CMSC 330: Organization of Programming Languages

Functional Programming with OCaml

What is a functional language?

A functional language:

- defines computations as **mathematical functions**
- *discourages* use of **mutable state**

State: the information maintained by a computation
Mutable: can be changed

```
x = x + 1  ?
```

Functional vs. Imperative

Functional languages

- *Higher* level of abstraction: *What* to compute, not *how*
- *Immutable* state: easier to reason about (meaning)
- *Easier* to develop robust software

Imperative languages

- *Lower* level of abstraction: *How* to compute, not *what*
- *Mutable* state: harder to reason about (behavior)
- *Harder* to develop robust software

Imperative Programming

Commands specify **how** to compute, by destructively changing state:

```
x = x+1;
a[i] = 42;
p.next = p.next.next;
```

The fantasy of changing state (mutability)

- It's easy to reason about: the machine does this, then this...

The reality?

- Machines are good at complicated manipulation of state
- Humans are not good at understanding it!

Imperative Programming: Reality

Functions/methods may **mutate** state, a **side effect**

```
int cnt = 0;

int f(Node *r) {
      r->data = cnt;
      cnt++;
      return cnt;
}
```

Mutation breaks **referential transparency**: ability to replace an expression with its value without affecting the result

$$f(x) + f(x) + f(x) \neq 3 * f(x)$$

Imperative Programming: Reality

Worse: There is no single state

- Programs have many threads, spread across many cores, spread across many processors, spread across many computers...
- each with its own view of memory

So: Can't look at one piece of code and reason about its behavior

Thread 1 on CPU 1

```
x = x+1;
a[i] = 42;
p.next = p.next.next;
```

Thread 2 on CPU 2

```
x = x+1;
a[i] = 42;
p.next = p.next.next;
```

Functional programming

Expressions specify **what** to compute

- Variables never change value
    - Like mathematical variables
- Functions (almost) never have side effects

The reality of immutability:

- No need to think about state
- Can perform local reasoning, assume referential transparency

Easier to build correct programs

ML-style (Functional) Languages

- ML (Meta Language)
  - Univ. of Edinburgh, 1973
  - Part of a theorem proving system LCF
- Standard ML
  - Bell Labs and Princeton, 1990; Yale, AT&T, U. Chicago
- OCaml (Objective CAML)
  - INRIA, 1996
    - French Nat'l Institute for Research in Computer Science
  - O is for "objective", meaning objects (which we'll ignore)
- Haskell (1998): *lazy* functional programming
- Scala (2004): functional and OO programming

Key Features of ML

- First-class functions
  - Functions can be parameters to other functions ("higher order") and return values, and stored as data
- Favor immutability ("assign once")
- Data types and pattern matching
  - Convenient for certain kinds of data structures
- Type inference
  - No need to write types in the source language
    - But the language is statically typed
  - Supports parametric polymorphism
    - *Generics* in Java, *templates* in C++
- Exceptions and garbage collection

Why study functional programming?

Functional languages predict the future:

- Garbage collection
  - LISP [1958], Java [1995], Python 2 [2000], Go [2007]
- Parametric polymorphism (generics)
  - ML [1973], SML [1990], Java 5 [2004], Rust [2010]
- Higher-order functions
  - LISP [1958], Haskell [1998], Python 2 [2000], Swift [2014]
- Type inference
  - ML [1973], C++11 [2011], Java 7 [2011], Rust [2010]
- Pattern matching
  - SML [1990], Scala [2002], Rust [2010], Java *X* [201?]
    - http://cr.openjdk.java.net/~briangoetz/amber/pattern-match.html

