CMSC 330: Organization of Programming Languages

OCaml 4

Exceptions, Modules, Assignment, Language Comparisons

This Lecture

- Exceptions
- Modules
- Imperative OCaml
- Language comparisons

OCaml Exceptions

```
exception My_exception of int
let f n =
  if n > 0 then
    raise (My_exception n)
  else
    raise (Failure "foo")
let bar n =
  try
    f n
  with My_exception n ->
      Printf.printf "Caught %d\n" n
    | Failure s ->
      Printf.printf "Caught %s\n" s
```


OCaml Exceptions (cont.)

- Exceptions are declared with exception
  - They may appear in the signature as well
- Exceptions may take arguments
  - Just like type constructors
  - May also be nullary
- Catch exceptions with try...with...
  - Pattern-matching can be used in with
  - If an exception is uncaught
    - Current function exits immediately
    - Control transfers up the call chain
    - Until the exception is caught, or reaches the top level

OCaml Exceptions (cont.)

- Exceptions may be thrown by I/O statements
  - Common way to detect end of file
  - Need to decide how to handle exception
- Example

```
try
  (input_char stdin)    (* reads 1 char *)
with End_of_file -> 0   (* return 0?    *)

try
  read_line ()          (* reads 1 line *)
with End_of_file -> ""  (* return ""?   *)
```


Modules

- So far, most everything we've defined
  - Has been at the "top-level" of OCaml
  - This is not good software engineering practice
- A better idea
  - Use modules to group together associated
    - Types, functions, and data
  - Avoid polluting the top-level with unnecessary stuff
- For lots of sample modules
  - See the OCaml standard library

Modularity and Abstraction

- Another reason for creating a module
  - So we can hide details
  - Example
    - Build a binary tree module
    - Hide exact representation of binary trees
  - This is also good software engineering practice
    - Prevents clients from relying on details that may change
    - Hides unimportant information
    - Promotes local understanding (clients can't inject arbitrary data structures, only ones our functions create)

Modularity

- Definition
  - Extent to which a computer program is composed of separate parts
  - Higher degree of modularity is better
- Modular programming
  - Programming techniques that increase modularity
    - Interface vs. implementation
- Modular programming languages
  - Explicit support for modules
  - Ada, Fortran, ML, Modula-2, Python, Ruby, OCaml

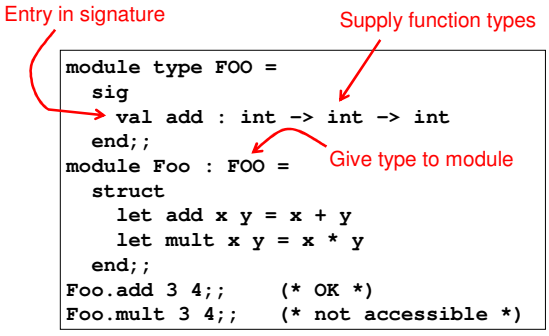
Creating a Module in OCaml

```
module Shapes =
  struct
    type shape =
       Rect of float * float  (* wid*len *)
     | Circle of float        (* radius  *)

    let area = function
       Rect (w, l) -> w *. l
     | Circle r -> r  *. r *. 3.14

    let unit_circle = Circle 1.0
  end;;
```


Creating a Module in OCaml (cont.)

```
module Shapes =
  struct
    type shape = …
    let area = …
    let unit_circle = …
  end;;
unit_circle;;   (* not defined *)
Shapes.unit_circle;;
Shapes.area (Shapes.Rect (3.0, 4.0));;
open Shapes;; (* import names
                 into curr scope *)
unit_circle;;   (* now defined *)
```


Module Signatures



Module Signatures (cont.)

- Convention
  - Signatures to be all capital letters
  - This isn't a strict requirement, though
- Items can be omitted from a module signature
  - This provides the ability to hide values
- The default signature for a module hides nothing
  - You'll notice this is what OCaml gives you if you just type in a module with no signature at the top-level

Abstract Types in Signatures

```
module type SHAPES =
  sig
    type shape
    val area : shape -> float
    val unit_circle : shape
    val make_circle : float -> shape
    val make_rect : float -> float -> shape
end;;

module Shapes : SHAPES =
  struct
    ...
    let make_circle r = Circle r
    let make_rect x y = Rect (x, y)
  end
```

- Now definition of **`shape`** is hidden

Abstract Types in Signatures

```
# Shapes.unit_circle
- : Shapes.shape = <abstr>  (* OCaml won't show impl *)
# Shapes.Circle 1.0
Unbound Constructor Shapes.Circle
# Shapes.area (Shapes.make_circle 3.0)
- : float = 29.5788
# open Shapes;;
# (* doesn't make anything abstract accessible *)
```

- How does this compare to modularity in...
  - C?
  - C++?
  - Java?

