

# O'Caml Intro

COS 326

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# Thinking Functionally

In **Java** or **C**, you get (most) work done by *changing* something

```
temp = pair.x;  
pair.x = pair.y;  
pair.y = temp;
```



commands *modify* or *change* an existing data structure (like pair)

In **OCaml**, you get (most) work done by *producing something new*

```
let  
  (x,y) = pair  
in  
  (y,x)
```



you *analyze* existing data (like pair) and you *produce* new data (y,x)

# Thinking Functionally

pure, functional code:

```
let  
  (x,y) = pair  
in  
  (y,x)
```

- *outputs are everything!*
- *output is function of input*
- *persistent*
- *repeatable*
- *parallelism apparent*
- *easier to test*
- *easier to compose*

imperative code:

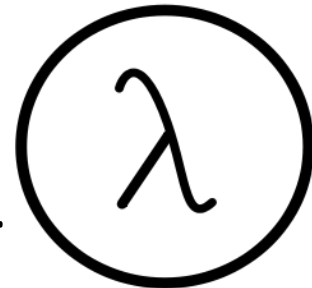
```
temp = pair.x;  
pair.x = pair.y;  
pair.y = temp;
```

- *outputs are irrelevant!*
- *output is not function of input*
- *volatile*
- *unrepeatable*
- *parallelism hidden*
- *harder to test*
- *harder to compose*

# What else makes OCaml different?

Small, *orthogonal* core based on the *lambda calculus*.

- Control is based on (recursive) functions.
- Instead of for-loops, while-loops, do-loops, iterators, etc.
  - can be defined as library functions.
- Makes it easy to define semantics



Supports *first-class*, *lexically-scoped*, *higher-order* procedures

- a.k.a. first-class functions or closures or lambdas.
- *first-class*: functions are data values like any other data value
  - like numbers, they can be stored, defined anonymously, ...
- *lexically-scoped*: meaning of variables determined statically.
- *higher-order*: functions as arguments and results
  - programs passed to programs; generated from programs

These aspects are in common with other functional languages such as Racket, Haskell, SML, F#, Clojure, CoffeeScript.

# What else makes OCaml different?

**Statically typed:** debugging and testing aid

- compiler catches many silly errors before you can run the code.
- e.g., calling a function with the wrong number of arguments
- Java is also strongly, statically typed.
- Scheme, Python, Javascript, etc. are all strongly, *dynamically typed* – type errors are discovered while the code is running.

**Strongly typed:** compiler enforces type abstraction.

- cannot cast an integer to a record, function, string, etc.
  - so we can utilize *types as capabilities*.
  - crucial for local reasoning
- C/C++ are *weakly-typed* languages. The compiler will happily let you do something smart (*more often stupid*).

**Type inference:** compiler fills in types for you



```
Integer Functor Ord Char  
Either          Monad  
Bool           Enum  
Int             [...]   
->              Eq  
Num            Read  
Bounded        (,...)  
Integral ()    IO Show  
Maybe String  Ratio Float
```

