Structure of Programming Languages: OCaml Tutorial

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(based on Dan Grossman’s tutorial)
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What is this

These slides contain the same code as play.ml and other files
• Plus some commentary
• Make of them what you will

(Live demos probably work better, but if these slides are useful reading, then great)

This “tutorial” is heavily skewed toward the features we need for studying programming languages
– Plus some other basics

Hello, World!

(* our first program *)
let x = print_string “Hello, World!

• A program is a sequence of bindings
• One kind of binding is a variable binding
• Evaluation evaluates bindings in order
• To evaluate a variable binding:
  – Evaluate the expression (right of =) in the environment created by the previous bindings.
  – This produces a value.
  – Extend the (top-level) environment, binding the variable to the value.

Some variations

let x = print_string “Hello, World!

(*same as previous with nothing bound to ()*)
let _ = print_string “Hello, World!

(*same w/ variables and infix concat function*)
let h = “Hello,”
let w = “World!”
let _ = print_string (h ^ w)

(*function f: ignores its argument & prints*)
let f x = print_string (h ^ w)

(*so these both print (call is juxtapose)*)
let y1 = f 37
let y2 = f f (* pass function itself *)
(*but this does not (y1 bound to ()*)
let y3 = y1

Compiling/running

<table>
<thead>
<tr>
<th>Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ocamlc file.ml</td>
<td>compile to bytecodes (put in executable)</td>
</tr>
<tr>
<td>ocamlopt file.ml</td>
<td>compile to native (1-5x faster, no need in class)</td>
</tr>
<tr>
<td>ocamlc -i file.ml</td>
<td>print types of all top-level bindings (an interface)</td>
</tr>
<tr>
<td>ocaml</td>
<td>read-eval-print loop (see manual for directives)</td>
</tr>
<tr>
<td>ocamldprof, ocamldebug, _</td>
<td>see the manual (probably unnecessary)</td>
</tr>
</tbody>
</table>

Installing, learning

• Links from the web page:
  – www.ocaml.org
  – The on-line manual (great reference)
  – An on-line book (less of a reference)
  – Installation/use instructions

• Contact us with install problems soon!

• Ask questions (we know the language, want to share)
Types

• Every expression has one type. So far:

```
int string unit t1->t2 'a
```

```
(* print_string : string->unit, "_" : string *)
let x = print_string "Hello, World!\n"
(* x : unit *)
...
(* ^ : string -> string -> string *)
let f x = print_string (h ^ w)
(* f : 'a -> unit *)
let y1 = f 37 (* y1 : unit *)
let y2 = f f (* y2 : unit *)
let y3 = y1 (* y3 : unit *)
```

Explicit types

• You (almost) never need to write down types
  – But can help debug or document
  – Can also constrain callers, e.g.:

```
let f x = print_string (h ^ w)
let g (x:int) = f x

let _ = g 37
let _ = g "hi" (*no typecheck, but f "hi" does*)
```

Theory break

Some terminology and pedantry to serve us well:
• Expressions are evaluated in an environment
• An environment maps variables to values
• Expressions are type-checked in a context
• A context maps variables to types
• Values are integers, strings, function-closures, …
  – “things already evaluated”
• Constructs have evaluation rules (except values) and type-checking rules

Recursion

• A let binding is not in scope for its expression, so:

```
let rec
  (* smallest infinite loop *)
let rec forever x = forever x
  (* factorial (if x>=0, parens necessary) *)
let rec fact x =
  if x==0 then 1 else x * (fact(x-1))
  (*everything an expression, e.g., if-then-else*)
let rec fact2 x =
  (if x==0 then 1 else x * (fact(x-1))) * 2 / 2
```

Locals

• Local variables and functions much like top-level ones (with in keyword)

```
let quadruple x =
  let double y = y + y in
  let ans = double x + double x in
  ans

let _ =
  print_string((string_of_int(quadruple 7)) ^ "\n")
```

Anonymous functions

• Functions need not be bound to names
  – In fact we can desugar what we have been doing

```
let quadruple2 x =
  (fun x -> x + x) x + (fun x -> x + x) x

let quadruple3 x =
  let double = fun x -> x + x in
  double x + double x
```
Passing functions

(* without sharing (shame) *)
print_string((string_of_int(quadruple 7)) ^ "\n");
print_string((string_of_int(quadruple2 7)) ^ "\n");
print_string((string_of_int(quadruple3 7)) ^ "\n");

(* with "boring" sharing (fine here) *)
let print_i_nl i =
  print_string ((string_of_int i) ^ "\n");
let _ = print_i_nl (quadruple 7);
let _ = print_i_nl (quadruple2 7);
let _ = print_i_nl (quadruple3 7);

(* passing functions instead *)
let print_i_nl2 i f =
  print_i_nl (f i);
let _ = print_i_nl2 7 quadruple;
let _ = print_i_nl2 7 quadruple2;
let _ = print_i_nl2 7 quadruple3;

