CMSC 330: Organization of Programming Languages

OCaml Imperative Programming

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

- Nevertheless, 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*, as we know, but

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

References

- `'a ref`: Pointer to a mutable value of type `'a`
  - `int ref` in OCaml is like type `int *` in C
- 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

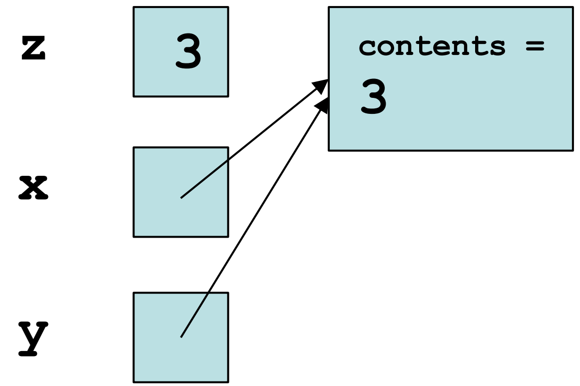
References Usage

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

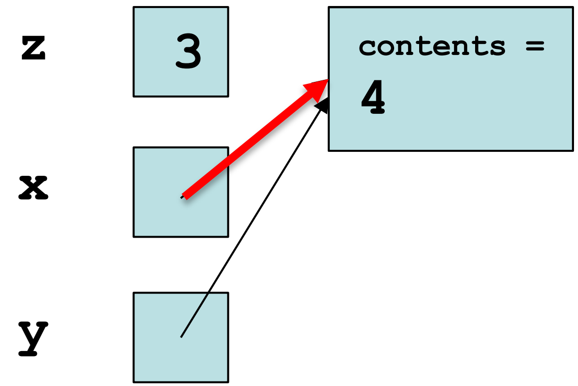
Example:

```
# 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:

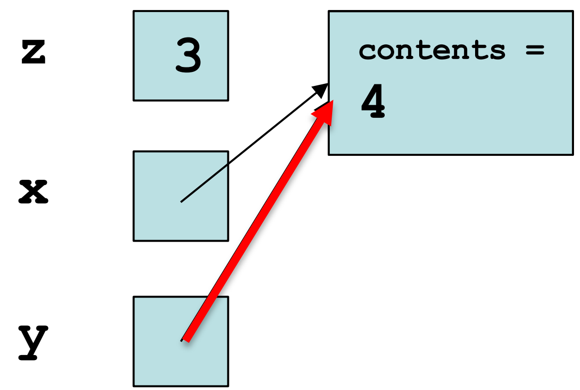
```
# let z = 3;;
val z : int = 3

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

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

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

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



Aliasing

- Reconsider our example

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

- 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 12 in
let y = ref 13 in
let z = y in
let _ = y := 4 in
let w = !y + !z in
w
```

A. 25
B. 8
C. 17
D. 16

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

```
let x = ref 12 in
let y = ref 13 in
let z = y in
let _ = y := 4 in
let w = !y + !z in
w
```

A. 25
B. 8
C. 17
D. 16

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

```
let x = ref 12 in
let y = ref 13 in
let z = !y in
let _ = y := 4 in
let w = !y + z in
w
```

A. 25
B. 8
C. 17
D. 16

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

```
let x = ref 12 in
let y = ref 13 in
let z = !y in
let _ = y := 4 in
let w = !y + z in
w
```

A. 25
B. 8
C. 17
D. 16

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`

OCaml warns if `e1`'s type is not `unit`

;; 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 always needed after each definition (but won't hurt if used)

- ***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

