COS 326
Functional Programming

Andrew Appel
Princeton University

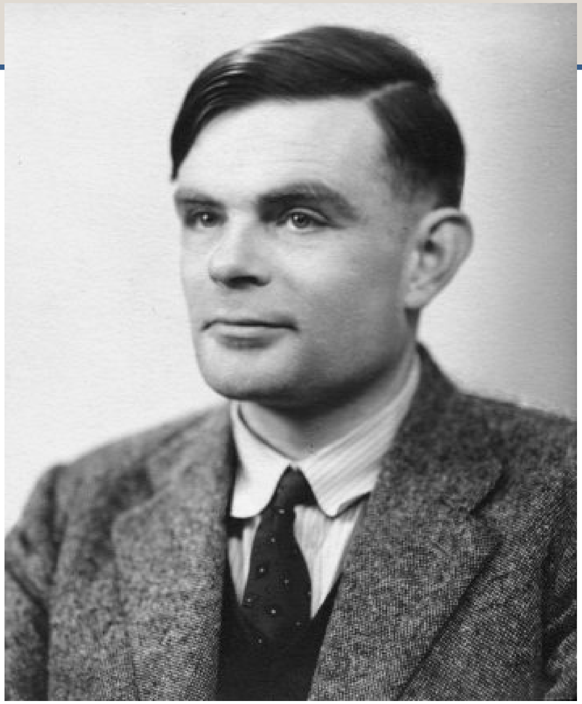
Alonzo Church, 1903-1995
Princeton Professor, 1929-1967

In 1936, Alonzo Church invented the lambda calculus. He called it a logic, but it was a language of pure functions -- the world's first programming language.

He said:

"*There may, indeed, be other applications of the system than its use as a logic.*"

Indeed!



