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
define 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 *)
```
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 Schönfinkelizing 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?

```plaintext
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 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 | b -> a / b;;`
C. `let f (a, b) = a / b;;`
D. `let f = fun a -> (fun 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
  - `let f (a,b) = a / b (* int*int -> int *)`
  - `let f a b = a / b (* int-> int-> int *)`

- Is there a benefit to using currying instead?
  - Supports **partial application** – useful when you want to provide some arguments now, the rest later
  - `let add a b = a + b;;`
  - `let addthree = add 3;;`
  - `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
let foo x =
    let bar y = x + y in
    bar
;;

foo 10 = ?

(fun y -> x + y) ?

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 ;;

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

$\text{let add } x = (\text{fun } y \rightarrow x + y)$

\[
\begin{align*}
\text{(add 3) 4} & \rightarrow <\text{cl}> 4 \rightarrow 3 + 4 \rightarrow 7
\end{align*}
\]
Example – Closure 2

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

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

```
fun w ->
  w * z
```

```
x = 3
y = 4
z = 7
```
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 \( z \)?

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

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

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

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

```plaintext
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
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);
}
```
Higher-Order Functions in C (cont.)

- 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));
    }
}