CMSC 330: Organization of Programming Languages

OCaml 2
Higher Order Functions

Anonymous Functions

- Recall code blocks in Ruby

  (1..10).each { |x| print x }

  - Here, we can think of { |x| print x } as a function
- We can do this (and more) in Ocaml

  range_each (1,10) (fun x -> print_int x)

  - where

```
let rec range_each (i,j) f =
  if i > j then ()
  else
    let _ = f i in (* ignore result *)
    range_each (i+1,j) f
```


Anonymous Functions

- Passing functions around is very common
  - So often we don't want to bother to give them names
- Use fun to make a function with no name

Parameter → `fun x -> x + 3` ← Body

```
(fun x -> x + 3) 5          = 8
```


All Functions Are Anonymous

- Functions are first-class, so you can bind them to other names as you like

```
let f x = x + 3
let g = f
g 5   = 8
```

- In fact, let for functions is just shorthand

```
let f x = body
   ↓       stands for
let f = fun x -> body
```

Examples

- `let next x = x + 1`
  - Short for `let next = fun x -> x + 1`
- `let plus (x, y) = x + y`
  - Short for `let plus = fun (x, y) -> x + y`
  - Which is short for
    - `let plus = fun z ->`
      `(match z with (x, y) -> x + y)`
- `let rec fact n =`
  `if n = 0 then 1 else n * fact (n-1)`
  - Short for `let rec fact = fun n ->`
    `(if n = 0 then 1 else n * fact (n-1))`

Higher-Order Functions

- In OCaml you can pass functions as arguments, and return functions as results

```
let plus_three x = x + 3
let twice f z = f (f z)
twice plus_three 5
twice : ('a->'a) -> 'a -> 'a

let plus_four x = x + 4
let pick_fn n =
    if n > 0 then plus_three else plus_four
(pick_fn 5) 0
pick_fn : int -> (int->int)
```


Currying

- We just saw a way for a function to take multiple arguments
  - The function consumes one argument at a time, returning a function that takes the rest
- This is called currying the function
  - Named after the logician Haskell B. Curry
  - But Schönfinkel and Frege discovered it
    - So it should probably be called Schönfinkelizing or Fregging

Curried Functions In OCaml

- OCaml has a really simple syntax for currying

```
let add x y = x + y
```

  - This is identical to all of the following:

```
let add = (fun x -> (fun y -> x + y))
let add = (fun x y -> x + y)
let add x = (fun y -> x+y)
```

- Thus:
  - `add` has type `int -> (int -> int)`
  - `add 3` has type `int -> int`
    - `add 3` is a function that adds 3 to its argument
  - `(add 3) 4 = 7`
- This works for any number of arguments

Curried Functions In OCaml (cont.)

- Because currying is so common, OCaml uses the following conventions:
  - `->` associates to the right
    - Thus `int -> int -> int` is the same as
    - `int -> (int -> int)`
  - function application associates to the left
    - Thus `add 3 4` is the same as
    - `(add 3) 4`

Mental Shorthand

- You can think of curried types as defining multi-argument functions
  - Type `int -> float -> float` is a function that takes an `int` and a `float` and returns a `float`
  - Type `int -> int -> int -> int` is a function that takes three `int`s and returns an `int`
- The bonus is that you can *partially* apply the function to some of its arguments
  - And apply that to the rest of the arguments later

Another Example Of Currying

- A curried add function with three arguments:

```
let add_th x y z = x + y + z
```

  - The same as

```
let add_th x = (fun y -> (fun z -> x+y+z))
```

- Then...
  - `add_th` has type `int -> (int -> (int -> int))`
  - `add_th 4` has type `int -> (int -> int)`
  - `add_th 4 5` has type `int -> int`
  - `add_th 4 5 6` is `15`

Implementing this is Challenging!

- Implementing functions that return other functions requires a clever data structure called a closure
  - We'll see how these are implemented later
- In the meantime, we will explore using higher order functions, and then discuss how they are implemented

The Map Function

- Let's write the map function (like Ruby's collect)
  - Takes a function and a list, applies the function to each element of the list, and returns a list of the results

```
let rec map f l = match l with
    [] -> []
  | (h::t) -> (f h)::(map f t)
```

```
let add_one x = x + 1
let negate x = -x
map add_one [1; 2; 3]
map negate [9; -5; 0]
```

- Type of `map`?

The Map Function (cont.)

