CMSC 330: Organization of Programming Languages

Closures
(Implementing Higher Order Functions)

Returning Functions as Results

- In OCaml you can pass functions as arguments
  - to **map**, **fold**, etc.
- *and* return functions as results

```
let pick_fn n =
  let plus_three x = x + 3 in
  let plus_four x = x + 4 in
  if n > 0 then plus_three else plus_four
pick_fn : int -> (int->int)
```

- Here, **pick_fn** takes an **int** argument, and returns a function

Multi-argument Functions

- Consider a rewriting of the previous code

```
let pick_fn n =
  if n > 0 then (fun x->x+3) else (fun x->x+4)
```

- Here's another version

```
let pick_fn n =
  (fun x -> if n > 0 then x+3 else x+4)
```

- which is just shorthand for

```
let pick_fn n x =
  if n > 0 then x+3 else x+4
```

I.e., a multi-argument function!

Currying

- We just saw a way for a function to take multiple arguments!
  - The function consumes one argument and returns 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 syntax defaults to currying. E.g.,

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

  - 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

Syntax Conventions for Currying

- 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`

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`

Syntax trick: `function` vs. `fun`

- Syntax **fun *x y* … *z* -> *e*** for curried functions
- Syntax **function *ps*** for single-argument funcs
  - Where ***ps*** has the form ***p1* -> *e1* | … | *pn* -> *en***
  - Permits more expressive patterns. E.g., can write this

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

  - as this

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

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
  - Because otherwise it would do a lot of useless allocation and destruction of closures
  - What are those, you ask? Let's see …

Quiz 1: What is enabled by currying?

A. Passing functions as arguments
B. Converting easily between tuples and multiple arguments
C. Passing only a portion of the expected arguments
D. Naming arguments

Quiz 1: What is enabled by currying?

A. Passing functions as arguments
B. Converting easily between tuples and multiple arguments
C. Passing only a portion of the expected arguments
D. Naming arguments

Quiz 2: Which f definition is equivalent?

```
let f a b = a / b;;
```

```
A. let f = (fun b -> (fun a -> a / b));;
B. let f = function a | b -> a / b;;
C. let f (a, b) = a / b;;
D. let f = (fun a -> (fun b -> a / b));;
```

Quiz 2: Which f definition is equivalent?

```
let f a b = a / b;;
```

A. `let f = (fun b -> (fun a -> a / b));;`

B. `let f = function a | b -> a / b;;`

C. `let f (a, b) = a / b;;`

D. `let f = (fun a -> (fun b -> a / b));;`

How Do We Implement Currying?

- Implementing currying is tricky. Consider:

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

Accessing variable from outer scope

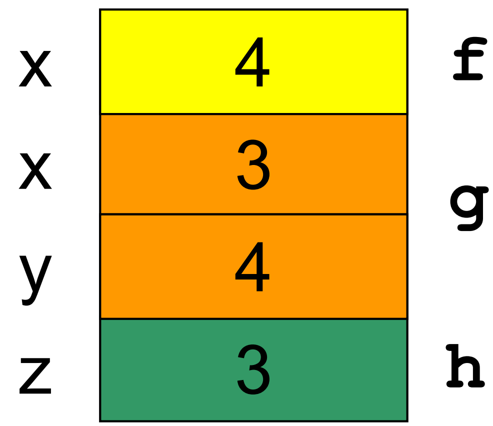
- (Equivalent to...)

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

- When the anonymous function is called by map, n may not be on the stack any more!
  - We need some way to keep n around after addN returns

