CMSC 330: Organization of Programming Languages

OCaml 3

Nested Functions, Closures

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

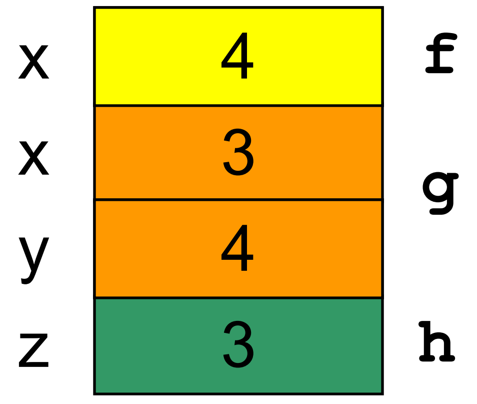
- In OCaml a function can return another function as a result; this is what currying is doing
  - Consider the following example

```
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.

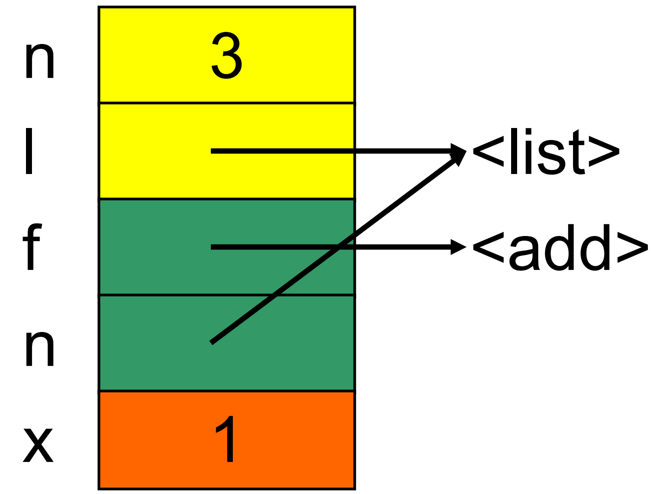
```
void f(void) {
  int x;
  x = g(3);
}
int g(int x) {
  int y;
  y = h(x);
  return y;
}
int h (int z) {
  return z + 1;
}
int main(){
  f();
  return 0;
}
```



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(); }
```

Static vs. Dynamic Scoping

```
let x = 10 ;;
let f y = x + y;;
let x = 5 ;;
let y = 7 ;;
let z = f (x + y) ;;
```

What is the value of z=?

Static vs. Dynamic Scoping

```
let x = 10 in
  let f = fun y -> x in
      let x = 20 in
  f 5
```

What is the value of z=?
10 or 20?