- What is the type of the map function?

```
let rec map f l = match l with
    [] -> []
  | (h::t) -> (f h)::(map f t)
```

```
('a -> 'b) -> 'a list -> 'b list
```

`('a -> 'b)` = f; `'a list` = l

Pattern Matching With Fun

- match can be used within fun

```
map (fun l -> match l with (h::_) -> h)
    [ [1; 2; 3]; [4; 5; 6; 7]; [8; 9] ]
    = [1; 4; 8]
```

- But use named functions for complicated matches
- May use standard pattern matching abbreviations

```
map (fun (x, y) -> x+y) [(1,2); (3,4)]
    = [3; 7]
```


The Fold Function

- Common pattern
  - Iterate through list and apply function to each element, keeping track of partial results computed so far

```
let rec fold f a l = match l with
    [] -> a
  | (h::t) -> fold f (f a h) t
```

  - a = "accumulator"
  - Usually called fold left to remind us that f takes the accumulator as its first argument
- What's the type of fold?

```
= ('a -> 'b -> 'a) -> 'a -> 'b list -> 'a
```

Example

```
let rec fold f a l = match l with
    [] -> a
  | (h::t) -> fold f (f a h) t
```

```
let add a x = a + x
fold add 0 [1; 2; 3; 4] →
fold add 1 [2; 3; 4] →
fold add 3 [3; 4] →
fold add 6 [4] →
fold add 10 [] →
10
```

We just built the `sum` function!

Another Example

```
let rec fold f a l = match l with
    [] -> a
  | (h::t) -> fold f (f a h) t
```

```
let next a _ = a + 1
fold next 0 [2; 3; 4; 5] →
fold next 1 [3; 4; 5] →
fold next 2 [4; 5] →
fold next 3 [5] →
fold next 4 [] →
4
```

We just built the `length` function!

Using Fold to Build Reverse

```
let rec fold f a l = match l with
    [] -> a
  | (h::t) -> fold f (f a h) t
```

- Can you build the reverse function with fold?

```
let prepend a x = x::a
fold prepend [] [1; 2; 3; 4] →
fold prepend [1] [2; 3; 4] →
fold prepend [2; 1] [3; 4] →
fold prepend [3; 2; 1] [4] →
fold prepend [4; 3; 2; 1] [] →
[4; 3; 2; 1]
```


Currying Is Standard In OCaml

- Pretty much all functions are curried
  - Like the standard library map, fold, etc.
  - See /usr/local/ocaml/lib/ocaml on Grace
    - In particular, look at the file list.ml for standard list functions
    - Access these functions using `List.<fn name>`
    - E.g., `List.hd`, `List.length`, `List.map`
- OCaml works hard to make currying efficient
  - Otherwise it would do a lot of useless allocation of closures (which we see later) when all arguments are provided

A Convention

- Since functions are curried, function can often be used instead of match
  - function declares an anonymous function of one argument
  - Instead of

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

  - It could be written

```
let rec sum = function
   [] -> 0
 | (h::t) -> h + (sum t)
```


A Convention (cont.)

Instead of

```
let rec map f l = match l with
  [] -> []
| (h::t) -> (f h)::(map f t)
```

It could be written

```
let rec map f = function
  [] -> []
| (h::t) -> (f h)::(map f t)
```


Nested Functions

- In OCaml, you can define functions anywhere
  - Even inside of other functions

```
let sum l =
  fold (fun a x -> a + x) 0 l
```

```
let pick_one n =
  if n > 0 then (fun x -> x + 1)
  else (fun x -> x - 1)
(pick_one -5) 6   (* returns 5 *)
```


Nested Functions (cont.)

- You can also use let to define functions inside of other functions

```
let sum l =
  let add a x = a + x in
  fold add 0 l
```

```
let pick_one n =
  let add_one x = x + 1 in
  let sub_one x = x - 1 in
  if n > 0 then add_one else sub_one
```

How About This?

```
let addN n l =
  let add x = n + x in
  map add l
```

Accessing variable from outer scope

- (Equivalent to...)

```
let addN n l =
  map (fun x -> n + x) l
```


Returned Functions

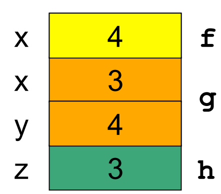
- In OCaml a function can return another function as a result; this is what currying is doing
  - Consider the following example

```
let addN n = (fun x -> x + n)
(addN 3) 4  (* returns 7 *)
```

  - When the anonymous function is called, n isn't even on the stack any more!
    - We need some way to keep n around after addN returns

The Call Stack in C/Java/etc.