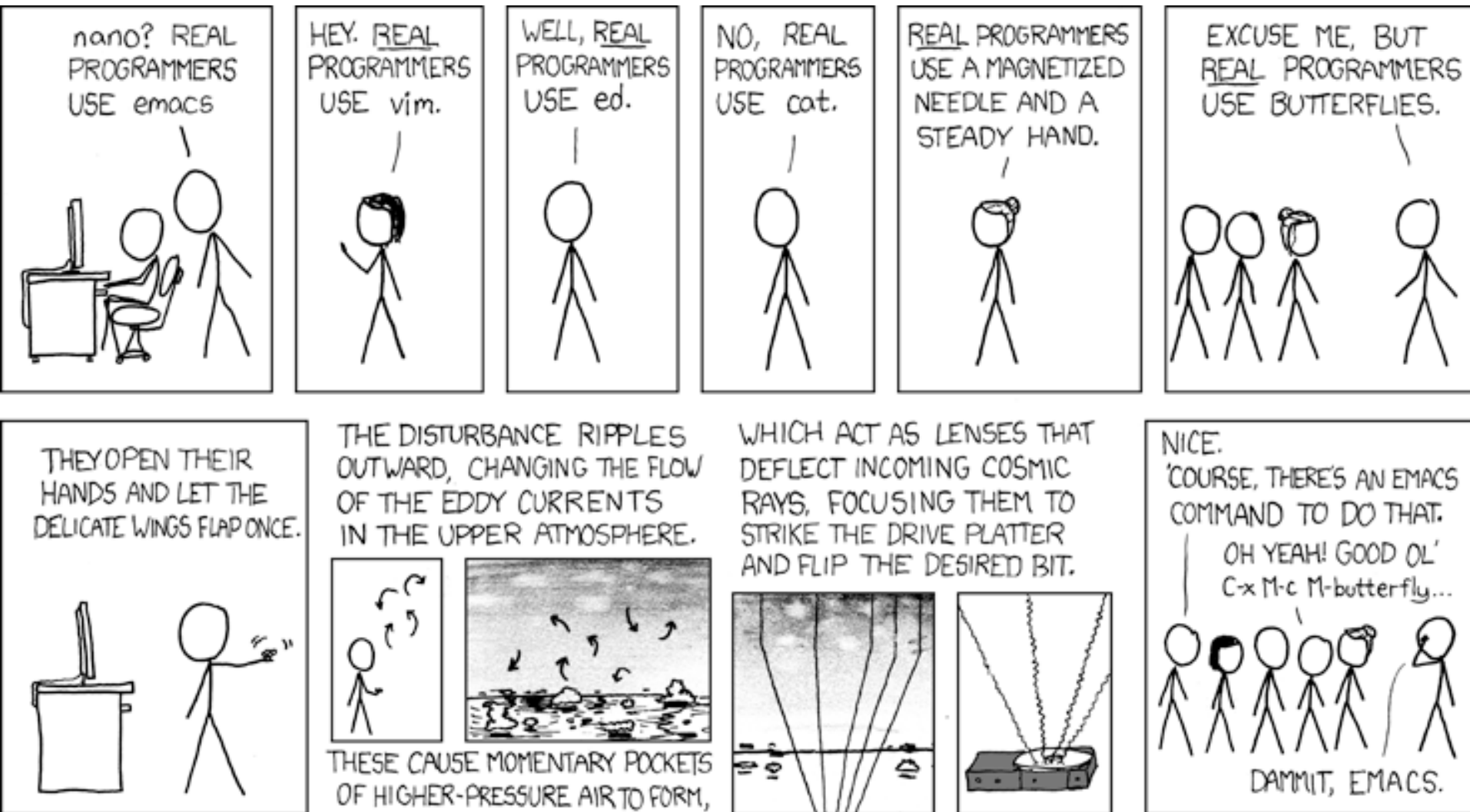
# Installing, running Ocaml

- Ocaml comes with an interactive, top-level loop.
  - useful for testing and debugging code.
  - “ocaml” at the prompt.
- It also comes with compilers
  - “ocamlc” – fast bytecode compiler
  - “ocamlopt” – optimizing, native code compiler
  - “ocamlbuild” – a nice wrapper that computes dependencies
- And many other tools
  - e.g., debugger, dependency generator, profiler, etc.
- See the course web pages for instructions on installing and using O’Caml

# Editing Ocaml Programs

- Many options: pick your own poison
  - Emacs
    - what I'll be using in class.
    - good but not great support for Ocaml.
    - on the other hand, it's still the best code editor I've encountered.
    - (extensions written in elisp – a functional language!)
  - Ocaml IDE
    - integrated development environment written in Ocaml.
    - haven't used it much, so can't comment.
  - Eclipse
    - I've put up a link to an Ocaml plugin
    - I haven't tried it but others recommend it

# XKCD on Editors





**AN INTRODUCTORY EXAMPLE  
(OR TWO)**

# Ocaml Compiler and Interpreter

- Demo:
  - emacs
  - ml files
  - writing simple programs: hello.ml, sum.ml
  - simple debugging and unit tests
  - ocamlc compiler
  - ocaml top-level loop
    - #use
    - #load
    - #quit

# A First O'Caml Program

hello.ml:

```
print_string "Hello COS 326!!\n";;
```

# A First O'Caml Program

hello.ml:

```
print_string "Hello COS 326!!\n";;
```

a function



it's string argument  
enclosed in "..."