Alonzo Church
1934 -- developed lambda calculus

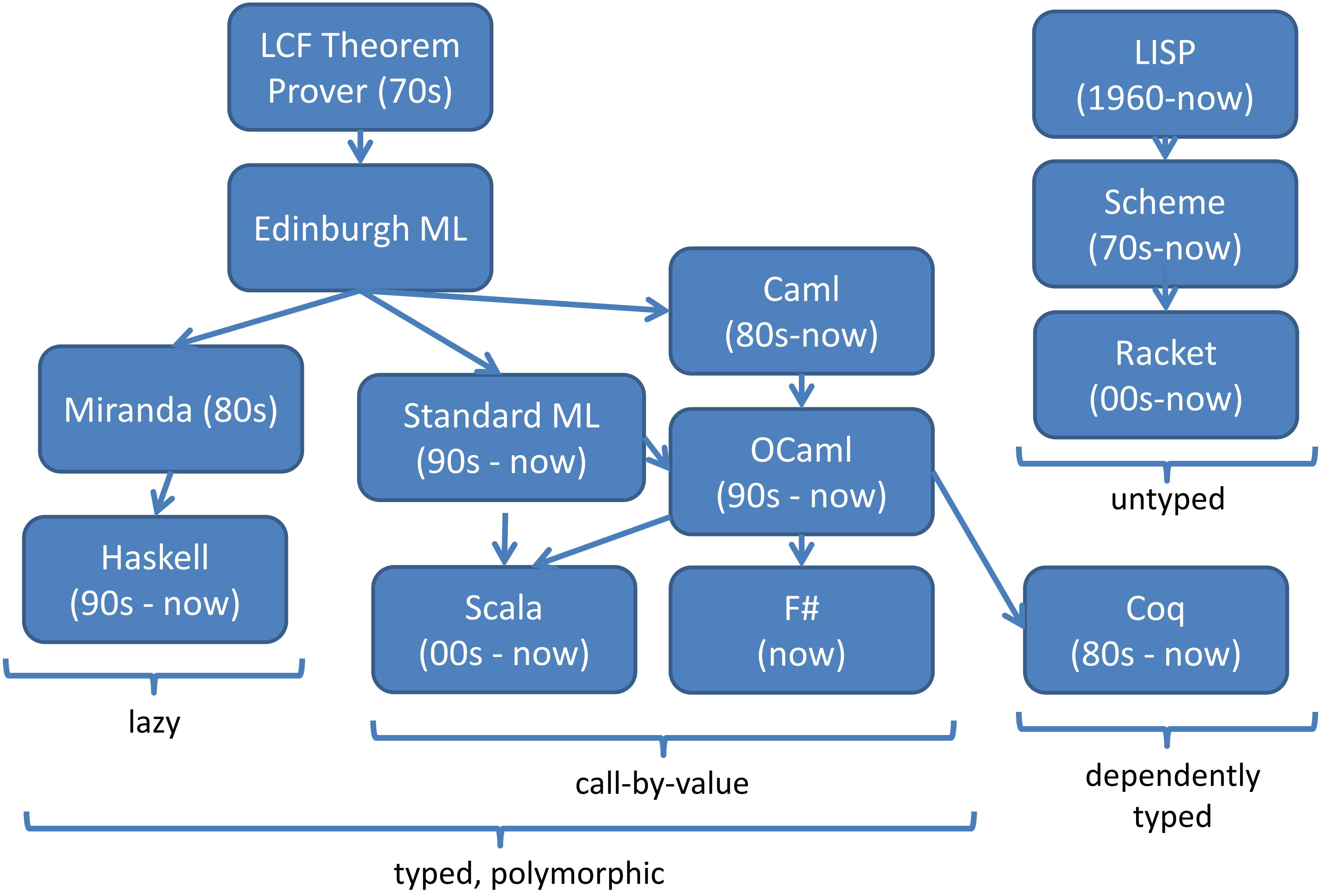
Programming Languages

Alan Turing (PhD Princeton 1938)
1936 -- developed Turing machines

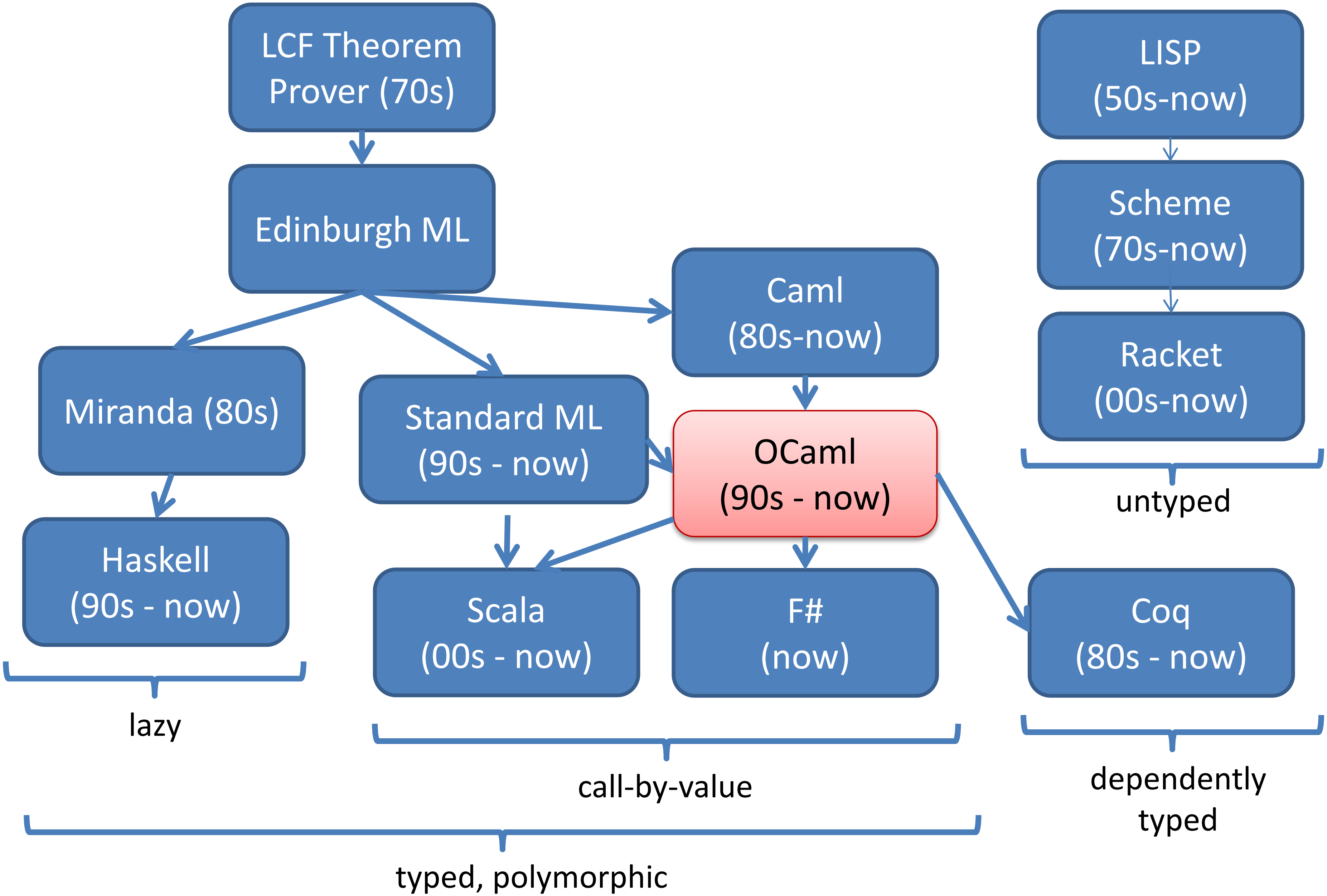
Computers

Optional reading: ***The Birth of Computer Science at Princeton in the 1930s***
by Andrew W. Appel, 2012. http://press.princeton.edu/chapters/s9780.pdf