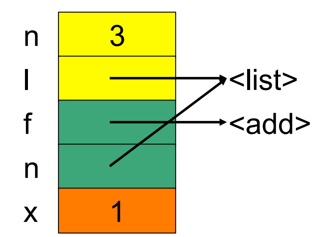
```
void f(void) {
  int x;
  x = g(3);
}
int g(int x) {
  int y;
  y = h(x);
  return y;
}
int h (int z) {
  return z + 1;
}
int main(){
  f();
  return 0;
}
```



Now Consider Returning Functions

```
let map f n = match n with
  [] -> []
| (h::t) -> (f h)::(map f t)
let addN n l =
  let add x = n + x in
  map add l
```

```
addN 3 [1; 2; 3]
```



- Uh oh...how does add know the value of n?
  - OCaml does not read it off the stack
    - The language could do this, but can be confusing (see above)
  - OCaml uses static scoping like C, C++, Java, and Ruby

Static Scoping (*aka* Lexical Scoping)

- In static or lexical scoping, (nonlocal) names refer to their nearest binding in the program text
  - Going from inner to outer scope
  - In our example, add refers to addN's n
  - C example:

Refers to the **x** at file scope – that's the nearest **x** going from inner scope to outer scope in the source code

```
int x;
void f() { x = 3; }
void g() { char *x = "hello"; f(); }
```

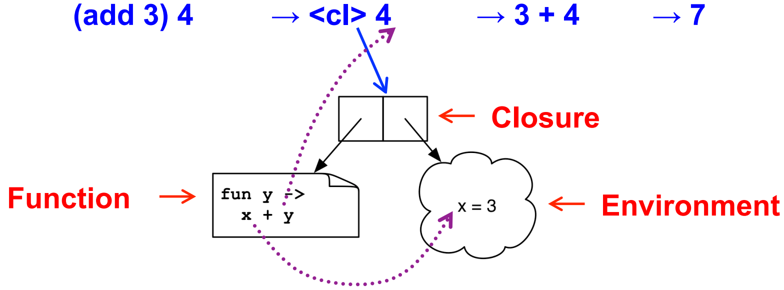

Closures Implement Static Scoping

- An environment is a mapping from variable names to values
  - Just like a stack frame
- A closure is a pair (f, e) consisting of function code f and an environment e
- When you invoke a closure, f is evaluated using e to look up variable bindings

Example – Closure 1

```
let add x = (fun y -> x + y)
```

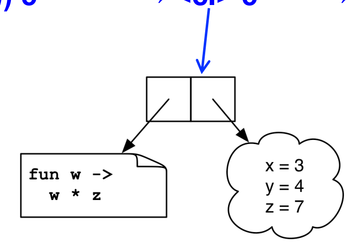
(add 3) 4 → <cl> 4 → 3 + 4 → 7



Example – Closure 2

```
let mult_sum (x, y) =
  let z = x + y in
    fun w -> w * z
```

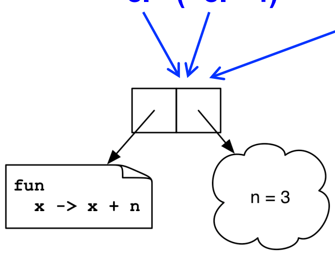
(mult_sum (3, 4)) 5 → <cl> 5 → 5 * 7 → 35



Example – Closure 3

```
let twice (n, y) =
  let f x = x + n in
    f (f y)
```

twice (3, 4) **→ <cl> (<cl> 4)** **→ <cl> 7** **→ 10**

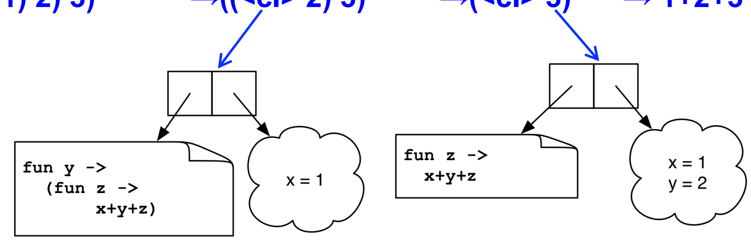


Example – Closure 4

```
let add x = (fun y -> (fun z -> x + y + z))
```

add( ) took 3 arguments? The compiler figures this out and avoids making closures

(((add 1) 2) 3) **→((<cl> 2) 3)** **→(<cl> 3)** **→ 1+2+3**



Higher-Order Functions in C

- C supports function pointers

```
typedef int (*int_func)(int);
void app(int_func f, int *a, int n) {
  for (int i = 0; i < n; i++)
    a[i] = f(a[i]);
}
int add_one(int x) { return x + 1; }
int main() {
  int a[] = {5, 6, 7};
  app(add_one, a, 3);
}
```


Higher-Order Functions in C (cont.)