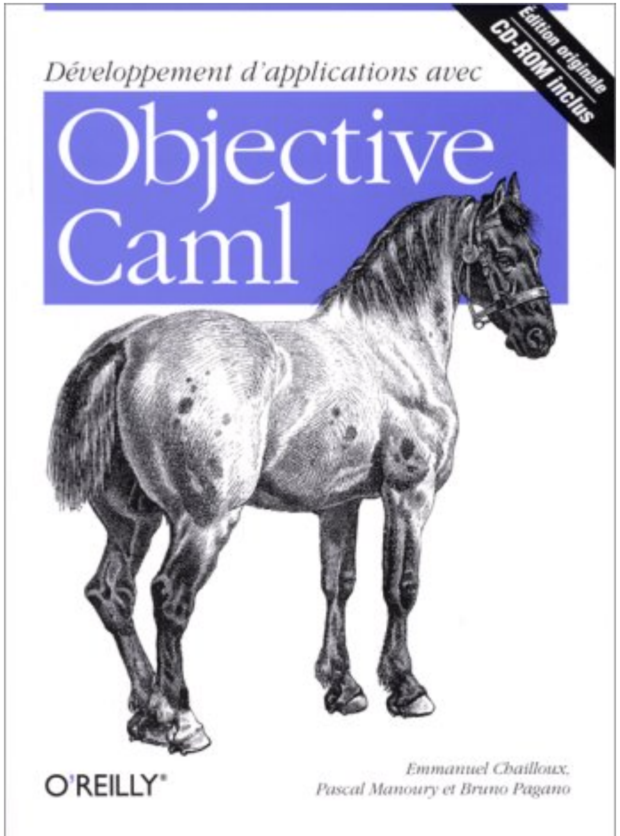
Why study functional programming?

Functional languages in the real world

This slide is old---now there are even more!

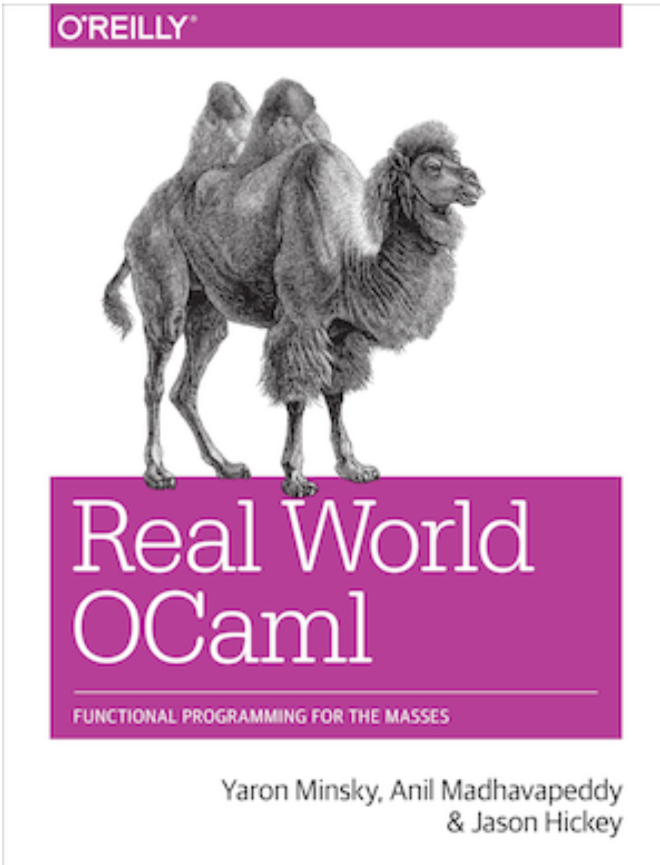
- **Java 8** ORACLE
- **F#, C# 3.0, LINQ** Microsoft
- **Scala** twitter foursquare LinkedIn
- **Haskell** facebook BARCLAYS at&t
- **Erlang** facebook amazon T-Mobile
- **OCaml** facebook Bloomberg CITRIX
  https://ocaml.org/learn/companies.html Jane Street

Useful Information on OCaml



- Translation available on the class webpage
  - *Developing Applications with Objective Caml*
- Webpage also has link to another book
  - *Introduction to the Objective Caml Programming Language*

More Information on OCaml



- Book designed to introduce and advance understanding of OCaml
  - Authors use OCaml in the real world
  - Introduces new libraries, tools
- Free HTML online
  - realworldocaml.org

OCaml Coding Guidelines

- We will not grade on style, but style is important
- Recommended coding guidelines:

- https://ocaml.org/learn/tutorials/guidelines.html

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Working with OCaml

OCaml Compiler

- OCaml programs can be compiled using ocamlc
  - Produces .cmo (“compiled object”) and .cmi (“compiled interface”) files
    - We’ll talk about interface files later
  - By default, also links to produce executable a.out
    - Use -o to set output file name
    - Use -c to compile only to .cmo/.cmi and not to link
- Can also compile with ocamlopt
  - Produces .cmx files, which contain native code
  - Faster, but not platform-independent (or as easily debugged)