Vastly Abbreviated FP Genealogy



Vastly Abbreviated FP Geneology



Functional Languages: Who's using them?

map-reduce in their data centers

Scala for
correctness, maintainability, flexibility

Erlang for concurrency,
Haskell for managing PHP,
OCaml for bug-finding

F# in Visual Studio

mathematicians

Coq (re)proof of
4-color theorem

Haskell to
synthesize hardware

Haskell
for specifying
equity derivatives

www.artima.com/scalazine/articles/twitter_on_scala.html
www.infoq.com/presentations/haskell-barclays
www.janestreet.com/technology/index.html#work-functionally
msdn.microsoft.com/en-us/fsharp/cc742182
research.google.com/archive/mapreduce-osdi04.pdf
www.lightbend.com/case-studies/how-apache-spark-scala-and-functional-programming-made-hard-problems-easy-at-barclays
www.haskell.org/haskellwiki/Haskell_in_industry

COURSE LOGISTICS

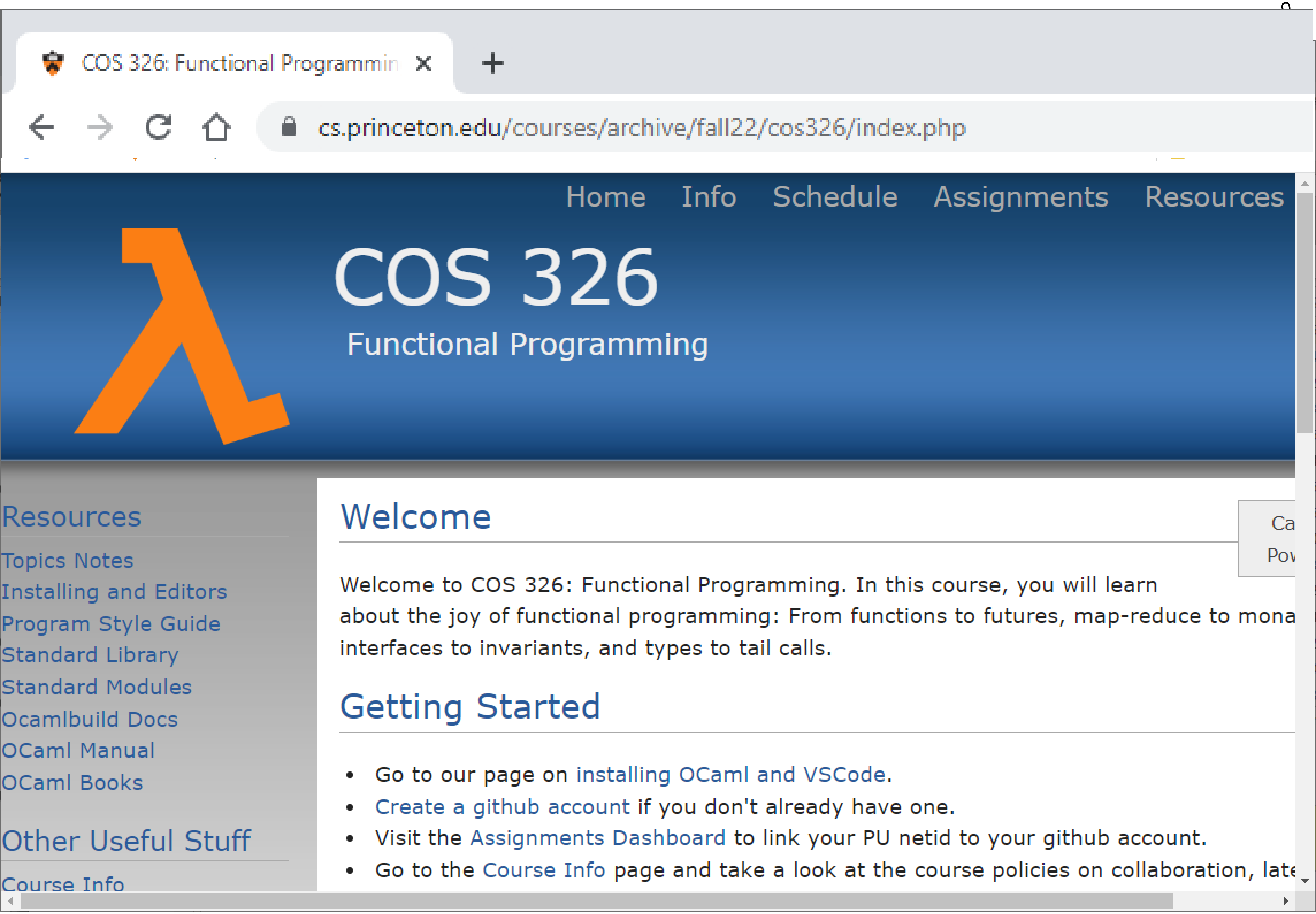
Course Staff

Andrew Appel
Professor
office: CS 209
email: appel@cs

Joomy Korkut
Preceptor

email: joomy@cs

Nikhil Pimpalkhare
Preceptor
nikhil.pimpalkhare
@princeton.edu


COS 326: Functional Programmin
cs.princeton.edu/courses/archive/fall22/cos326/index.php
Home
Info
Schedule
Assignments
Resources
COS 326
Functional Programming
Resources
Topics Notes
Installing and Editors
Program Style Guide
Standard Library
Standard Modules
Ocamlbuild Docs
OCaml Manual
OCaml Books
Other Useful Stuff
Course Info
Welcome
Welcome to COS 326: Functional Programming. In this course, you will learn about the joy of functional programming: From functions to futures, map-reduce to mona interfaces to invariants, and types to tail calls.
Getting Started
