CMSC 330: Organization of Programming Languages

OCaml 4
Data Types & Modules

OCaml Data

- So far, we've seen the following kinds of data
  - Basic types (int, float, char, string)
  - Lists
    - One kind of data structure
    - A list is either [ ] or h::t, deconstructed with pattern matching
  - Tuples
    - Let you collect data together in fixed-size pieces
  - Functions
- How can we build other data structures?
  - Building everything from lists and tuples is awkward

User Defined Types

- type can be used to create new names for types
  - Useful for combinations of lists and tuples
- Examples
  - `type my_type = int * (int list)`
    `((3, [1; 2]) : my_type)`
  - `type my_type2 = int * char * (int * float)`
    `((3, 'a', (5, 3.0)) : my_type2)`

Variation: Shapes in Java

```
public interface Shape {
    public double area();
}
```

How to achieve this in Ocaml?

```
class Rect implements Shape {
  private double width, length;

  Rect (double width, double length) {
    this.width = width;
    this.length = length;
  }

  double area() {
    return width * length;
  }
}
```

```
class Circle implements Shape {
  private double radius;

  Circle (double radius) {
    this.radius = radius;
  }

  double area() {
    return radius * radius * 3.14159;
  }
}
```

Data Types

- type can also be used to create variant types
  - Equivalent to C-style unions

```
type shape =
    Rect of float * float  (* width*length *)
  | Circle of float        (* radius *)
```

- `Rect` and `Circle` are value constructors
  - Here a `shape` is either a `Rect` or a `Circle`
- Constructors must begin with uppercase letter

Data Types (cont.)

```
let area s =
  match s with
     Rect (w, l) -> w *. l
   | Circle r -> r *. r *. 3.14

area (Rect (3.0, 4.0))
area (Circle 3.0)
```

Unlike classes in Java, shape functions are separate from shape data – will later examine tradeoffs

- Use pattern matching to deconstruct values
  - s is a `shape`
  - Do different things for s depending on its constructor

Data Types (cont.)

```
type shape =
    Rect of float * float (* width*length *)
  | Circle of float       (* radius *)

let lst = [Rect (3.0, 4.0) ; Circle 3.0]
```

- What's the type of `lst`?
  - `shape list`
- What's the type of `lst`'s first element?
  - `shape`

Option Type

```
type optional_int =
    None
  | Some of int
let add_with_default a x = match x with
     None -> a + 42
   | Some n -> a + n
add_with_default 3 None      (* 45 *)
add_with_default 3 (Some 4)  (* 7  *)
```

- This option type can work with any kind of data
  - In fact, this option type is built into Ocaml
  - Specify as: int option, char option, etc...

Recursive Data Types

- We can build up lists with variant types

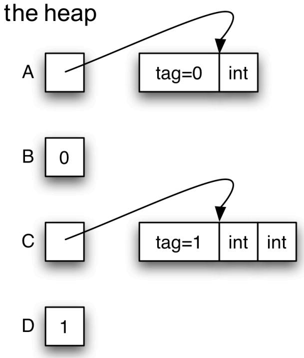
```
type 'a list =
   Nil
 | Cons of 'a * 'a list

let rec len = function
   Nil -> 0
 | Cons (_, t) -> 1 + (len t)

len (Cons (10, Cons (20, Cons (30, Nil))))
```

  - Won't have nice [1; 2; 3] syntax for this kind of list

Data Type Representations

- Values in a data type are stored
  1. Directly as integers
  2. As pointers to blocks in the heap

```
type t =
   A of int
 | B
 | C of int * int
 | D
```



Exercise: A Binary Tree Data Type

- Write type **bin_tree** for binary trees over **int**
  - Trees should be ordered (binary search tree)
- Implement the following

```
empty : bin_tree
is_empty : bin_tree -> bool
member : int -> bin_tree -> bool
insert : int -> bin_tree -> bin_tree
remove: int -> bin_tree -> bin_tree
equal : bin_tree -> bin_tree -> bool
fold : (int -> 'a -> 'a) -> bin_tree
       -> 'a -> 'a
```


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 associated types, functions, and data together
  - Avoid polluting the top-level with unnecessary stuff
- For lots of sample modules, see the OCaml standard library

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  *)
```


Modularity And Abstraction

- Another reason for creating a module is so we can hide details
  - Ex: Binary tree module
    - May not want to expose 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)

Module Signatures

Entry in signature

Supply function types

Give type to module

```
module type FOO =
  sig
    val add : int -> int -> int
  end;;
module Foo : FOO =
  struct
    let add x y = x + y
    let mult x y = x * y
  end;;
Foo.add 3 4;;    (* OK *)
Foo.mult 3 4;;   (* not accessible *)
```

Module Signatures (cont.)

- Convention: Signature names in all-caps
  - 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?

Modules 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

Modules 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
```