OCaml Compiler

- Compiling and running the following small program:

hello.ml:

```
(* A small OCaml program *)
print_string "Hello world!\n";;
```

```
% ocamlc hello.ml
% ./a.out
Hello world!
%
```

OCaml Compiler: Multiple Files

main.ml:

```
let main () =
  print_int (Util.add 10 20);
  print_string "\n"

let () = main ()
```

util.ml:

```
let add x y = x+y
```

- Compile both together (produces `a.out`)

  `ocamlc util.ml main.ml`

- Or compile separately

  `ocamlc -c util.ml`

  `ocamlc util.cmo main.ml`

- To execute

  `./a.out`

OCaml Top-level

- The *top-level* is a read-eval-print loop (REPL) for OCaml
  - Like Ruby's **irb**

- Start the top-level via the **ocaml** command

```
ocaml
        OCaml version 4.07.0
# print_string "Hello world!\n";;
Hello world!
- : unit = ()
# exit 0;;
```

utop is an alternative top-level; improves on **ocaml**

- To exit the top-level, type ^D (Control D) or call the exit 0

OCaml Top-level

Expressions can be typed and evaluated at the top-level

```
# 3 + 4;;
- : int = 7

# let x = 37;;
val x : int = 37

# x;;
- : int = 37

# let y = 5;;
val y : int = 5

# let z = 5 + x;;
val z : int = 42

# print_int z;;
42- : unit = ()

# print_string "Colorless green ideas sleep furiously";;
Colorless green ideas sleep furiously- : unit = ()

# print_int  "Colorless green ideas sleep furiously";;
This expression has type string but is here used with type int
```

gives type and value of each expr

"-" = "the expression you just typed"

unit = "no interesting value" (like void)

Loading Code Files into the Top-level

File **hello.ml** :

```
print_string "Hello world!\n";;
```

- Load a file into top-level

  #use "*filename.ml*"

- Example: ← #use processes a file a line at a time

```
# #use "hello.ml";;
Hello world!
- : unit = ()
#
```

OPAM: OCaml Package Manager

- **`opam`** is the package manager for OCaml
  - Manages libraries and different compiler installations

- You should install the following packages with **`opam`**
  - **`ounit`**, a testing framework similar to minitest
  - **`utop`**, a top-level interface similar to **`irb`**
  - **`dune`**, a build system for larger projects

Project Builds with **dune**

- Use **dune** to compile projects---automatically finds dependencies, invokes compiler and linker
- Define a **dune** file, similar to a **Makefile**:

dune:

```
(executable
 (name main))
```

Indicates that an executable (rather than a library) is to be built

Name of main file (entry point)

```
% dune build main.exe
% _build/default/main.exe
30
%
```

Check out https://medium.com/@bobbypriambodo/starting-an-ocaml-app-project-using-dune-d4f74e291de8

Dune commands

- If defined, run a project's test suite:

  ```
  dune runtest
  ```

- Load the modules defined in src/ into the **`utop`** top-level interface:

  ```
  dune utop src
  ```

  - **`utop`** is a replacement for **`ocaml`** that includes dependent files, so they don't have be be **`#load`**ed

A Note on ;;

- ;; 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
- There is also a single semi-colon ; in OCaml
  - But we won't need it for now
  - It's only useful when programming imperatively, i.e., with side effects
    - Which we won't do for a while

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OCaml Expressions, Functions

Lecture Presentation Style

- Our focus: semantics and idioms for OCaml
  - *Semantics* is what the language does
  - *Idioms* are ways to use the language well

- We will also cover some useful libraries

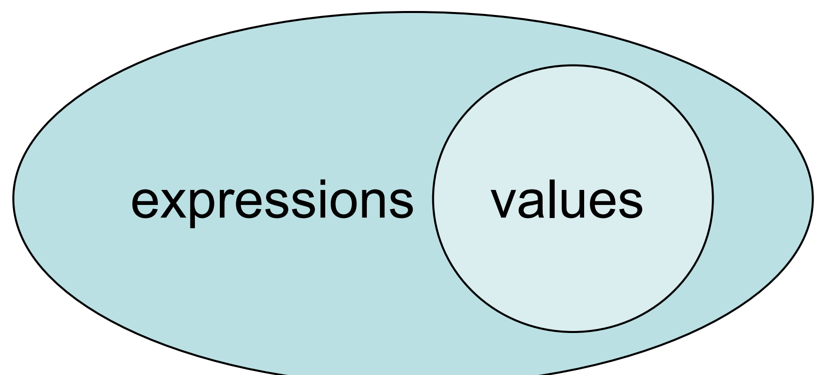
- Syntax is what you type, not what you mean
  - In one lang: Different syntax for similar concepts
  - Across langs: Same syntax for different concepts
  - Syntax can be a source of fierce disagreement among language designers!