Go to our page on installing OCaml and VSCode.
Create a github account if you don't already have one.
Visit the Assignments Dashboard to link your PU netid to your github account.
Go to the Course Info page and take a look at the course policies on collaboration, late
Ca
Pov

Collaboration Policy

The COS 326 collaboration policy can be found here:

http://www.cs.princeton.edu/~cos326/info.php#collab

Read it in full prior to beginning the first assignment.

Please ask questions whenever anything is unclear, at any time during the course.

A Typical Week

Monday

- Lecture

Tuesday

- Assignment from last week due (7 assignments total)
- Your first assignment is due Tuesday Sept 13 at 11:59pm

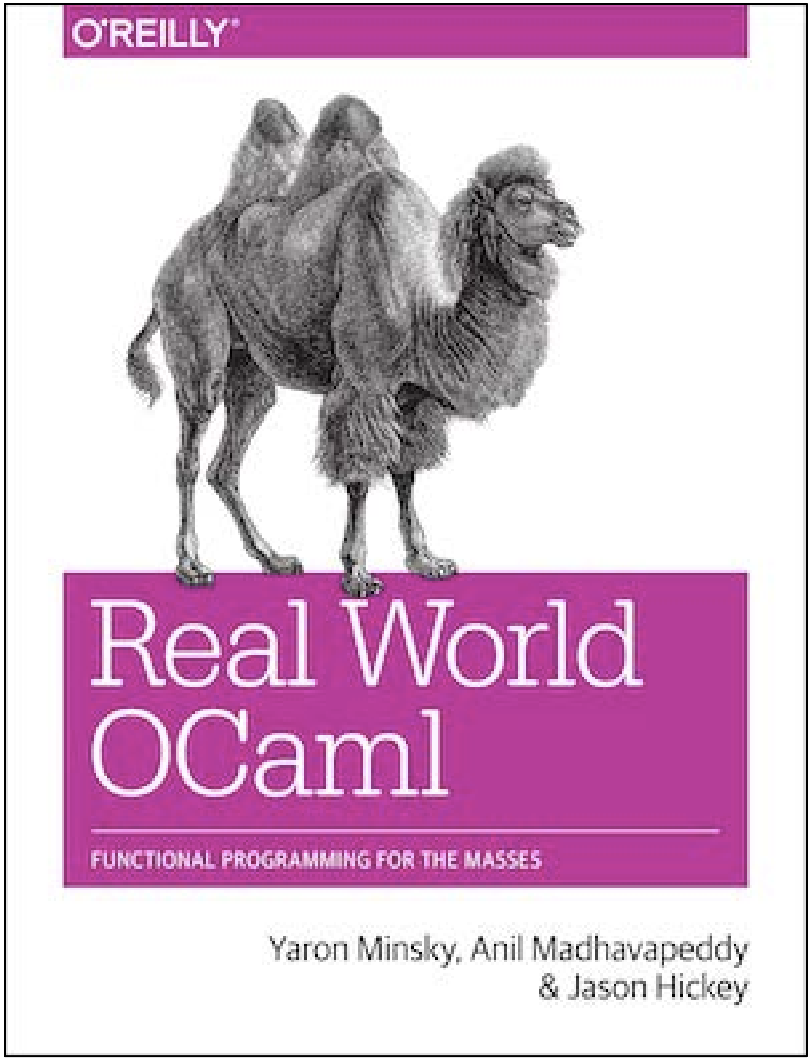
Wednesday

- Lecture
- Next assignment is available
- *start assignment* with material from lecture

Thursday/Friday

- mandatory precept reinforces lecture content
- you may have questions for your preceptor about the assignment

Course Textbook



http://realworldocaml.org/

Exams

Midterm

- in class during midterm week

Final

- during exam period in December
- make your travel plans accordingly
- I have *no control at all* over when the exam occurs, the Registrar schedules exams.
- The final is ***not*** "cumulative" over the whole semester, it covers just "equational reasoning"

Special Calendar Note

DECEMBER 2022

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
				1	2	3
4	5 Lecture	6	7 Lecture	8 Precept	9 Precept	10
11	12	13 Reading Period	14	15	16	17
18	19	20 Final Exams	21	22	23	24
25	26	27	28	29	30	31

Friday precepts ***will meet*** on December 9th, even though it may officially be Reading Period.

