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

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

Here’s another version

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

which is just shorthand for

```plaintext
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.,

```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
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. 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:

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

• (Equivalent to...)

```ocaml
def 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
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

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

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

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

\[(\text{mult}_\text{sum} (3, 4)) 5 \rightarrow \text{<cl> 5} \rightarrow 5 \times 7 \rightarrow 35\]
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
```

```
fun y ->
  (fun z ->
    x + y + z)

fun z ->
  x + y + z

x = 1
y = 2
x = 1
```
Quiz 3: What is x?

```ml
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?

```ocaml
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 \( z \)?

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

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

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

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?

```
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);
}
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; /* compiler 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
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