CMSC 330: Organization of Programming Languages

OCaml 2
Data Types & Recursion

This Lecture

- Tuples
- Polymorphic functions & types
- User-defined data types
- Defining recursive functions with let rec
- Recursive functions

OCaml Functions Take One Argument

- Recall this example

```
let plus (x, y) = x + y;;
plus (3, 4);;
```

  - It looks like you're passing in two arguments
- Actually, you're passing in a tuple instead

```
let plus t = match t with
    (x, y) -> x + y;;
plus (3, 4);;
```

  - And using pattern matching to extract its contents

Tuples

- Constructed using `(e1, ..., en)`
- Deconstructed using pattern matching
- Tuples are like C structs
  - But without field labels
  - Allocated on the heap
- Tuples can be heterogenous
  - Unlike lists, which must be homogenous
  - `(1, ["string1"; "string2"])` is a valid tuple

Tuples – Examples

- `let plusThree (x, y, z) = x+y+z`
  `let addOne (x, y, z) = (x+1, y+1, z+1)`
  - `plusThree (addOne (3,4,5)) = 15`
- `let sum ((a, b), c) = (a+c, b+c)`
  - `sum ((1, 2), 3) = (4,5)`
- `let plusFirstTwo (x::y::_, a) = (x+a, y+a)`
  - `plusFirstTwo ([1; 2; 3], 4) = (5,6)`

Tuples – More Examples

- `let tls (_::xs, _::ys) = (xs, ys)`
  - `tls ([1;2;3],[4;5;6;7]) = ([2;3],[5;6;7])`
- Remember
  - Semicolon for lists
  - Comma for tuples
- Example
  - `[1, 2]` = `[(1, 2)]` = a list of size one
  - `(1; 2)` = a syntax error

Another Tuple Example

- Given
  - `let f l = match l with x::(_::y) -> (x,y)`
- What is the value of
  - `f [1;2;3;4]`
- Possibilities
  - `([1],[3])`
  - `(1,3)`
  - `(1,[3])`
  - `(1,4)`
  - `(1,[3;4])` ←

List and Tuple Types

- Tuple types use `*` to separate components
- Examples
  - `(1,2) :` `int * int`
  - `(1,"string",3.5) :` `int * string * float`
  - `(1,["a";"b"],'c'):` `int * string list * char`
  - `[(1,2)] :` `(int * int) list`
  - `[(1,2);(3, 4)] :` `(int * int) list`
  - `[(1,2);(1,2,3)] :` `error`

Polymorphic Functions

- Some functions require specific list types
  - `let plusFirstTwo (x::y::_, a) =`
    `(x + a, y + a)`
  - `plusFirstTwo :`
    `int list * int -> (int * int)`
- But other functions work for a list of any type
  - `let hd (h::_) = h`
  - `hd [1; 2; 3]` `(* returns 1 *)`
  - `hd ["a"; "b"; "c"]` `(* returns "a" *)`
- These functions are polymorphic

Polymorphic Types

- OCaml gives such functions polymorphic types
  - `hd : 'a list -> 'a`
  - Read as
    - Function takes a list of any element type 'a
    - And returns something of that type
- Example
  - `let tl (_::t) = t`
    `tl : 'a list -> 'a list`

Polymorphic Types (cont.)

- More Examples
  - `let swap (x, y) = (y, x)`
    `swap : 'a * 'b -> 'b * 'a`
  - `let tls (_::xs, _::ys) = (xs, ys)`
    `tls : 'a list * 'b list ->`
    `'a list * 'b list`

Tuples Are a Fixed Size

- This OCaml definition
  - `# let foo x = match x with`
    `(a, b) -> a + b`
    `| (a, b, c) -> a + b + c;;`
- Would yield this error message
  - This pattern matches values of type `'a * 'b * 'c`
    but is here used to match values of type `'d * 'e`
- Tuples of different size have different types
  - Thus never more than one match case with tuples

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`

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 type constructors
  - Here a `shape` is either a `Rect` or a `Circle`

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)
```

- 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 l = [Rect (3.0, 4.0) ; Circle 3.0]
```

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

Data Types Constructor

- Constructors must begin with uppercase letter
- The arity of a constructor
  - Is the number of arguments it takes
  - A constructor with no arguments is nullary

```
type optional_int =
   None
 | Some of int
```

- Example
  - Arity of `None` = 0
  - Arity of `Some` = 1

Polymorphic Data Types

```
type optional_int =
   None
 | Some of int
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 into OCaml

Recursive Data Types

- We can build up lists this way

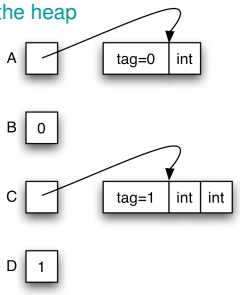
```
type 'a list =
   Nil
 | Cons of 'a * 'a list

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
```


Type Annotations

- The syntax `(e : t)` asserts that "`e` has type `t`"
  - This can be added anywhere you like

```
let (x : int) = 3
let z = (x : int) + 5
```

- Use to give functions parameter and return types