Assignment 0

Install opam, ocaml, VS Code

[and if you use Windows: WSL2]

on your machine by the time precept begins tomorrow.

Resources Page:

http://www.cs.princeton.edu/~cos326/resources.php

Hint:

ocaml.org

Public Service Announcement

The Pen is Mighter than the Keyboard: Advantages of Longhand Over Laptop Note Taking

Pam Mueller (Princeton University)
Daniel Oppenheimer (UCLA)
Journal of Psychological Science, June 2014, vol 25, no 6

http://pss.sagepub.com/content/25/6/1159.fullkeytype=ref&siteid=sppss&ijkey=CjRAwmrlURGNw

https://www.scientificamerican.com/article/a-learning-secret-don-t-take-notes-with-a-laptop/

- You learn conceptual topics better by taking notes by hand.
- Instagram and Fortnite distract your classmates.

Functional Programming

Thinking Functionally

pure, functional code:

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

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

imperative code:

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

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

Thinking Functionally

pure, functional code:

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

- *outputs are everything!*
- *output is <u>function</u> of input*
- *data properties are stable*
- *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*
- *data properties change*
- *unrepeatable*
- *parallelism hidden*
- *harder to test*
- *harder to compose*

This simple switch in perspective can change the way you

think

about programming and problem solving.

Why OCaml?

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 features also found in Scheme, Haskell, Scala, F#, Clojure, ...

Why OCaml?

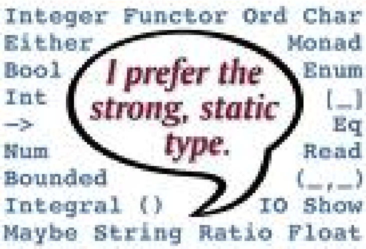
Statically typed: debugging and testing aid

- compiler catches many silly errors before you can run the code.
  - A type is worth a thousand tests
- 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* (statically typed) languages. The compiler will happily let you do something smart (*more often stupid*).

Type inference: compiler fills in types for you



Installing, Running OCaml

- OCaml comes with compilers:
  - "ocamlc" – fast bytecode compiler
  - "ocamlopt" – optimizing, native code compiler
  - "dune" – a build system for OCaml
- And an interactive, top-level shell:
  - useful for trying something out.
  - "ocaml" or "utop" at the prompt.
  - *but use the compiler (via dune) most of the time*
- See the course web pages for installation pointers
  - also OCaml.org

