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 you can 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
val pick_fn : int -> (int->int) = <fun>
```

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

```ocaml
# let g = pick_fn 2;;
val g : int -> int = <fun>
# g 4;;  (* evaluates to 7 *)
```
Multi-argument Functions

- Consider a rewriting of the prior code (above)

  ```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)
  ```

- … the shorthand for which is just

  ```ml
  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!
  - I.e., no separate concept of multi-argument functions – can encode one as a function that takes a single argument and returns a function that takes the rest

- This encoding is called currying the function
  - Named after the logician Haskell B. Curry
  - But Schönfinkel and Frege discovered it
    - So maybe it should 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 from the right
    - Thus `int -> int -> int` is the same as
    - `int -> (int -> int)`

  - function application associates from the left
    - Thus `add 3 4` is the same as
    - `(add 3) 4`
Quiz 1: Which f definition is equivalent?

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

A. let f b = fun a -> a / b;;  
B. let f = fun a -> (fun b -> a / b);;  
C. let f = fun a | b -> a / b;;  
D. let f (a, b) = a / b;;
Quiz 1: Which f definition is equivalent?

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

A. `let f b = fun a -> a / b;;`
B. `let f = fun a -> (fun b -> a / b);;`
C. `let f = fun a | b -> a / b;;`
D. `let f (a, b) = a / b;;`
Quiz 2: What is enabled by currying?

A. Passing functions as arguments
B. Passing only a portion of the expected arguments
C. Naming arguments
D. Recursive functions
Quiz 2: What is enabled by currying?

A. Passing functions as arguments
B. Passing only a portion of the expected arguments
C. Naming arguments
D. Recursive functions
Multiple Arguments, Partial Application

Another way you could encode support for multiple arguments is using tuples

- \( \text{let } f \ (a,b) = a / b \) (* int*int \( \rightarrow \) int *
- \( \text{let } f \ a \ b = a / b \) (* int\( \rightarrow \) int\( \rightarrow \) int *

Is there a benefit to using currying instead?
- Supports **partial application** – useful when you want to provide some arguments now, the rest later
  - \( \text{let } \text{add} \ a \ b = a + b;; \)
  - \( \text{let } \text{addthree} = \text{add} \ 3;; \)
  - \( \text{addthree} \ 4;; \) (* evaluates to 7 *)
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 …
Closure
public class Test{
    public void doSomething(){
        int a = 10; //must be final
        Runnable runnable = new Runnable(){
            public void run(){
                int b = a + 1;
                System.out.println(b);
            }
        };
        (new Thread(runnable)).start(); //runs later
        //a = 100; //not allowed
    }
    public static void main(String[] args){
        Test t = new Test();
        t.doSomething();
    }
} // a=10 is removed from the stack here

Needed later, makes copy of a
let foo x =
  let bar = fun y -> x + y in
  bar
;;

foo 10 = ?

(fun y -> x + y) 10?

Where is x?
Another Example

```ocaml
let x = 1 in
let f = fun y -> x in
let x = 2 in
f 0
```

What does this expression should evaluate to?

A. 1
B. 2
Another Example

let x = 1 in
let f = fun y -> x in
let x = 2 in
f 0

What does this expression should evaluate to?

A. 1
B. 2
Scope

- **Dynamic scope**
  - The body of a function is evaluated in the current dynamic environment at the time the function is **called**, not the old dynamic environment that existed at the time the function was defined.

- **Lexical scope**
  - The body of a function is evaluated in the old dynamic environment that existed at the time the function was **defined**, not the current environment when the function is called.
Closure

let foo x =
    let bar y = x + y
in
bar ;;

foo 3

let x = 1 in
let f = fun y -> x
in
let x = 2 in
f 0
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)

(\( \text{add 3} \)) 4 \rightarrow \langle \text{cl} \rangle 4 \rightarrow 3 + 4 \rightarrow 7
Example – Closure 2

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

\((\text{mult}_\text{sum} (3, 4)) 5\)

\(\rightarrow \langle \text{cl} \rangle \ 5 \quad \rightarrow \ 5 \ast 7 \quad \rightarrow \ 35\)
Quiz 3: What is x?

```ocaml
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?

```
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?

\[
\begin{align*}
\text{let } & f \ x = \text{fun } y \rightarrow x - y \text{ in} \\
\text{let } & g = f \ 2 \text{ in} \\
\text{let } & x = 3 \text{ in} \\
\text{let } & z = g \ 4 \text{ in} \\
\text{z};;
\end{align*}
\]

A. 7
B. -2
C. -1
D. Type Error – insufficient arguments
Quiz 5: What does this evaluate to?

```ocaml
let f x = x+1 in
let g = f in
g (fun i -> i+1) 1
```

A. Type Error
B. 1
C. 2
D. 3
Quiz 5: What does this evaluate to?

```
let f x = x+1 in
let g = f in
(g (fun i -> i+1)) 1
```

A. Type Error – Too many arguments passed to g (application is left associative)

B. 1

C. 2

D. 3
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);
}
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 */
}
```
Higher-Order Functions in C (cont.)

- OCaml code

```ocaml
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

```c
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
  \[
  \text{fun } (a, b) \rightarrow a + b
  \]

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

- Java 8 supports closures, and variations on this syntax
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));
    }
}