Expressions

- Expressions are our primary building block
  - Akin to *statements* in imperative languages
- Every kind of expression has
  - Syntax
    - We use metavariable *e* to designate an arbitrary expression
  - Semantics
    - Type checking rules (static semantics): produce a type or fail with an error message
    - Evaluation rules (dynamic semantics): produce a value
      - (or an exception or infinite loop)
      - Used *only* on expressions that type-check

Values

- A value is an expression that is final
  - **`34`** is a value, **`true`** is a value
  - **`34+17`** is an *expression*, but *not* a value
- Evaluating an expression means running it until it's a value
  - **`34+17`** *evaluates* to **`51`**
- We use metavariable *v* to designate an arbitrary value



Types

- Types classify expressions
  - The set of values an expression could evaluate to
  - We use metavariable ***t*** to designate an arbitrary type
    - Examples include **`int`**, **`bool`**, **`string`**, and more.
- Expression ***e*** has type ***t*** if ***e*** will (always) evaluate to a value of type ***t***
  - **`0`**, **`1`**, and **`-1`** are values of type **`int`** while **`true`** has type **`bool`**
  - **`34+17`** is an expression of type **`int`**, since it evaluates to **`51`**, which has type **`int`**
- Write ***e : t*** to say ***e*** has type ***t***
  - Determining that ***e*** has type ***t*** is called type checking
    - or simply, typing

If Expressions

- Syntax `(if e1 then e2 else e3) : t`

  `e1` : `bool`

  `e2`, `e3` : `t` *(each has the same type t)*

- Type checking
  - Conclude `if e1 then e2 else e3` has type *t* if
    - *e1* has type `bool`
    - Both *e2* and *e3* have type *t* (for some *t*)

If Expressions: Type Checking and Evaluation

```
# if 7 > 42 then "hello" else "goodbye";;
-  : string = "goodbye"

# if true then 3 else 4;;
-  : int = 3

# if false then 3 else 3.0;;
Error: This expression has type float but an expression was
expected of type int
```

- Evaluation (happens if type checking succeeds)
  - If ***e1*** evaluates to **`true`**, and if ***e2*** evaluates to ***v***,
    then **`if`** ***e1*** **`then`** ***e2*** **`else`** ***e3*** evaluates to ***v***
  - If ***e1*** evaluates to **`false`**, and if ***e3*** evaluates to ***v***,
    then **`if`** ***e1*** **`then`** ***e2*** **`else`** ***e3*** evaluates to ***v***

Quiz 1

To what value does this expression evaluate?

```
if 10 < 0 then 2 else 1
```

A. 2
B. 1
C. 0
D. none of the above

Quiz 1

To what value does this expression evaluate?

```
if 10 < 0 then 2 else 1
```

A. 2

B. 1

C. 0

D. none of the above

Quiz 2

To what value does this expression evaluate?

```
if 22 < 0 then 2021 else "home"
```

A. 2
B. 1
C. 0
D. none of the above

Quiz 2

To what value does this expression evaluate?

```
if 22 < 0 then 2021 else "home"
```

A. 2

B. 1

C. 0

D. none of the above: doesn't type check so never gets a chance to be evaluated

Function Definitions

- OCaml functions are like mathematical functions
  - Compute a result from provided arguments

```
(* requires n>=0 *)
(* returns: n! *)
let rec fact n =
  if n = 0 then
     1
  else
     n * fact (n-1)
```

function body

Use (* *) for comments (may nest)

Parameter (type inferred)

`rec` needed for recursion (else `fact` not in scope)

Structural equality

Line breaks, spacing ignored (like C, C++, Java, not like Ruby)

Type Inference

- As we just saw, a declared variable need not be annotated with its type
  - The type can be inferred

```
(* requires n>=0 *)
(* returns: n! *)
let rec fact n =
  if n = 0 then
     1
  else
     n * fact (n-1)
```

n's type is **int**. Why?