Editing OCaml Programs

- Many options:
  - We recommend VS Code, with its OCaml mode

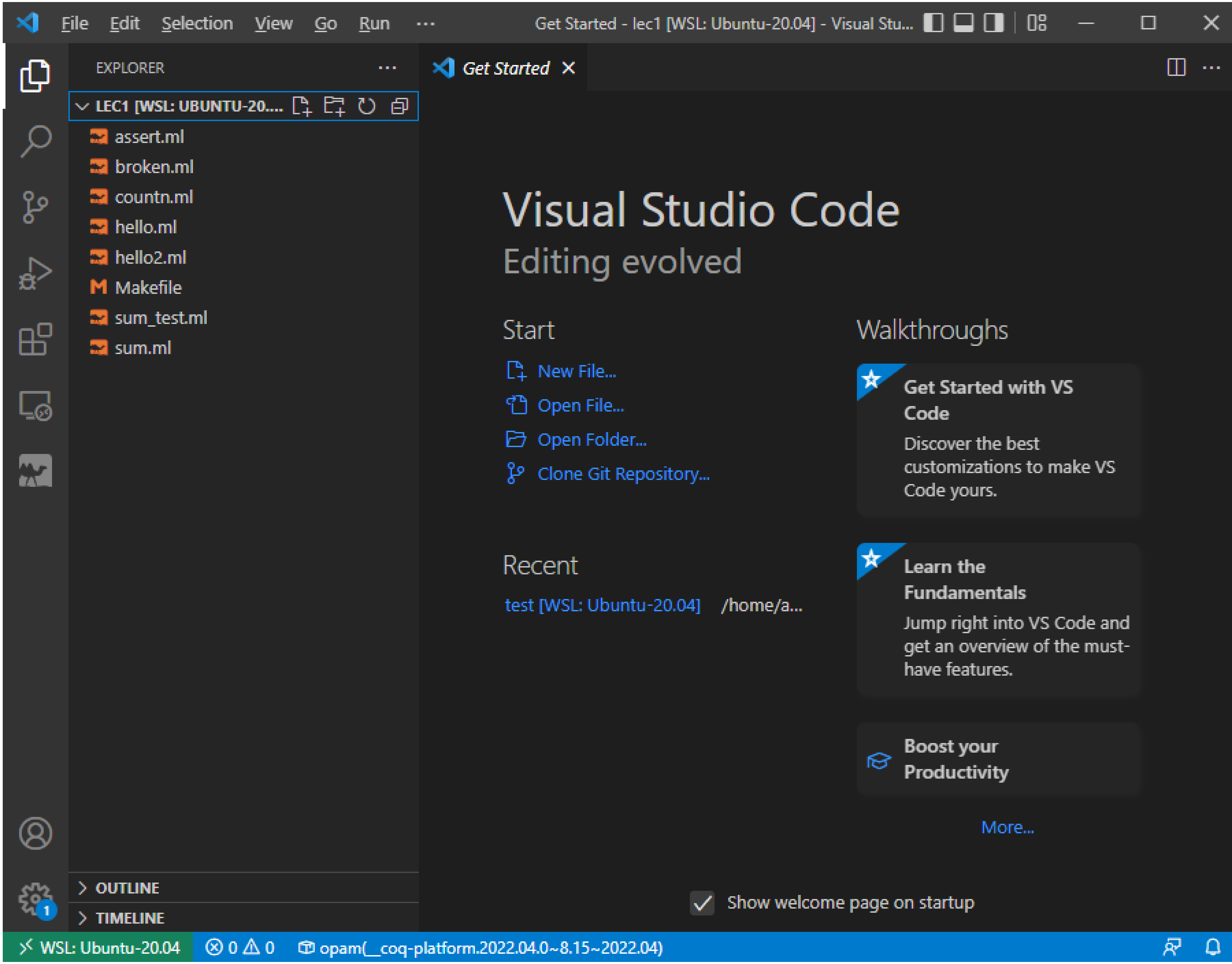
  But you can use other text editors if you want, such as:
  - Emacs