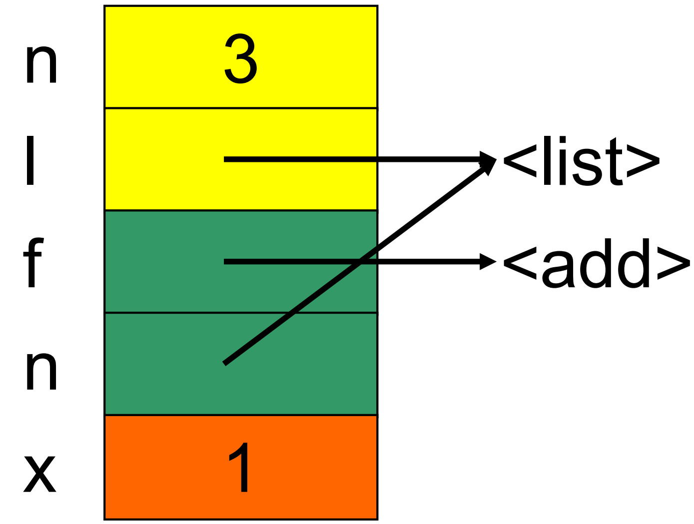
The Call Stack in C/Java/etc.

```
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

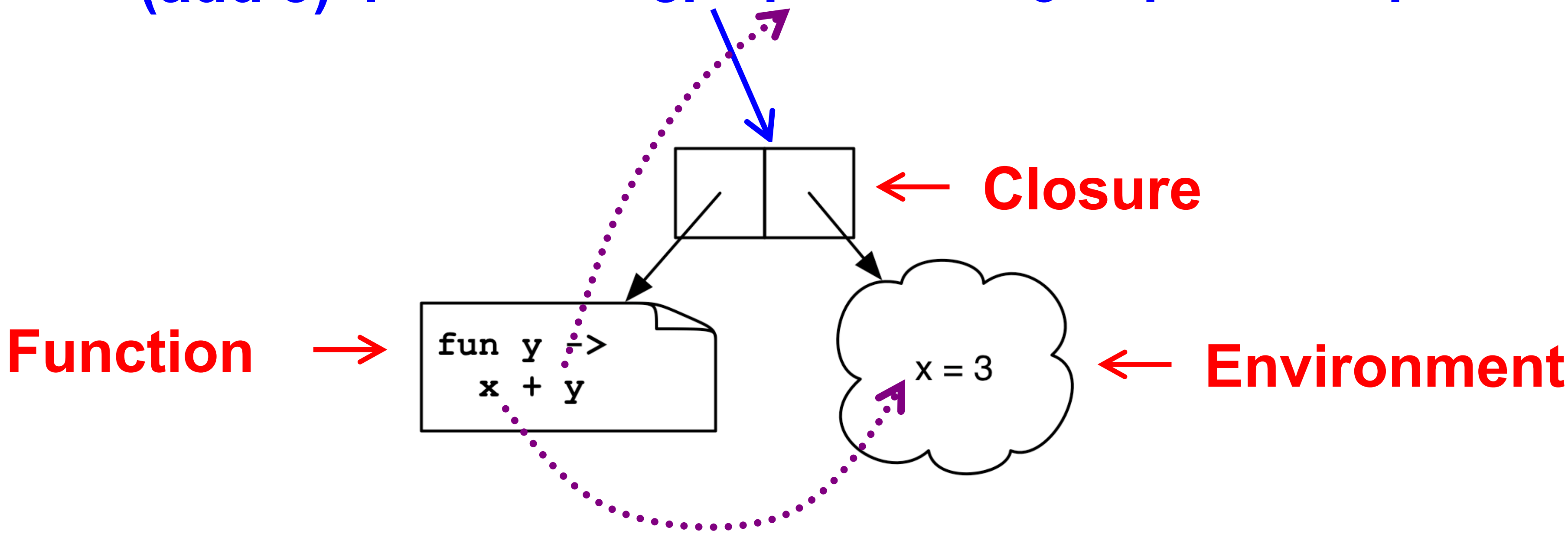
- A closure is a pair (f, e) consisting of function code f and an environment e

- 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)
```