top-level  
expressions  
terminated by ;;



# A First O'Caml Program

hello.ml:

```
print_string "Hello COS 326!!\n";;
```

compiling and running hello.ml:

```
$ ocamlbuild hello.d.byte  
$ ./hello.d.byte  
Hello COS 326!!  
$
```

# A First O'Caml Program

hello.ml:

```
print_string "Hello COS 326!!\n";;
```

interpreting and playing with hello.ml:

```
$ ocaml
      Objective Caml Version 3.12.0
#
```

# A First O'Caml Program

hello.ml:

```
print_string "Hello COS 326!!\n";;
```

interpreting and playing with hello.ml:

```
$ ocaml
      Objective Caml Version 3.12.0
# 3 + 1;;
- : int = 4
#
```

# A First O'Caml Program

hello.ml:

```
print_string "Hello COS 326!!\n";;
```

interpreting and playing with hello.ml:

```
$ ocaml
      Objective Caml Version 3.12.0
# 3 + 1;;
- : int = 4
# #use "hello.ml";;
hello cos326!!
- : unit = ()
#
```



# A First O'Caml Program

hello.ml:

```
print_string "Hello COS 326!!\n";;
```

interpreting and playing with hello.ml:

```
$ ocaml
      Objective Caml Version 3.12.0
# 3 + 1;;
- : int = 4
# #use "hello.ml";;
hello cos326!!
- : unit = ()
# #quit;;
$
```

# A Second O'Caml Program

sumTo8.ml:

```
(* sum the numbers from 0 to n
   precondition: n must be a natural number
*)
let rec sumTo (n:int) : int =
  match n with
  | 0 -> 0
  | n -> n + sumTo (n-1)
;;

print_int (sumTo 8);;
print_newline();;
```

a comment  
(\* ... \*)



# A Second O'Caml Program

the name of the function being defined

sumTo8.ml:

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   precondition: n must be a natural number
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let rec sumTo (n:int) : int =
  match n with
    0 -> 0
  | n -> n + sumTo (n-1)
;;

print_int (sumTo 8);;
print_newline();;
```

top-level  
declaration  
ends with  
“;;”

the keyword “let” begins a definition  
the keyword “rec” indicates the definition is recursive

# A Second O'Caml Program

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```
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let rec sumTo (n:int) : int =
  match n with
    0 -> 0
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;;

print_int (sumTo 8);;
print_newline();;
```

result type int

argument  
named n  
with type int

# A Second O'Caml Program

deconstruct the value *n*  
using pattern matching

sumTo8.ml:

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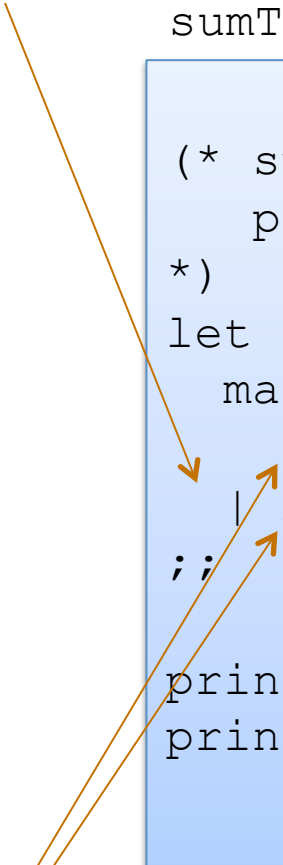
print_int (sumTo 8);;
print_newline();;
```

data to be  
deconstructed  
appears  
between  
key words  
“match” and  
“with”

# A Second O'Caml Program

vertical bar "|" separates the alternative patterns

sumTo8.ml:



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   precondition: n must be a natural number
   *)
let rec sumTo (n:int) : int =
  match n with
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  | n -> n + sumTo (n-1)
;;

print_int (sumTo 8);;
print_newline();;
```

deconstructed data matches one of 2 cases:

(i) the data matches the pattern 0, or (ii) the data matches the variable pattern n