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
```


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 have no arguments
- 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 until it 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  “”?     *)
```


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 in some ways
  - Don't care whether data is shared in memory
    - Aliasing is irrelevant
  - Provides strong support for compositional reasoning and abstraction
    - Ex: Calling a function f with argument x always produces the same result

Imperative OCaml

- There are three basic operations on memory:
  - `ref : 'a -> 'a ref`
    - Allocate an updatable reference
  - `! : 'a ref -> 'a`
    - Read the value stored in reference
  - `:= : '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

l-value

y = x;

r-value

- 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

```
int x, y;

x = 3;

y = x;

3 = x;
```

Store 3 in location x → `x = 3;`

Read contents of x and store in location y → `y = x;`

Makes no sense → `3 = x;`

- Notice that x, y, and 3 all have 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 Needed For Side Effects

- Now that we can update memory, we have a 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

Examples – Semicolon

- Definition
  - e1 ; e2 (* evaluate e1, evaluate e2, return e2)
- 1 ; 2 ;;
  - (* 2 – value of 2nd expression is returned *)
- (1 + 2) ; 4 ;;
  - (* 4 – value of 2nd expression is returned *)
- 1 + (2 ; 4) ;;
  - (* 5 – value of 2nd expression is returned to 1 + *)
- 1 + 2 ; 4 ;;
  - (* 4 – because + has higher precedence than ; *)

;; versus ;

- ;; ends an expression in the top-level of OCaml
  - Use it to say: "Give me the value of this expression"
  - Not used in the body of a function
  - Not needed after each function definition
    - Though for now it won't hurt if used there
- e1; e2 evaluates e1 and then e2, and returns e2

```
let print_both (s, t) = print_string s; print_string t;
                        "Printed s and t"
```

  - notice no ; at end – it's a separator, not a terminator

```
print_both ("Colorless green ", "ideas sleep")
```

Prints `"Colorless green ideas sleep"`, and returns `"Printed s and t"`

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
- They also make reasoning harder
  - Order of evaluation now matters
  - Calling the same function in different places may produce different results
  - Aliasing (two references to same object) is an issue
    - If we call a function with refs r1 and r2, it might do strange things if r1 and r2 are aliased

Structural Vs. Physical Equality

- In OCaml, the = operator compares objects structurally
  - [1;2;3] = [1;2;3]   (* true *)
  - (1,2) = (1,2)   (* true *)
  - The = operator is used for pattern matching
- The == operator compares objects physically
  - [1;2;3] == [1;2;3]   (* false *)
- Mostly you want to use the first one
  - But it's a problem with cyclic data structures

Cyclic Data Structures Possible With Ref

- type 'a reflist = Nil | Cons of 'a * ('a reflist ref)
- let newcell x y = Cons(x,ref y);;
- let updnext (Cons (_,r)) y = r := y;;
- let x = newcell 1 Nil;;
- updnext x x;; (* makes cycle *)
- x == x;; (* true *)
- x = x;; (* hangs *)

OCaml Language Choices

- Implicit or explicit declarations?
  - Explicit – variables must be introduced with let before use
  - But you don't need to specify types
- Static or dynamic types?
  - Static – but you don't need to state types
  - OCaml does type inference to figure out types for you
  - Good: less work to write programs
  - Bad: easier to make mistakes, harder to find errors

OCaml Programming Tips

- Compile your program often, after small changes
  - The OCaml parser often produces inscrutable error messages
  - It's easier to figure out what's wrong if you've only changed a few things since the last compile
- If you're getting strange type error messages, add in type declarations
  - Try writing down types of arguments
  - For any expression e, can write (e:t) to assert e has type t

OCaml Programming Tips (cont.)

- Watch out for precedence and function application

```
let mult x y = x*y

mult 2 2+3    (* returns 7 *)
              (* parsed as (mult 2 2)+3 *)

mult 2 (2+3)  (* returns 10 *)
```


OCaml Programming Tips (cont.)

- All branches of a pattern match must return the same type

```
match x with
... -> -1   (* branch returns int *)
| ... -> ()  (* uh-oh, branch returns unit *)
| ... -> print_string "foo"
           (* also returns unit *)
```


OCaml Programming Tips (cont.)

- You cannot assign to ordinary variables!

```
# let x = 42;;
val x : int = 42
# x = x + 1;;         (* this is a comparison *)
-: bool = false
# x := 3;;
Error: This expression has type int but is here
used with type 'a ref
```


OCaml Programming Tips (cont.)

- Again: You cannot assign to ordinary variables!

```
# let x = 42;;
val x : int = 42
# let f y = y + x;;    (* captures x = 42*)
val f : int -> int = <fun>
# let x = 0;;          (* shadows binding of x *)
val x : int = 0
# f 10;;               (* but f still refers to x=42 *)
- : int = 52
```