CMSC 330: Organization of Programming Languages

Object Oriented Programming
with OCaml

Reminders and Review

- Homework 2 was posted on Oct. 20
  - Due on Oct. 30
- Project 3 due on Oct. 31
  - Project 4 will be posted by then
- Midterm 2 on Nov. 1

- Closures
- Currying

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

Data Types

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

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)
```

- `Rect` and `Circle` are *type constructors*- here a `shape` is either a `Rect` or a `Circle`
- Use pattern matching to *deconstruct* values, and do different things depending on constructor

Data Types, con't.

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

let l = [Rect (3.0, 4.0) ; Circle 3.0; Rect (10.0, 22.5)]
```

- What's the type of `l`?

  `l : shape list`

- What's the type of `l`'s first element?

  `shape`

Data Types (

- The *arity* of
  arguments
  – A construc

```
type optio
   None
 | Some o

let add
     No
   | Som

add_with_
add_with_
```

  – Constructors

NOTES

```
# type int_option = None | Some of int;;
```

The OCaml compiler will warn of a function matching only `Some …` values and neglecting the `None` value:

```
# let extract = function Some i -> i;;
Warning: this pattern-matching is not exhaustive.
Here is an example of a value that is not matched:
None
val extract : int_option -> int = <fun>
```

This `extract` function then works as expected on `Some …` values:

```
# extract (Some 3);;
- : int = 3
```

but causes a `Match_failure` exception to be raised at run-time if a `None` value is given, as none of the patterns in the pattern match of the `extract` function match this value:

```
# extract None;;
Exception: Match_failure ("", 5, -40).
```

Polymorphic Data Types

```
type 'a option =
    None
  | Some of 'a

let add_with_default a = function
    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-in to OCaml

Recursive Data Types

- Do you get the feeling we can build up lists this way?

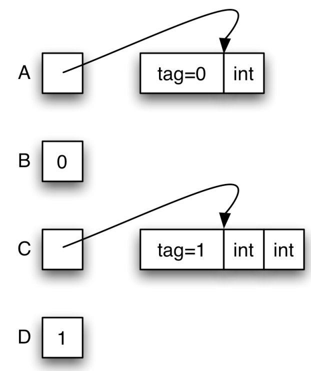
```
type 'a list =
   Nil
 | Cons of 'a * 'a list

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

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

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

Data Type Representations

- Values in a data type are stored either directly as integers or 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
- 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

```
module Shapes =
  struct
    type shape =
       Rect of float * float    (* width * length *)
     | 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;;

unit_circle;;    (* not defined *)
Shapes.unit_circle;;
Shapes.area (Shapes.Rect (3.0, 4.0));;
open Shapes;;    (* import all names into current scope *)
unit_circle;;    (* now defined *)
```

Modularity and Abstraction

- Another reason for creating a module is so we can *hide* details
  – For example, we can build a binary tree module, but we may not want to expose our 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

```
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 *)
```

Give type to module

Module Signatures (cont'd)

- The convention is for 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 *)
```


.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

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 *)
```

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
    - Ex: Calling a function f with argument x always produces the same result

Imperative OCaml

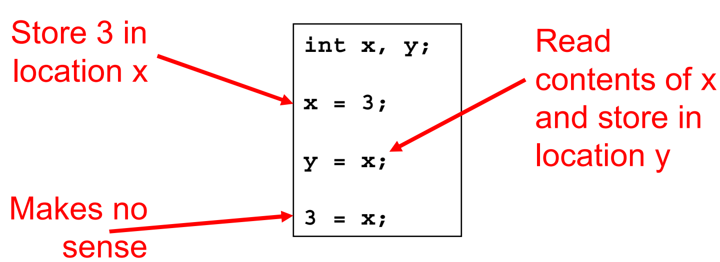
- There are three basic operations on memory:
  - `ref : 'a -> 'a ref`
    - Allocate an updatable reference
  - `! : 'a ref -> 'a`
    - Read the value stored in reference
  - `:= : 'a ref -> 'a -> unit`
    - Write to a reference

```
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
- 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 (cont’d) (in C)



- Notice that x, y, and 3 all have type **`int`**

Comparison to OCaml

```
int x, y;

x = 3;

y = x;

3 = x;
```

```
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
```

unit: this is how a function takes no argument

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
- 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

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'd)

- 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, the current function exits immediately and control transfers up the call chain until the exception is caught, or until it reaches the top level

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