static: 10
dynamic: 20

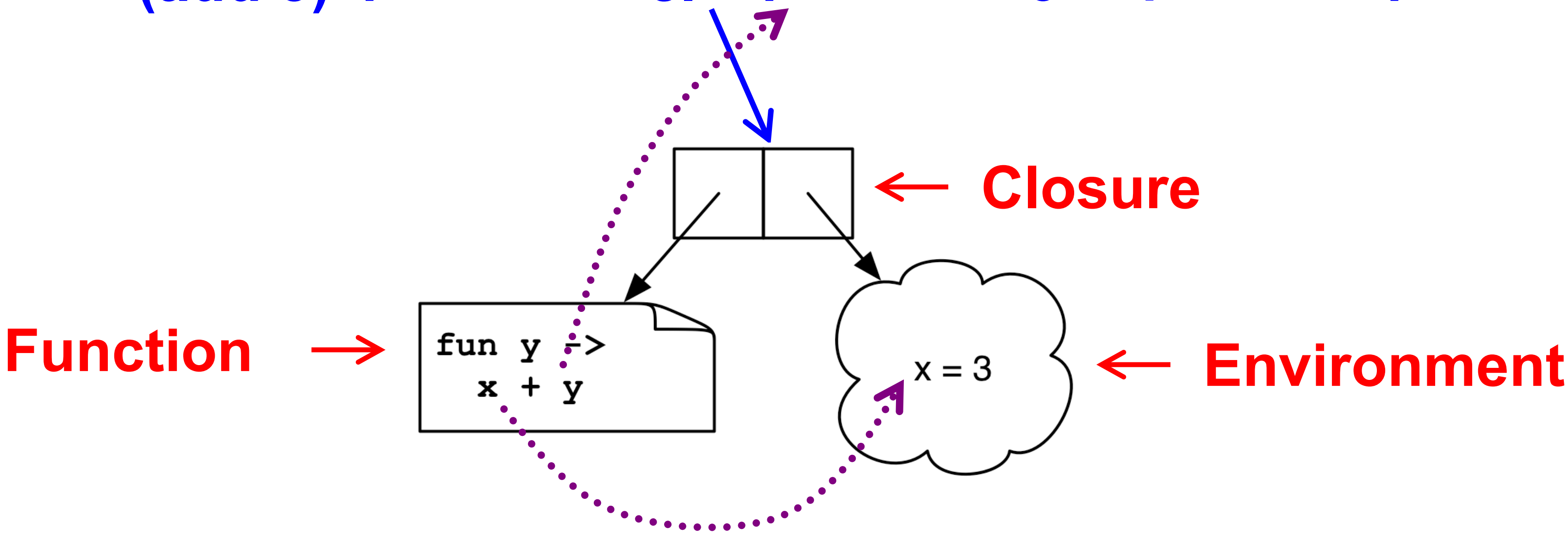
Closures Implement Static Scoping

- 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)
```

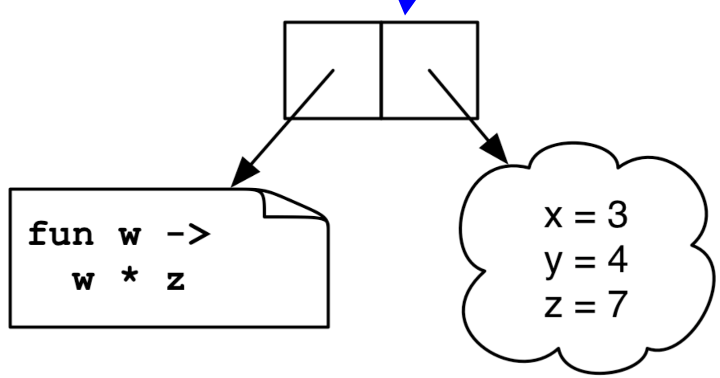
(add 3) 4 → <cl> 4 → 3 + 4 → 7



Example – Closure 2

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

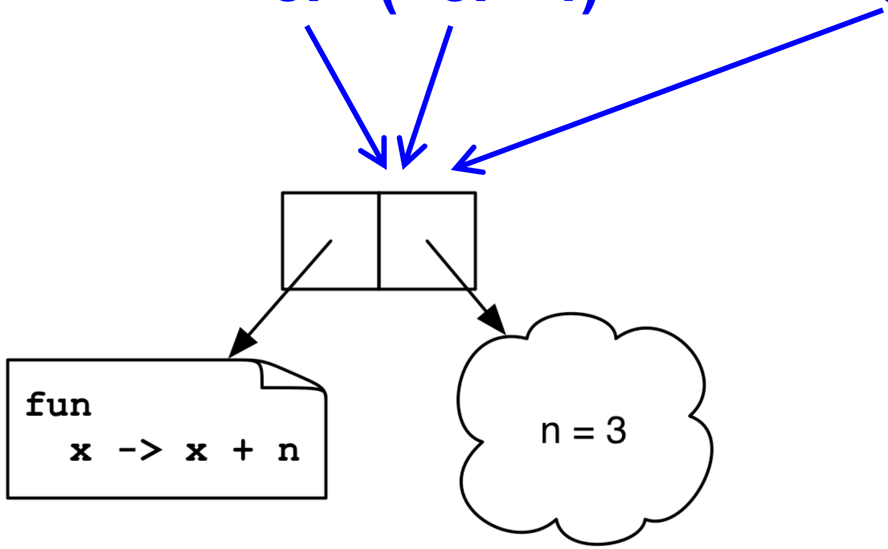
(mult_sum (3, 4)) 5 → <cl> 5 → 5 * 7 → 35



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**

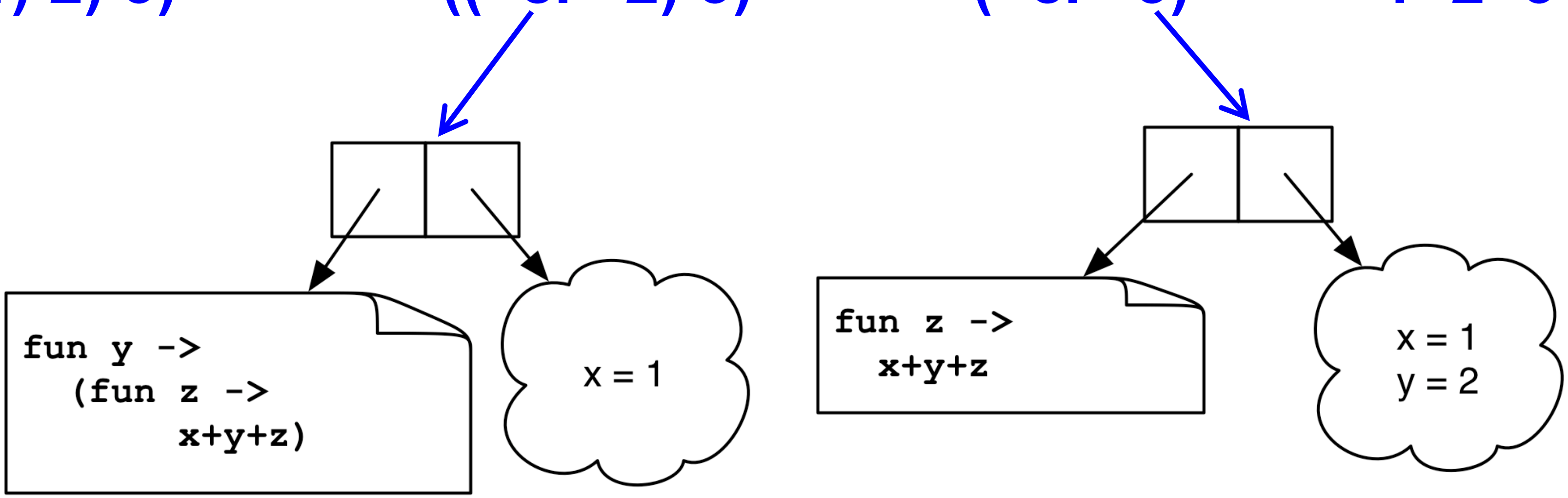


Example – Closure 4

```
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