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Currying exposed

(* 2 ways to write the same thing *)
let print_i_nl2 i f = print_i_nl (f i);
let print_i_nl2 =
  fun i -> (fun f -> print_i_nl (f i));
(*)

(* 2 ways to write the same thing *)
print_i_nl2 7 quadruple;
  (print_i_nl2 7 quadruple)

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Elegant generalization

• Partial application is just an idiom
  – Every function takes exactly one argument
  – Call (application) “associates to the left”
  – Function types “associate to the right”

• Using functions to simulate multiple arguments is called currying (somebody’s name)

• Caml implementation plays cool tricks so full application is efficient (merges n calls into 1)

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Closures

Static (a.k.a. lexical) scope; a really big idea

let y = 5
let return11 = (* unit -> int *)
  let x = 6 in
    fun () -> x + y
let y = 7
let x = 8
let _ = print_i_nl (return11 ()) (* prints 11! *)

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The semantics

A function call e1 e2:
1. evaluates e1, e2 to values v1, v2 (order undefined)
   where v1 is a function with argument x, body e3
2. Evaluates e3 in the environment where v1 was defined, extended to map x to v2
   Equivalent description:
   • A function fun x -> e evaluates to a triple of x, e, and the current environment
     – Triple called a closure
   • Call evaluates closure’s body in closure’s environment extended to map x to v2

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Closures are closed

let y = 5
let return11 = (* unit -> int *)
    let y = 6 in
fun () -> x + y

return11 is bound to a value v
• All you can do with this value is call it (with ()
• It will always return 11
– Which environment is not determined by caller
– The environment contents are immutable
• let return11 () = 11
    guaranteed not to change the program

Another example

let x = 9
let f () = x+1
let x = x+1
let g () = x+1
let _ = print_i_nl (f() + g())

Mutation exists

There is a built-in type for mutable locations that can be read and assigned to:

let x = ref 9
let f () = (!x)+1
let _ = x := (!x)+1
let g () = (!x)+1
let _ = print_i_nl (f() + g())

While sometimes awkward to avoid, need it much less often than you think (and it leads to sadness)

On homework, do not use mutation unless we say

Summary so far

• Bindings (top-level and local)
• Functions
  – Recursion
  – Currying
  – Closures
• Types
  – “base” types (unit, int, string, bool, …)
  – Function types
  – Type variables
Now: compound data

Record types

type int_pair = {first : int; second : int}
let sum_int_pr x = x.first + x.second
let pr1 = {first = 3; second = 4}
let _ = sum_int_pr pr1
    + sum_int_pr {first=5;second=6}

A type constructor for polymorphic data/code:

type 'a pair = {a_first : 'a; a_second : 'a}
let sum_pr f x = f x.first + f x.second
let pr2 = {a_first = 3; a_second = 4}(* int pair*)
let _ = sum_pr pr1
    + sum_pr (fun x->x) {a_first=5;a_second=6}

More polymorphic code

type 'a pair = {a_first : 'a; a_second : 'a}
let sum_pr f x = f x.first + f x.second
let pr2 = {a_first = 3; a_second = 4}
let pr3 = {a_first = "hi"; a_second = "mom"}
let pr4 = {a_first = pr2; a_second = pr2}
let sum_int = sum_pr (fun x -> x)
let sum_str = sum_pr String.length
let sum_int_pair = sum_pr sum_int
let _ = print_i_nl (sum_int pr2)
let _ = print_i_nl (sum_str pr3)
let _ = print_i_nl (sum_int_pair pr4)
Each-of vs. one-of

- Records build new types via “each of” existing types
- Also need new types via “one of” existing types
  - Subclasses in OOP
  - Enums or unions (with tags) in C
- Caml does this directly; the tags are constructors
  - Type is called a datatype

Datatypes

```
type food = Foo of int | Bar of int_pair
    | Baz of int * int | Quux

let foo3 = Foo (1 + 2)
let bar12 = Bar pr1
let bazl_120 = Baz(1,fact 5)
let quux = Quux (* not much point in this *)

let is_a_foo x =
  match x with
  | Foo i -> true
  | Bar pr -> false
  | Baz(i,j) -> false
  | Quux -> false
```

Datatypes

- Syntax note: Constructors capitalized, variables not
- Use constructor to make a value of the type
- Use pattern-matching to use a value of the type
  - Only way to do it
  - Pattern-matching actually much more powerful

Booleans revealed

Predefined datatype (violating capitalization rules ©):

```
type bool = true | false
```

if is just sugar for match (but better style):

```
- if el then e2 else e3
- match el with
  true -> e2
  false -> e3
```

Recursive types

A datatype can be recursive, allowing data structures of unbounded size
And it can be polymorphic, just like records

```
type int_tree = Leaf
  | Node of int * int_tree * int_tree

type 'a lst = Null
  | Cons of 'a * 'a lst

let lst1 = Cons(3,Null)
let lst2 = Cons(1,Cons(2, lst1))
(* let lst_bad = Cons("hi", Cons("mom", Null)) *)
let lst3 = Cons("hi", Cons("mom", Null))
let lst4 = Cons (Cons (3,Null), Cons (Cons (4,Null), Null))
```