= is an infix function that takes two **int**s and returns a **bool**; so **n** must be an **int** for **n = 0** to type check

  - Type inference happens *as a part of type checking*
    - Determines a type that satisfies code's constraints

Calling Functions, *aka* Function Application

- Syntax **`f`** **`e1`** … **`en`**
  - Parentheses not required around argument(s)
  - No commas; use spaces instead
- Evaluation
  - Find the definition of **`f`**
    - i.e., **`let rec f x1 … xn = e`**
  - Evaluate arguments **`e1`** … **`en`** to values **`v1`** … **`vn`**
  - **Substitute** arguments **`v1`**, … **`vn`** for params **`x1`**, … **`xn`** in body **`e`**
    - Call the resulting expression **`e'`**
  - Evaluate **`e'`** to value **`v`**, which is the final result

Calling Functions: Evaluation

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

<u>Example evaluation</u>

- `fact 2`
  - ➢ `if 2=0 then 1 else 2*fact(2-1)`
  - ➢ `2 * fact 1`
  - ➢ `2 * (if 1=0 then 1 else 1*fact(1-1))`
  - ➢ `2 * 1 * fact 0`
  - ➢ `2 * 1 * (if 0=0 then 1 else 0*fact(0-1))`
  - ➢ `2 * 1 * 1`
  - ➢ `2`

Fun fact: Evaluation order for function call arguments in OCaml is **right to left** (not left to right)

Function Types

- In OCaml, `->` is the function type constructor
  - Type `t1 -> t` is a function with argument or *domain* type `t1` and return or *range* type `t`
  - Type `t1 -> t2 -> t` is a function that takes *two* inputs, of types `t1` and `t2`, and returns a value of type `t`. Etc.
- Examples
  - `not` `(* type bool -> bool *)`
  - `int_of_float` `(* type float -> int *)`
  - `+` `(* type int -> int -> int *)`

Type Checking: Calling Functions

- Syntax ***f e1* … *en***
- Type checking
  - If ***f* : *t1* -> … -> *tn* -> *u***
  - and ***e1* : *t1***,
  - …, ***en* : *tn***
  - then ***f e1* … *en* : *u***

- Example:
  - **not true : bool**
  - since **not : bool -> bool**
  - and **true : bool**

Type Checking: Defining Functions

- Syntax **let rec *f x1* … *xn* = *e***
- Type checking
  - Conclude that ***f*** : ***t1* -> … -> *tn* -> *u*** if ***e*** : ***u*** under the following assumptions:
    - ***x1*** : ***t1***, …, ***xn*** : ***tn*** (arguments with their types)
    - ***f*** : ***t1* -> … -> *tn* -> *u*** (for recursion)

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

:**bool** assuming **n**:**int**

:**int** since **fact(n-1)**:**int** and **(n-1)**:**int** assuming **fact**:**int->int**

Function Type Checking: More Examples

- `let next x = x + 1` `(* type int -> int *)`
- `let fn x = (int_of_float x) * 3` `(* type float -> int *)`
- `fact` `(* type int -> int *)`
- `let sum x y = x + y` `(* type int -> int -> int *)`

Quiz 3: What is the type of `foo 3 1.5`

```
let rec foo n m =
  if n >= 9 || n > 0 then
    m
  else
    m +. 10.3
```

`: float -> float -> float`

a) Type Error

b) `int`

c) `float`

d) `int -> int -> int`

Quiz 3: What is the type of `foo 3 1.5`

```
let rec foo n m =
  if n >= 9 || n > 0 then
    m
  else
    m +. 10.3
```

`: float -> float -> float`

a) Type Error

b) `int`

c) `float`

d) `int -> int -> int`

Type Annotations

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

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

- Define functions' parameter and return types

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

- Checked by compiler: Very useful for debugging

Quiz 4: What is the value of `bar 4`

```
let rec bar(n:int):int =
  if n = 0 || n = 1 then 1
  else
    bar (n-1) + bar (n-2)
```

a) Syntax Error
b) 4
c) 5
d) 8

Quiz 4: What is the value of **`bar 4`**

```
let rec bar(n:int):int =
  if n = 0 || n = 1 then 1
  else
    bar (n-1) + bar (n-2)
```

a) Syntax Error

b) 4

c) 5

d) 8