    - what your professors tend to use
    - good but not great support for OCaml.
  - Sublime, atom
    - Many CS326 students have used these

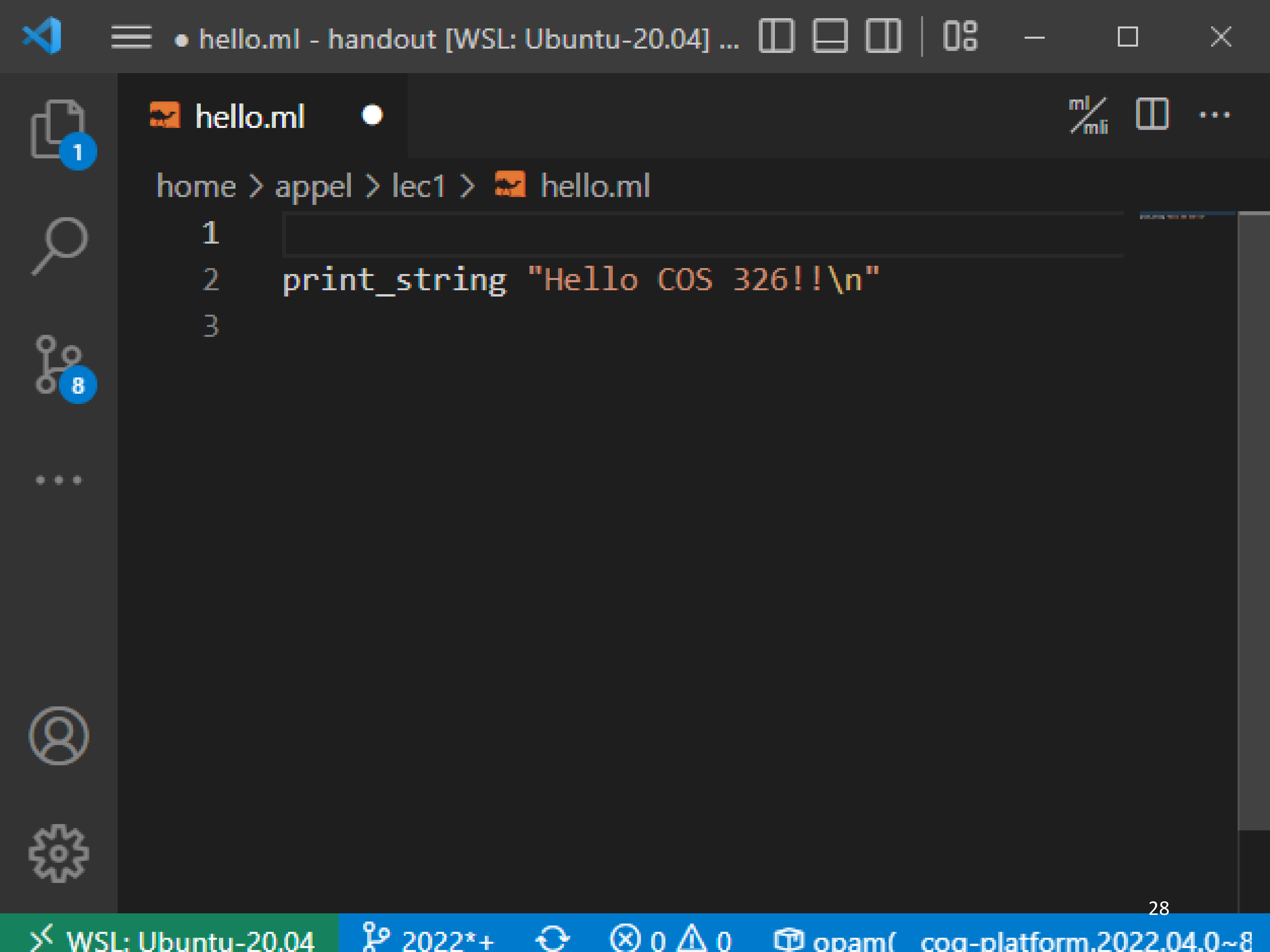
AN INTRODUCTORY EXAMPLE (OR TWO)

