 100 *)
m "bar";; (* 200 *)
let m = update m "foo" 101;;
m "foo";; (* 101 *)
```

Challenge: change the code to return all the values for a key