```
print_both ("Colorless green ", "ideas sleep")
```

Prints **"Colorless green ideas sleep"**, and returns **"Printed s and t"**

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 =
    fun () ->
      counter := !counter + 1; !counter ;;
val next : unit -> int = <fun>

# next ();;
- : int = 1

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

Hide the Reference

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

# 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

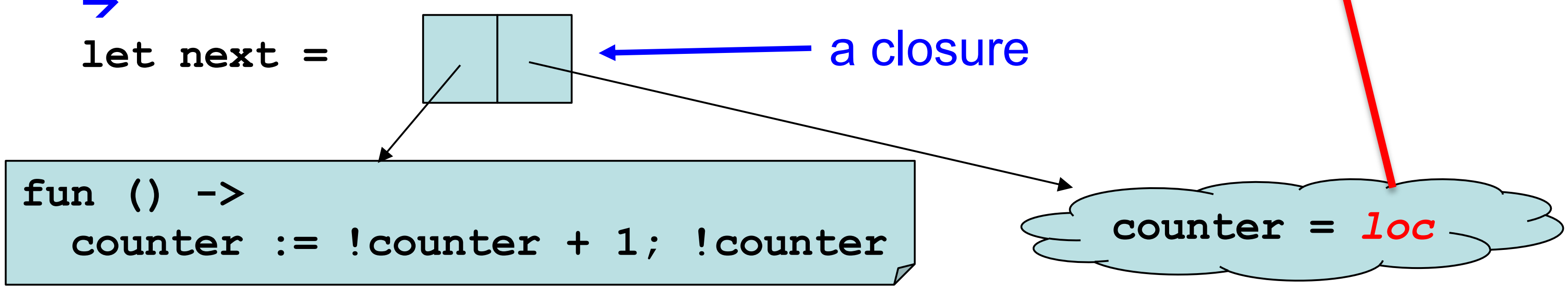
```
let next =
  let counter = ref 0 in
    fun () ->
      counter := !counter + 1; !counter
```

→

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

→

```
let next =
```



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?

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The Trade-Off Of Side Effects

- Side effects are absolutely 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+2;;   (* ignores first arg *)
let w = f (y:=2) !y;;
w;;
```

  - The first argument to the call to `f` is the result of evaluating the assignment expression `y:=2`, which is unit `()`
  - The second argument is the current contents of reference `y`
- What is `w` if `f`'s arguments are evaluated left to right?
  - **4**
- What if they are evaluated right to left?
  - **3**

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

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

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

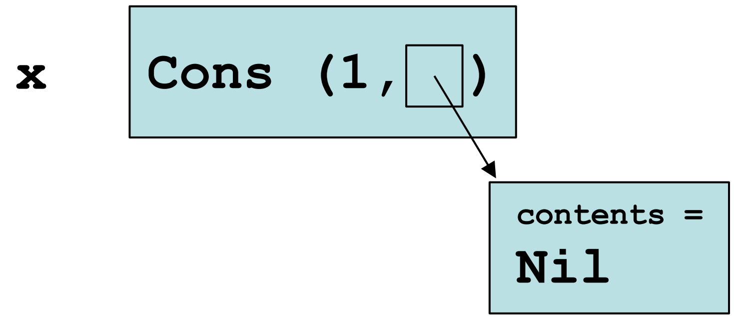
Structural vs. Physical Equality

- The = operator compares objects structurally
  - The <> operator is the negation of structural equality
- The == operator compares objects physically
  - The != operator is the negation of physical equality
- Examples
  - ([1;2;3] = [1;2;3]) = true   ([1;2;3] <> [1;2;3]) = false
  - ([1;2;3] == [1;2;3]) = false   ([1;2;3] != [1;2;3]) = true
- Mostly you want to use = and <>
  - E.g., the = operator is used for pattern matching
- But = is a problem with cyclic data structures

Cyclic Data Structures Possible With Ref

```
type 'a rlist =
  Nil | Cons of 'a * ('a rlist ref);;

let newcell x y = Cons(x,ref y);;

let updnext (Cons (_,r)) y = r := y;;
```