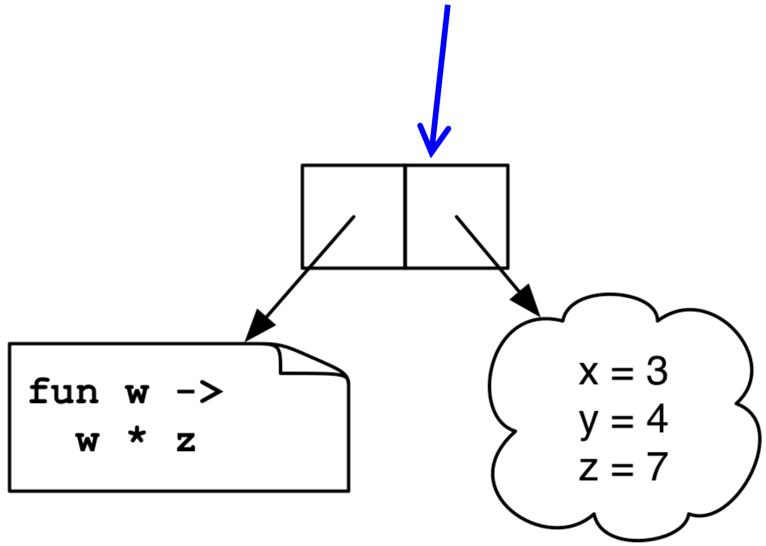
(add 3) 4 → <cl> 4 → 3 + 4 → 7



Example – Closure 2

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

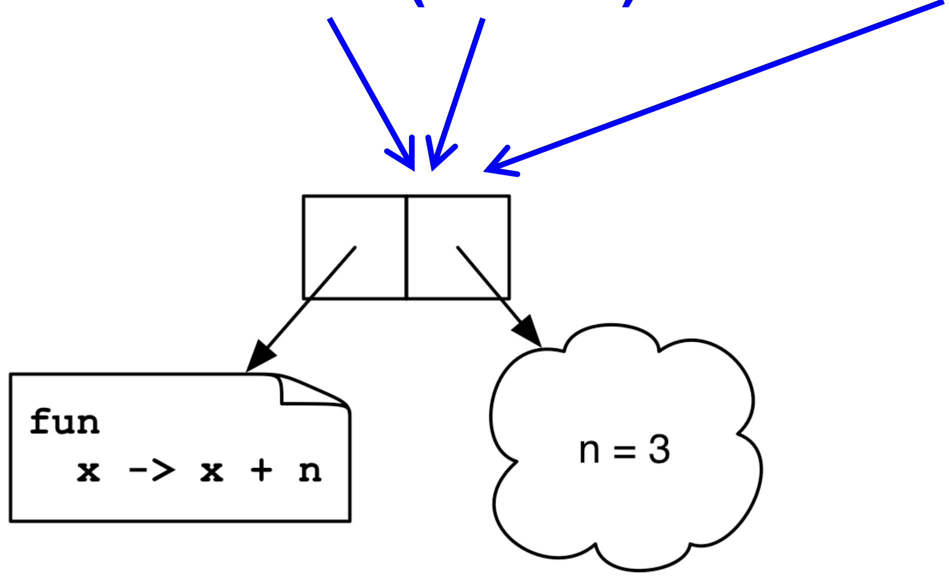
(mult_sum (3, 4)) 5 → <cl> 5 → 5 * 7 → 35



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

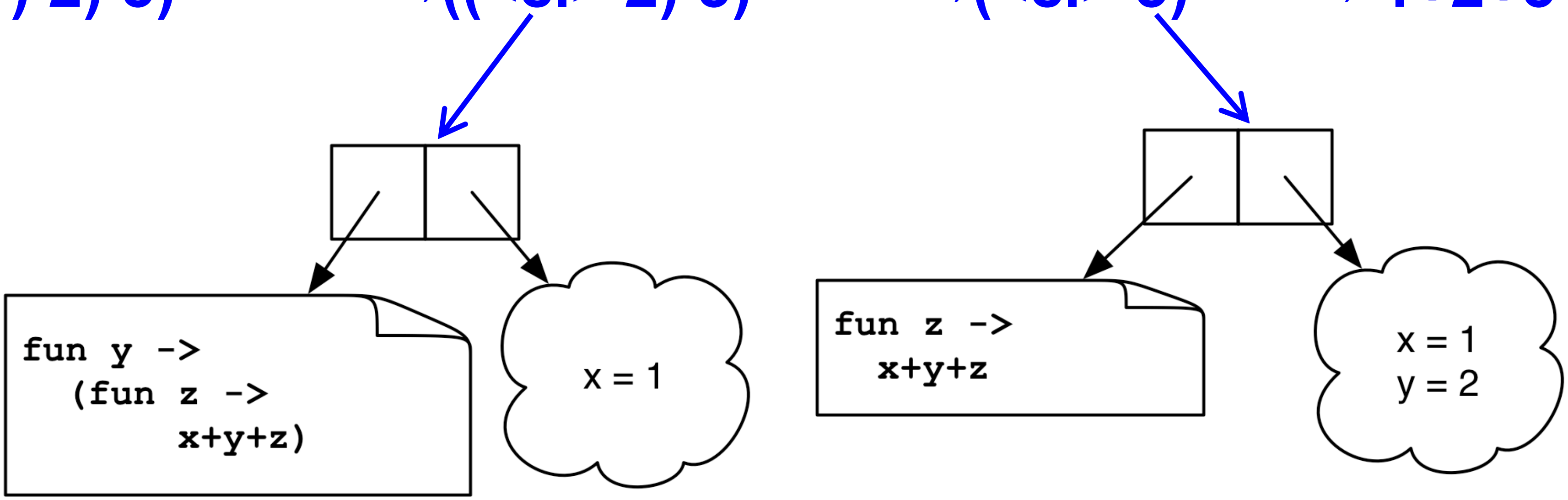


Example – Closure 4

```
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



Quiz 3: What is x?

```
let a = 0;;
let b = 1;;
let b = 10;;
let f () = a + b;;
let a = 5;;
let x = f ();;
```

A. **10**

B. **1**

C. **15**

D. Error - variable name conflicts

Quiz 3: What is x?

```
let a = 0;;
let b = 1;;
let b = 10;;
let f () = a + b;;
let a = 5;;
let x = f ();;
```

A. **10**
B. **1**
C. **15**
D. Error - variable name conflicts

Quiz 4: What is z?

```
let f x y = x - y in
let g = f 2 in
let x = 3 in
let z = g 4 in
z;;
```

A. `-1`

B. `7`

C. `-2`

D. Type Error – insufficient arguments

Quiz 4: What is z?

```
let f x y = x - y in
let g = f 2 in
let x = 3 in
let z = g 4 in
z;;
```

A. -1

B. 7

C. -2

D. Type Error – insufficient arguments

Quiz 5: What is z?

```
let f x =
  let rec g y =
    if y = 0 then x
    else g (y-1) in
  (fun z -> g z) in
let z = f 2 0 in
z;;
```

A. Type Error
B. 0
C. Infinite loop
D. 2

Quiz 5: What is z?

```
let f x =
  let rec g y =
    if y = 0 then x
    else g (y-1) in
  (fun z -> g z) in
let z = f 2 0 in
z;;
```

A. Type Error
B. 0
C. Infinite loop
D. 2

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; /* compiler error: 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

```
fun (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