.ml and .mli files

- Put the signature in a foo.mli file, the struct in a foo.ml file
  - Use the same names
  - Omit the sig...end and struct...end parts
  - The OCaml compiler will make a Foo module from these

Example – OCaml Module Signatures

shapes.mli

```
type shape
val area : shape -> float
val unit_circle : shape
val make_circle : float -> shape
val make_rect : float -> float -> shape
```

shapes.ml

```
type shape =
  Rect of ...
...
let make_circle r = Circle r
let make_rect x y = Rect (x, y)
```

```
% ocamlc shapes.mli   # produces shapes.cmi
% ocamlc shapes.ml    # produces shapes.cmo
ocaml
# #load "shapes.cmo"  (* load Shapes module *)
```


Functors

- Modules can take other modules as arguments
  - Such a module is called a functor
  - You're mostly on your own if you want to use these
- Example: **`Set`** in standard library

```
module type OrderedType = sig
  type t
  val compare : t -> t -> int
end

module Make(Ord: OrderedType) =
struct ... end

module StringSet = Set.Make(String);;
(* works because String has type t,
implements compare *)
```


Module in Java

- Java classes are like modules
  - Provides implementations for a group of functions
  - But classes can also
    - Instantiate objects
    - Inherit attributes from other classes
- Java interfaces are like module signatures
  - Defines a group of functions that may be used
  - Implementation is hidden

Module in C

- .c files are like modules
  - Provides implementations for a group of functions
- .h files are like module signatures
  - Defines a group of functions that may be used
  - Implementation is hidden
- Usage is not enforced by C language
  - Can put C code in .h file

Module in Ruby

- Ruby explicitly supports modules
  - Modules defined by module … end
  - Modules cannot
    - Instantiate objects
    - Derive subclasses

```
puts Math.sqrt(4)     # 2
puts Math::PI         # 3.1416

include Math          # open Math
puts Sqrt(4)          # 2
puts PI               # 3.1416
```


So Far, Only Functional Programming

- We haven't given you any way so far to change something in memory
  - All you can do is create new values from old
- This actually makes programming easier !
  - Don't care whether data is shared in memory
    - Aliasing is irrelevant
  - Provides strong support for compositional reasoning and abstraction
    - Example: Calling a function f with argument x always produces the same result
  - But could take (much) more memory & time to execute

Imperative OCaml

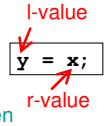
- There are three basic operations on memory

1) `ref : 'a -> 'a ref`
   - Allocate an updatable reference
2) `! : 'a ref -> 'a`
   - Read the value stored in reference
3) `:= : 'a ref -> 'a -> unit`
   - Write to a reference

```
let x = ref 3   (* x : int ref *)
let y = !x
x := 4
```

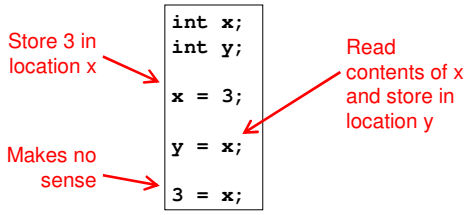

Comparison to L- and R-values

- Recall that in C/C++/Java, there's a strong distinction between l- and r-values
  - An r-value refers to just a value, like an integer
  - An l-value refers to a location that can be written



- A variable's meaning depends on where it appears
  - On the right-hand side, it's an r-value, and it refers to the contents of the variable
  - On the left-hand side of an assignment, it's an l-value, and it refers to the location the variable is stored in

L-Values and R-Values in C (cont.)



- Notice that x, y, 3 all have the same type: `int`

Comparison to OCaml

C
```
int x;
Int y;

x = 3;

y = x;

3 = x;
```

OCaml
```
let x = ref 0;;
let y = ref 0;;

x := 3;;   (* x : int ref *)

y := (!x);;

3 := x;;   (* 3 : int; error *)
```

- In OCaml, an updatable location and the contents of the location have different types
  - The location has a **ref** type

Capturing a ref in a Closure

- We can use refs to make things like counters that produce a fresh number "everywhere"

```
let next =
  let count = ref 0 in
    function () ->
      let temp = !count in
        count := (!count) + 1;
        temp;;
# next ();;
- : int = 0
# next ();;
- : int = 1
```


Semicolon Revisited; Side Effects

- Now that we can update memory, we have a real use for ; and ( ) : unit
  - e1; e2 means evaluate e1, throw away the result, and then evaluate e2, and return the value of e2
  - () means "no interesting result here"
  - It's only interesting to throw away values or use ()
    - If computation does something besides return a result
- A side effect is a visible state change
  - Modifying memory
  - Printing to output
  - Writing to disk

Grouping with begin...end

- If you're not sure about the scoping rules, use begin...end to group together statements with semicolons

```
let x = ref 0

let f () =
  begin
    print_string "hello";
    x := (!x) + 1
  end
```


The Trade-Off of Side Effects

- Side effects are absolutely necessary
  - That's usually why we run software!
  - We want something to happen that we can observe
- But…they also make reasoning harder
  - Order of evaluation now matters
  - Calling the same function in different places may produce different results
  - Aliasing is an issue
    - If we call a function with refs r1 and r2, it might do strange things if r1 and r2 are aliased

OCaml Language Choices

- Implicit or explicit declarations?
  - Explicit – variables must be introduced with let before use
  - But you don't need to specify type of variable
- Static or dynamic types?
  - Static – but without type declarations
  - OCaml does type inference to figure out types for you
    - Advantage – less work to write programs
    - Disadvantages – easier to make mistakes, harder to find errors

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; // 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

```
int (* add(int x))(int) {
  int add_y(int y) {
    return x + y;
  }
  return add_y;
}
```


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