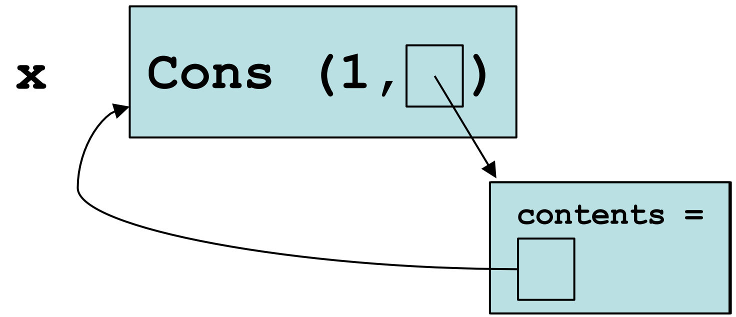
```
# let x = newcell 1 Nil;;
val x : int reflist = Cons (1, {contents = Nil})
```



Cyclic Data Structures Possible With Ref

```
type 'a rlist =
  Nil | Cons of 'a * ('a rlist ref);;

let newcell x y = Cons(x,ref y);;

let updnext (Cons (_,r)) y = r := y;;
```

```
# let x = newcell 1 Nil;;
val x : int reflist = Cons (1, {contents = Nil})

# updnext x x;;
- : unit = ()

# x == x;;
- : bool = true

# x = x;; (* hangs *)
```

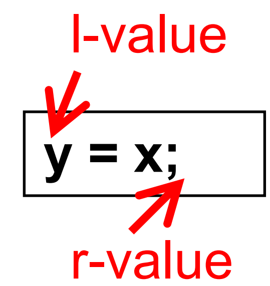


Equality of **`ref`**s themselves

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

Comparison To L- and R-values

- Recall that in C/C++/Java, there's a strong distinction between l- and r-values
  - An r-value refers to just a value, like an integer
  - An l-value refers to a location that can be written



- A variable's meaning depends on where it appears
  - On the right-hand side, it's an r-value, and it refers to the contents of the variable
  - On the left-hand side of an assignment, it's an l-value, and it refers to the location the variable is stored in

L-Values and R-Values In C

Store 3 in location x

```
int x, y;

x = 3;

y = x;

3 = x;
```

Read contents of x and store in location y

Makes no sense

- Notice that x, y, and 3 all have type **`int`**

Comparison To OCaml

C

```
int x;
int y;

x = 3;

y = x;

3 = x;
```

OCaml

```
let x = ref 0;;
let y = ref 0;;

x := 3;;   (* x : int ref *)

y := (!x);;

3 := x;;   (* 3 : int; error *)
```

- In OCaml, an updatable location and the contents of the location have different types
  - The location has a `ref` type

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;;
val 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 the above

Arrays

- **Arrays** generalize reference 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.|]
```

Arrays

- Syntax: `[|e1; ...; en|]`
- Evaluation
  - Evaluates to an n-element array, whose elements are initialized to `v1 … vn`, where `e1` evaluates to `v1`, ..., `en` evaluates to `vn`
    - Evaluates them *right to left*
- Type checking
  - `[|e1; …; en|] : t array`
    - If for all *i*, each `ei : t`

Arrays

- Syntax: `e1.(e2)`
- Evaluation
  - Evaluate *e2* to integer value *v2*
  - Evaluate *e1* to array value *v1*
  - If $0 \leq$ *v2* $< n$, where n is the length of array *v1*, then return element at offset *v2* of *v1*
  - Else raise `Invalid_argument` exception
- Type checking: `e1.(e2) : t`
  - if `e1 : t array` and `e2 : int`

Arrays

- Syntax: `e1.(e2) <- e3`
- Evaluation
  - Evaluate `e3` to `v3`
  - Evaluate `e2` to integer value `v2`
  - Evaluate `e1` to array value `v1`
  - If $0 \leq v2 < n$, where n is the length of array `v1`, then update element at offset `v2` of `v1` to `v3`
    - Else raise `Invalid_argument` exception
  - Return `()`
- Type checking: `e1.(e2) <- e3` : `unit`
  - if `e1 : t array` and `e2 : int` and `e3 : t`

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
```

Summary

- Immutability is preferred
  - Immutability makes aliasing and order of evaluation irrelevant
  - Ensures referential transparency
  - All of these make programs easier to reason about, locally

- But sometimes mutability is useful, or necessary
  - Implementing more efficient data structures
  - Interacting with the outside world

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