Recursive functions

```
type 'a lst = Null
  | Cons of 'a * 'a lst

let rec length lst = (* 'a lst -> int *)
match lst with
  Null -> 0
  | Cons(x,rest) -> 1 + length rest
```
Recursive functions

```ocaml
type 'a lst = Null
      | Cons of 'a * 'a lst

let rec sum lst = (* int lst -> int *)
  match lst with
  | Null -> 0
  | Cons(x,rest) -> x + sum rest
```

Another built-in

Actually the type 'a list is built-in:
• Null is written []
• Cons(x,y) is written x::y
• And sugar for list literals [5; 6; 7]

```ocaml
let rec append lst1 lst2 = (* built-in infix @ *)
  match lst1 with
  | [] -> lst2
  | x::rest -> x :: (append rest lst2)
```

Summary

• Now we really have it all
  – Recursive higher-order functions
  – Records
  – Recursive datatypes
• Some important odds and ends
  – Tuples
  – Nested patterns
  – Exceptions
• Then (simple) modules

Tuples

Defining record types all the time is unnecessary:
• Types: t1 * t2 * ... * tn
• Construct tuples e1,e2,...,en
• Get elements with pattern-matching x1,x2,...,xn
• Advice: use parentheses

```ocaml
let x = (3,"hi",(fun x -> x), fun x -> x ^ "ism")
let z = match x with (i,s,f1,f2) -> f1 i
let z = (let (i,s,f1,f2) = x in f1 i)
```

Pattern-matching revealed

• You can pattern-match anything
  – Only way to access datatypes and tuples
  – A variable or _ matches anything
  – Patterns can nest
  – Patterns can include constants (3, "hi", ...)
• let can have patterns, just sugar for match!
• “Quiz”: What is
  - let f x y = x + y
  - let f pr = (match pr with (x,y) -> x+y)
  - let f (x,y) = x + y
  - let f (x1,y1) (x2,y2) = x1 + y2
Fancy patterns example

```ocaml
let multsign x1 x2 = 
  match (sign x1,sign x2) with 
    (P,P) -> P 
    (N,N) -> P 
    (Z,_) -> Z 
    (_,Z) -> Z 
    _ -> raise ZipLengthMismatch
```

To avoid overlap, two more cases
(more robust if datatype changes)

```
exception ZipLengthMismatch
```

Modules

- So far, only way to hide things is local let
  - Not good for large programs
  - Caml has a great module system, but we need only the basics
- Modules and signatures give
  - Namespace management
  - Hiding of values and types
  - Abstraction of types
  - Separate compilation
- By default, Caml builds on the filesystem

Module pragmatics

- foo.ml defines module Foo
- Bar uses variable x, type t, constructor C in Foo via Foo.x,Foo.t,Foo.C
  - Can open a module, use sparingly
- foo.mli defines signature for module Foo
  - Or “everything public” if no foo.mli
- Order matters (command-line)
  - No forward references (long story)
  - Program-evaluation order
- See manual for .cm[i,o] files, -c flag, etc.

foo.ml

```ocaml
type t1 = X1 of int |
        X2 of int
let get_int t =
  match t with 
    X1 i -> i |
    X2 i -> i
let type even = int
let makeEven i = i+2
let isEven i = true (* isEven2 is "private" *)
let isEven i = (i mod 2)=0
```

foo.mli

```ocaml
(* choose to show *)
[ -]
| type t1 = X1 of int |
|        X2 of int
val get_int : t1->int 

(* choose to hide *)
| type even
val makeEven : int->even
val isEven : even->bool
```

bar.ml

```ocaml
type t1 = X1 of int |
        X2 of int
let conv1 t =
  match t with 
    X1 i -> Foo.X1 i |
    X2 i -> Foo.X2 i
let conv2 t =
  match t with 
    Foo.X1 i -> X1 i |
    Foo.X2 i -> X2 i
let _ =
  Foo.get_int(conv1(X1 17));
  Foo.isEven(Foo.makeEven 17)
```

fax.ml

```ocaml
(* choose to show *)
[ -]
| type t1 = X1 of int |
|        X2 of int
val get_int : t1->int 

(* choose to hide *)
| type even
val makeEven : int->even
val isEven : even->bool
```

```
exception ZipLengthMismatch
```

Try that in your favorite language ⊙

`'a list -> 'b list -> 'c list -> ('a*'b*'c) list`

foo.mli

```
```

```
```
Not the whole language

- Objects
- Loop forms
- Fancy module stuff (functors)
- Polymorphic variants
- Mutable fields
- Catching exceptions; exceptions carrying values

Just don’t need much of this for class
(nor do I use these features much)