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

```ocaml
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

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

- Here’s another version

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

- which is just shorthand for

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

*l.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 **Schönfinkeling** or **Fregging**
Curried Functions In OCaml

- OCaml syntax defaults to currying. E.g.,

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

• is identical to all of the following:

```ocaml
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`
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. Passing only a portion of the expected arguments
C. Naming arguments
D. Converting easily between tuples and multiple arguments
Quiz 1: What is enabled by currying?

A. Passing functions as arguments
B. Passing only a portion of the expected arguments
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D. Converting easily between tuples and multiple arguments
Quiz 2: Which f definition is equivalent?

\[
\text{let } f \ a \ b = a / b ; ;
\]

A. let f b = fun a -> a / b ;;
B. let f = fun 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 b = fun a -> a / b;;
B. let f = fun 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:

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

• (Equivalent to...)

```ocaml
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.

```c
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;
}
```

```
x  4  f
x  3  g
y  4  h
z  3
```

x = 3
y = 4
z = 3
Now Consider Returning Functions

Let's consider the function `addN`:

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

This example uses the `map` function from the OCaml standard library. The function `addN` takes two arguments: `n` (the value to add to each element of the list `l`) and the list `l` itself. The inner function `add x = n + x` is used to add `n` to each element of the list.

### 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

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

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

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

Function  Closure  Environment
Example – Closure 2

```ocaml
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

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

A. 10
B. 1
C. 15
D. Error - variable name conflicts
Quiz 3: What is x?

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

A. 10
B. 1
C. 15
D. Error - variable name conflicts
Quiz 4: What is z?

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

A. 7
B. -2
C. -1
D. Type Error – insufficient arguments
Quiz 4: What is z?

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

A. 7
B. -2
C. -1
D. Type Error – insufficient arguments
Quiz 5: What is $z$?

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

```ocaml

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;;

```
Quiz 5: What is \( z \)?

```ocaml
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**

```c
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);
}
```
C does not support closures

• Since no nested functions allowed
• Unbound symbols always in global scope

```c
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

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

- Equivalent code in C is illegal

```c
int (* add(int x))(int) {
    return add_y;
}
int add_y(int y) {
    return x + y; /* error: x undefined */
}```
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
Java 8 Supports Lambda Expressions

- Ocaml’s
  
  \[
  \text{fun (a, b) -> a + b}
  \]

- Is like the following in Java 8
  
  \[
  (a, b) -> a + b
  \]

- Java 8 supports closures, and variations on this syntax
Java 8 Example

```java
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