# A Second O'Caml Program

Each branch of the match statement constructs a result

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  match n with
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  | n -> n + sumTo (n-1)
;;

print_int (sumTo 8);;
print_newline();;
```

construct  
the result 0

construct  
a result  
using a  
recursive  
call to sumTo

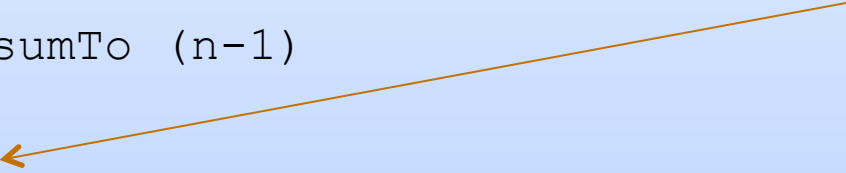
# A Second O'Caml Program

sumTo8.ml:

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let rec sumTo (n:int) : int =
  match n with
    0 -> 0
  | n -> n + sumTo (n-1)
;;

print_int (sumTo 8);;
print_newline();;
```

print the  
result of  
calling  
sumTo on 8



print a  
new line





# **O'CAML BASICS:**

## **EXPRESSIONS, VALUES, SIMPLE TYPES**

# Expressions, Values, Types

- **Expressions** are computations
  - $2 + 3$  is a computation
- **Values** are the results of computations
  - 5 is a value
- **Types** describe collections of values and the computations that generate those values
  - int is a type
  - values of type int include
    - 0, 1, 2, 3, ..., max\_int
    - -1, -2, ..., min\_int

# More simple types, values, operations

<u>Type:</u>	<u>Values:</u>	<u>Expressions:</u>
int	-2, 0, 42	42 * (13 + 1)
float	3.14, -1., 2e12	(3.14 +. 12.0) *. 10e6
char	'a', 'b', '&'	int_of_char 'a'
string	"moo", "cow"	"moo" ^ "cow"
bool	true, false	if true then 3 else 4
unit	()	print_int 3

For more primitive types and functions over them,  
see the Ocaml Reference Manual here:

<http://caml.inria.fr/pub/docs/manual-ocaml/libref/Pervasives.html>

# Language Definition

- There are a number of ways to define a programming language
- In this class, we will briefly investigate:
  - Syntax
  - Evaluation
  - Type checking
- Standard ML, a very close relative of O'Caml, has a full definition of each of these parts and a number of proofs of correctness
  - For more on this theme, see COS 441/510
- The O'Caml Manual fleshes out the syntax, evaluation and type checking rules informally

# **O'CAML BASICS:**

## **CORE EXPRESSION SYNTAX**

# Core Expression Syntax

The simplest O'Caml expressions **e** are:

- values *numbers, strings, bools, ...*
- id *variables (x, foo, ...)*
- $e_1 \text{ op } e_2$  *operators (x+3, ...)*
- id  $e_1 e_2 \dots e_n$  *function call (foo 3 42)*
- **let** id =  $e_1$  **in**  $e_2$  *local variable decl.*
- **if**  $e_1$  **then**  $e_2$  **else**  $e_3$  *a conditional*
- (e) *a parenthesized expression*
- (e : t) *an expression with its type*

# A note on parentheses

In most languages, arguments are parenthesized & separated by commas:

`f(x, y, z)`      `sum(3, 4, 5)`

In OCaml, we don't write the parentheses or the commas:

`f x y z`      `sum 3 4 5`

But we do have to worry about *grouping*. For example,

`f x y z`  
`f x (y z)`

The first one passes three arguments to `f` (`x`, `y`, and `z`)

The second passes two arguments to `f` (`x`, and the result of applying the function `y` to `z`.)

# **O'CAML BASICS: TYPE CHECKING**



# Type Checking

- Every value has a type and so does every expression
- This is a concept that is familiar from Java but it becomes more important when programming in a functional language
- The type of an expression is determined by the type of its subexpressions
- We write  $(e : t)$  to say that expression  $e$  has type  $t$ . eg:

$2 : \text{int}$

$\text{"hello"} : \text{string}$

$2 + 2 : \text{int}$

$\text{"I say " ^ "hello"} : \text{string}$

# Type Checking Rules

- There are a set of *simple rules* that govern type checking
  - programs that do not follow the rules will not type check and O'Caml will refuse to compile them for you (the nerve!)
  - at first you may find this to be a pain ...
- But types are a great thing:
  - they *help us think* about *how to construct* our programs
  - they helps us *find stupid programming errors*
  - they help us track down compatibility errors quickly when we edit and *maintain our code*
  - they allow us to *enforce powerful invariants* about our data structures