- C does not support closures
  - Since no nested functions allowed
  - Unbound symbols always in global scope

```
int y = 1;
void app(int(*f)(int), n) {
  return f(n);
}
int add_y(int x) {
  return x + y;
}
int main() {
  app(add_y, 2);
}
```

Higher-Order Functions in C (cont.)

- Cannot access non-local variables in C
- OCaml code

```
let add x y = x + y
```

- Equivalent code in C is illegal

```
int (* add(int x))(int) {
  return add_y;
}
int add_y(int y) {
  return x + y; // x undefined
}
```


Higher-Order Functions in C (cont.)

- OCaml code

```
let add x y = x + y
```

- Works if C supports nested functions
  - Not in ISO C, but in gcc; but not allowed to return them

```
int (* add(int x))(int) {
  int add_y(int y) {
    return x + y;
  }
  return add_y; }
```

  - Does not allocate closure, so x popped from stack and add_y will get garbage (potentially) when called

Higher-Order Functions in Ruby

- Ruby supports higher-order functions
  - Use yield within method to call code block argument

```
def my_collect(a)
  b = Array.new(a.length)
  0.upto(a.length-1) { |i|
    b[i] = yield(a[i])
  }
  return b
end
b = my_collect([5, 6, 7]) { |x| x+1 }
```


Higher-Order Functions in Ruby (cont.)

- Ruby supports closures
  - Code blocks can access non-local variables
  - Binding determined by lexical scoping

```
def twice
  yield
  yield
end
x = 1
twice {x += 1}
puts x  # 3
```

```
def twice
  x = 0 #dynamic
  yield
  yield
end
x = 1   #lexical
twice {x += 1}
puts x  # 3 not 1
```

Higher-Order Functions in Ruby (cont.)

- Ruby code blocks are actual variables

```
def twice    # implicit block
  yield      # invoked with yield
  yield
end
twice { x += 1 }  # same as x += 2
           ↓
def quad (&block) # explicit block
  twice (&block)  # used as argument
  twice (&block)
end
quad { x += 1 }   # same as x += 4
```


Higher-Order Functions in Ruby (cont.)

- Code blocks may be saved

```
def quad (&block) # explicit block
  c = block       # no ampersand!
  twice (c)       # used as argument
  twice (c)
end
           ↓
def twice c       # arg = explicit closure
  c.call          # invoke with .call
  c.call
end
quad { x += 1 }   # same as x += 4
```


Higher-Order Functions in Ruby (cont.)

- Ruby supports creating closures directly
  - Proc.new
  - proc
  - lambda
  - method

```
c1 = Proc.new { x+=1 }
c2 = proc     { x+=1 }
c3 = lambda   { x+=1 }
def foo
  x+=1
end
c4 = method   { :foo }
          ↓
c.call    # x+=1
```


Higher-Order Functions in Java/C++

- An object in Java or C++ is kind of like a closure
  - It has some data (like an environment)
  - Along with some methods (i.e., function code)
  - So objects can be used to simulate closures
- So is an anonymous Java inner class
  - Inner class methods can access fields of outer class
- Back in CMSC 132 (OOP II)
  - We studied how to implement some functional patterns in OO languages

Java 8 Supports Lambda Expressions

- Ocaml's

  function (a, b) -> a + b

- Is like the following in Java 8

  (a, b) -> a + b

- Java 8 supports closures, and variations on this syntax

Java 8 Example

```
public class Calculator {
   interface IntegerMath { int operation(int a, int b);  }
   public int operateBinary(int a, int b, IntegerMath op) {
      return op.operation(a, b);
   }
   public static void main(String... args) {
      Calculator myApp = new Calculator();
      IntegerMath addition = (a, b) -> a + b;
      IntegerMath subtraction = (a, b) -> a - b;
      System.out.println("40 + 2 = " +
         myApp.operateBinary(40, 2, addition));
      System.out.println("20 - 10 = " +
         myApp.operateBinary(20, 10, subtraction));
   }
}
```

Lambda expressions