```
let fn (x:int):float = (float_of_int x) *. 3.14
```

  - Note special position for return type
  - Thus `let g x:int =` ... means `g` returns `int`
- Not needed for this course
- But can be useful for debugging
  - Especially for more complicated types

Conditionals

- Use if...then...else just like C/Java
  - No parentheses and no end

```
if grade >= 90 then
  print_string "You got an A"
else if grade >= 80 then
  print_string "You got a B"
else if grade >= 70 then
  print_string "You got a C"
else
  print_string "You're not doing so well"
```

Conditionals (cont.)

- In OCaml, conditionals return a result
  - The value of whichever branch is true/false
  - Like ? : in C, C++, and Java

```
# if 7 > 42 then "hello" else "goodbye";;
- : string = "goodbye"
# let x = if true then 3 else 4;;
x : int = 3
# if false then 3 else 3.0;;
This expression has type float but is
  here used with type int
```


The Factorial Function

- Using conditionals & functions
  - Can you write fact, the factorial function?

```
let rec fact n =
  if n = 0 then
     1
  else
     n * fact (n-1);;
```

- Notice no return statements
  - This is pretty much how it needs to be written

Let Rec

- The rec part means "define a recursive function"
- Let vs. let rec
  - let x = e1 in e2 x in scope within e2
  - let rec x = e1 in e2 x in scope within e2 and e1
- Why use let rec?
  - If you used let instead of let rec to define fact

```
let fact n =
  if n = 0 then 1
  else n * fact (n-1) in e2
```

Fact is not bound here!

Examples – Let

- x;;
  - (* Unbound value x *)
- let x = 1 in x + 1;;
  - (* 2 *)
- let x = x in x + 1;;
  - (* Unbound value x *)

Examples – Let

- let x = 1 in(x + 1 ; x) ;;
  - (* 1 – ; has higher precedence than let … in *)
- (let x = 1 in x + 1) ; x;;
  - (* Unbound value x *)
- let x = 4 in(let x = x + 1 in x);;
  - (* 5 *)

Let – More Examples

- let f n = 10;;
  let f n = if n = 0 then 1 else n * f (n – 1);;
  - f 0;; (* 1 *)
  - f 1;; (* 10 *)
- let f x = … f … in … f …
  - (* Unbound value f *)
- let rec f x = … f … in … f …
  - (* Bound value f *)

Recursion = Looping

- Recursion is essentially the only way to iterate
  - The only way we're going to talk about, anyway
  - Feature of functional programming languages
- Another example

```
let rec print_up_to (n, m) =
  print_int n; print_string "\n";
  if n < m then print_up_to (n + 1, m)
```


Lists and Recursion

- Lists have a recursive structure
  - And so most functions over lists will be recursive

```
let rec length l = match l with
    [] -> 0
  | (_::t) -> 1 + (length t)
```

  - This is just like an inductive definition
    - *The length of the empty list is zero*
    - *The length of a nonempty list is 1 plus the length of the tail*
  - Type of length?

Examples – Recursive Functions

- `sum l (* sum of elts in l *)`

```
let rec sum l = match l with
    [] -> 0
  | (x::xs) -> x + (sum xs)
```

- `negate l (* negate elements in list *)`

```
let rec negate l = match l with
    [] -> []
  | (x::xs) -> (-x) :: (negate xs)
```


Examples – Recursive Functions

- `last l (* last element of l *)`

```
let rec last l = match l with
    [x] -> x
  | (_::xs) -> last xs
```

- `append (l, m)`

```
(* list containing all elements in list
l followed by all elements in list m *)
let rec append (l, m) = match l with
   [] -> m
 | (x::xs) -> x::(append (xs, m))
```


Examples – Recursive Functions

- `rev l (* reverse list; hint: use append *)`

```
let rec rev l = match l with
    [] -> []
  | (x::xs) -> append ((rev xs), [x])
```

  - `rev` takes $O(n^2)$ time. Can you do better?

A Clever Version of Reverse

```
let rec rev_helper (l, a) = match l with
    [] -> a
  | (x::xs) -> rev_helper (xs, (x::a))
let rev l = rev_helper (l, [])
```

- Let's give it a try

```
rev [1; 2; 3] →
rev_helper ([1;2;3], []) →
rev_helper ([2;3], [1]) →
rev_helper ([3], [2;1]) →
rev_helper ([], [3;2;1]) →
[3;2;1]
```

Examples – Recursive Functions

```
flattenPairs l (* ('a * 'a) list -> 'a list *)
 let rec flattenPairs l = match l with
   [] -> []
  | ((a, b)::t) -> a :: b :: (flattenPairs t)
```

```
take (n, l) (* return first n elements of l *)
 let rec take (n, l) =
   if n = 0 then []
   else match l with
       [] -> []
    | (x::xs) -> x :: (take (n-1, xs))
```


Working with Lists

- Several of these examples have the same flavor
  - Walk through the list and do something to every element
  - Walk through the list and keep track of something
- Recall the following example code from Ruby:

```
a = [1,2,3,4,5]
b = a.collect { |x| -x }
```

  - Here we passed a code block into the collect method
  - Wouldn't it be nice to do the same in OCaml?