# Type Checking Rules

- Example rules:

(1) `0 : int` (and similarly for any other integer constant `n`)

(2) `"abc" : string` (and similarly for any other string constant `"..."`)

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(3) if  $e1 : \text{int}$  and  $e2 : \text{int}$   
then  $e1 + e2 : \text{int}$

(4) if  $e1 : \text{int}$  and  $e2 : \text{int}$   
then  $e1 * e2 : \text{int}$

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- Using the rules:

`2 : int` and `3 : int`. (By rule 1)

# Type Checking Rules

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(2)  $"\text{abc}" : \text{string}$  (and similarly for any other string constant "...")

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then  $e1 + e2 : \text{int}$

(4) if  $e1 : \text{int}$  and  $e2 : \text{int}$   
then  $e1 * e2 : \text{int}$

(5) if  $e1 : \text{string}$  and  $e2 : \text{string}$   
then  $e1 \wedge e2 : \text{string}$

(6) if  $e : \text{int}$   
then  $\text{string\_of\_int } e : \text{string}$

- Using the rules:

$2 : \text{int}$  and  $3 : \text{int}$ . (By rule 1)

Therefore,  $(2 + 3) : \text{int}$  (By rule 3)

# Type Checking Rules

- Example rules:

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- Using the rules:

$2 : \text{int}$ and $3 : \text{int}$ .	(By rule 1)
Therefore, $(2 + 3) : \text{int}$	(By rule 3)
$5 : \text{int}$	(By rule 1)



# Type Checking Rules

- Example rules:

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- (6) if  $e : \text{int}$   
then  $\text{string\_of\_int } e : \text{string}$

- Using the rules:

$2 : \text{int}$  and  $3 : \text{int}$ . (By rule 1)  
Therefore,  $(2 + 3) : \text{int}$  (By rule 3)  
 $5 : \text{int}$  (By rule 1)  
Therefore,  $(2 + 3) * 5 : \text{int}$  (By rule 4 and our previous work)

# Type Checking Rules

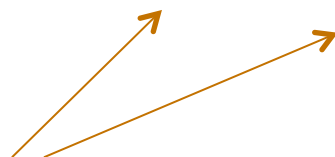
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then `string_of_int e : string`

- Another perspective:

rule (4) for typing expressions  
says I can put any expression  
with type `int` in place of the `????`

`???? * ???? : int`



# Type Checking Rules

- Example rules:

(1) `0 : int` (and similarly for any other integer constant `n`)

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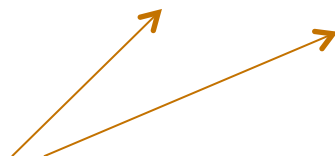
(5) if `e1 : string` and `e2 : string`  
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(6) if `e : int`  
then `string_of_int e : string`

- Another perspective:

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`7 * ???? : int`



# Type Checking Rules

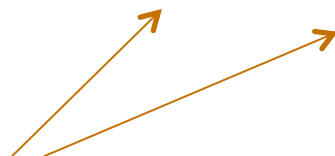
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then `string_of_int e : string`

- Another perspective:

rule (4) for typing expressions  
says I can put any expression  
with type `int` in place of the `???`

`7 * (add_one 17) : int`



# Type Checking Rules

- You can always start up the O'Caml interpreter to find out a type of a simple expression:

```
$ ocaml
      Objective Caml Version 3.12.0
#
```

# Type Checking Rules

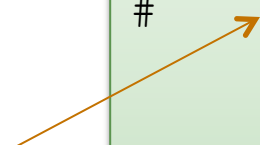
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```
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# 3 + 1;;
```

# Type Checking Rules

- You can always start up the O'Caml interpreter to find out a type of a simple expression:

```
$ ocaml
      Objective Caml Version 3.12.0
# 3 + 1;;
- : int = 4
#
```

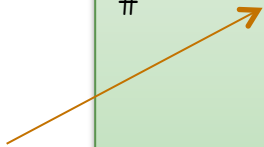


press  
return  
and you  
find out  
the type  
and the  
value

# Type Checking Rules

- You can always start up the O'Caml interpreter to find out a type of a simple expression:

```
$ ocaml
      Objective Caml Version 3.12.0
# 3 + 1;;
- : int = 4
# "hello " ^ "world";;
- : string = "hello world"
#
```



press  
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# Type Checking Rules

- You can always start up the O'Caml interpreter to find out a type of a simple expression:

```
$ ocaml
      Objective Caml Version 3.12.0
# 3 + 1;;
- : int = 4
# "hello " ^ "world";;
- : string = "hello world"
# #quit;;
$
```

# Type Checking Rules

- Example rules:

(1) `0 : int` (and similarly for any other integer constant `n`)

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(5) if `e1 : string` and `e2 : string`  
then `e1 ^ e2 : string`

(6) if `e : int`  
then `string_of_int e : string`

- Violating the rules:

`"hello" : string`

`1 : int`

`1 + "hello" : ??`

(By rule 2)

(By rule 1)

(NO TYPE! Rule 3 does not apply!)

# Type Checking Rules

- Violating the rules:

```
# "hello" + 1;;
```

```
Error: This expression has type string but an  
expression was expected of type int
```

- The type error message tells you the type that was **expected** and the type that it **inferred** for your subexpression
- By the way, this was one of the nonsensical expressions that did not evaluate to a value
- I consider it a good thing that this expression does not type check

# Type Checking Rules

- Violating the rules:

```
# "hello" + 1;;
```

Error: This expression has type string but an expression was expected of type int

- A possible fix:

```
# "hello" ^ (string_of_int 1);;  
- : string = "hello1"
```

- *One of the keys to becoming a good ML programmer is to understand type error messages.*

# Type Checking Rules

- More rules:

(7) `true : bool`

(8) `false : bool`

(9) `if e1 : bool`  
and `e2 : t` and `e3 : t` (for some type `t`)  
then `if e1 then e2 else e3 : t`

- Using the rules:

`if ??? then ??? else ??? : int`

# Type Checking Rules

- More rules:

(7) `true : bool`

(8) `false : bool`

(9) if `e1 : bool`  
and `e2 : t` and `e3 : t` (for some type `t`)  
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- Using the rules:

`if true then ???? else ???? : int`

# Type Checking Rules

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- Using the rules:

`if true then 7 else ??? : int`

# Type Checking Rules

- More rules:

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and `e2 : t` and `e3 : t` (for some type `t`)  
then `if e1 then e2 else e3 : t`

- Using the rules:

`if true then 7 else 8 : int`



# Type Checking Rules

- More rules:

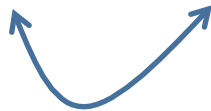
(7) `true : bool`

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(9) if `e1 : bool`  
and `e2 : t` and `e3 : t` (for some type `t`)  
then `if e1 then e2 else e3 : t`

- Violating the rules

`if false then "1" else 2 : ????`



types don't agree -- one is a string and one is an int

# Type Checking Rules

- Violating the rules:

```
# if true then "1" else 2;;
```

```
Error: This expression has type int but an  
expression was expected of type string
```

```
#
```

# Type Checking Rules

- What about this expression:

```
# 3 / 0 ;;  
Exception: Division_by_zero.
```

- Why doesn't the ML type checker do us the favor of telling us the expression will raise an exception?

# Type Checking Rules

- What about this expression:

```
# 3 / 0 ;;  
Exception: Division_by_zero.
```

- Why doesn't the ML type checker do us the favor of telling us the expression will raise an exception?
  - In general, detecting a divide-by-zero error requires we know that the divisor evaluates to 0.
  - In general, deciding whether the divisor evaluates to 0 requires solving the halting problem:

```
# 3 / (if turing_machine_halts m then 0 else 1) ;;
```

- There are type systems that will rule out divide-by-zero errors, but they require programmers supply proofs to the type checker

**OVERALL SUMMARY:**  
**A SHORT INTRODUCTION TO**  
**FUNCTIONAL PROGRAMMING**

# OCaml

OCaml is a *functional* programming language

- Java gets most work done by *modifying* data
- OCaml gets most work done by producing *new, immutable* data

OCaml is typed programming language

- the *type* of an expression *correctly predicts* the kind of *value* the expression will generate when it is executed
- types help us *understand* and *write* our programs

**END**