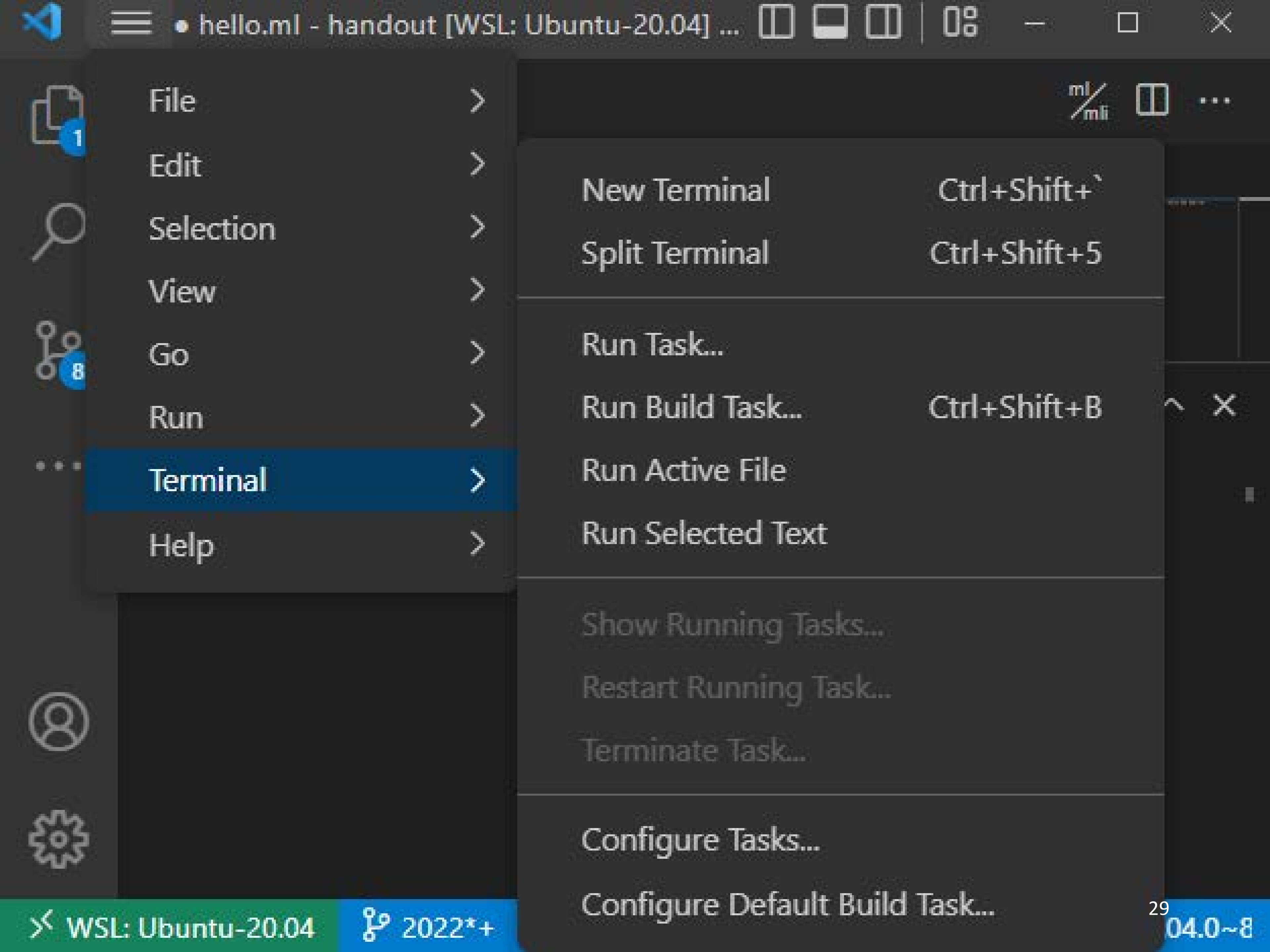
A First OCaml Program

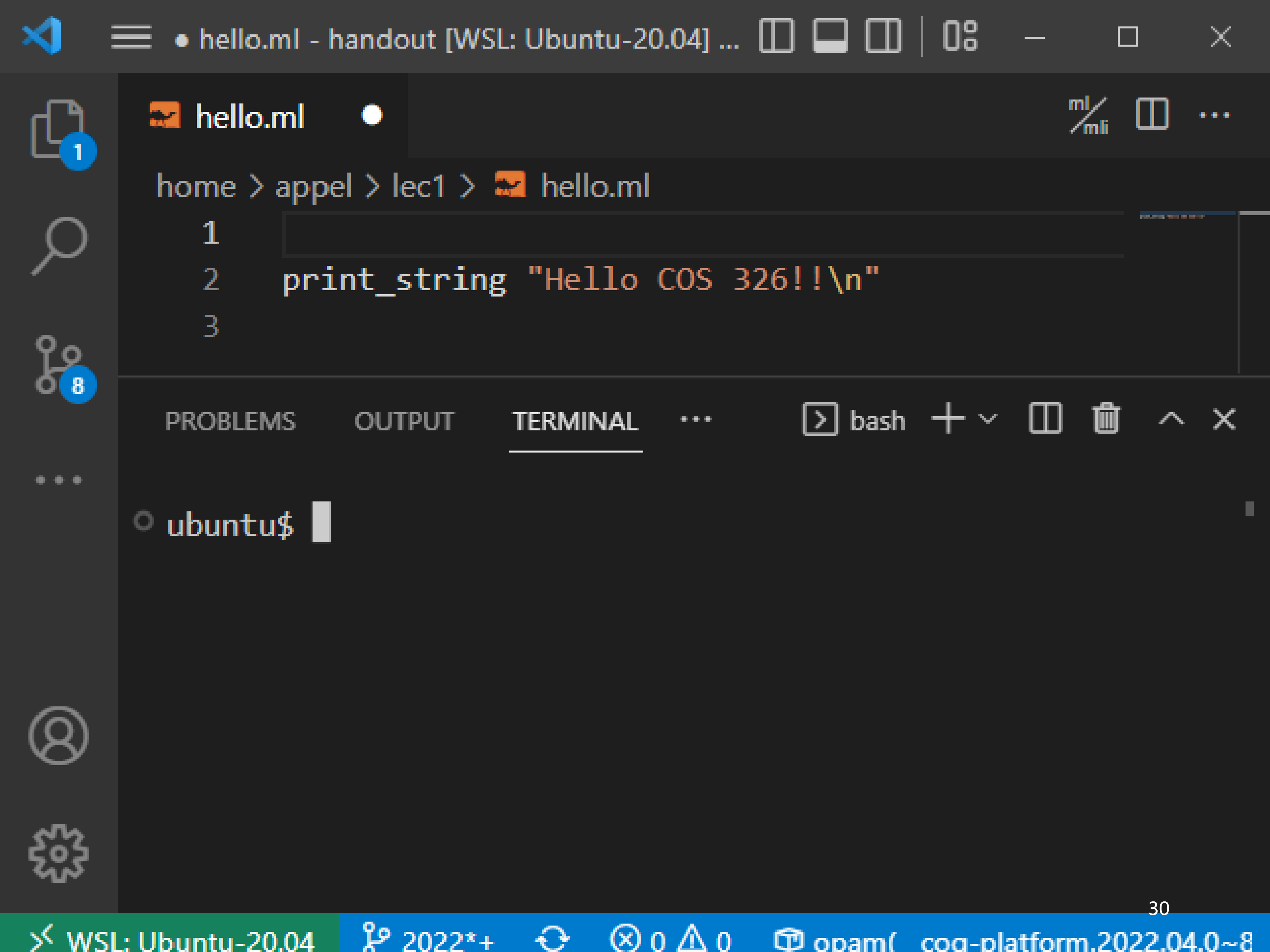
`hello.ml:`

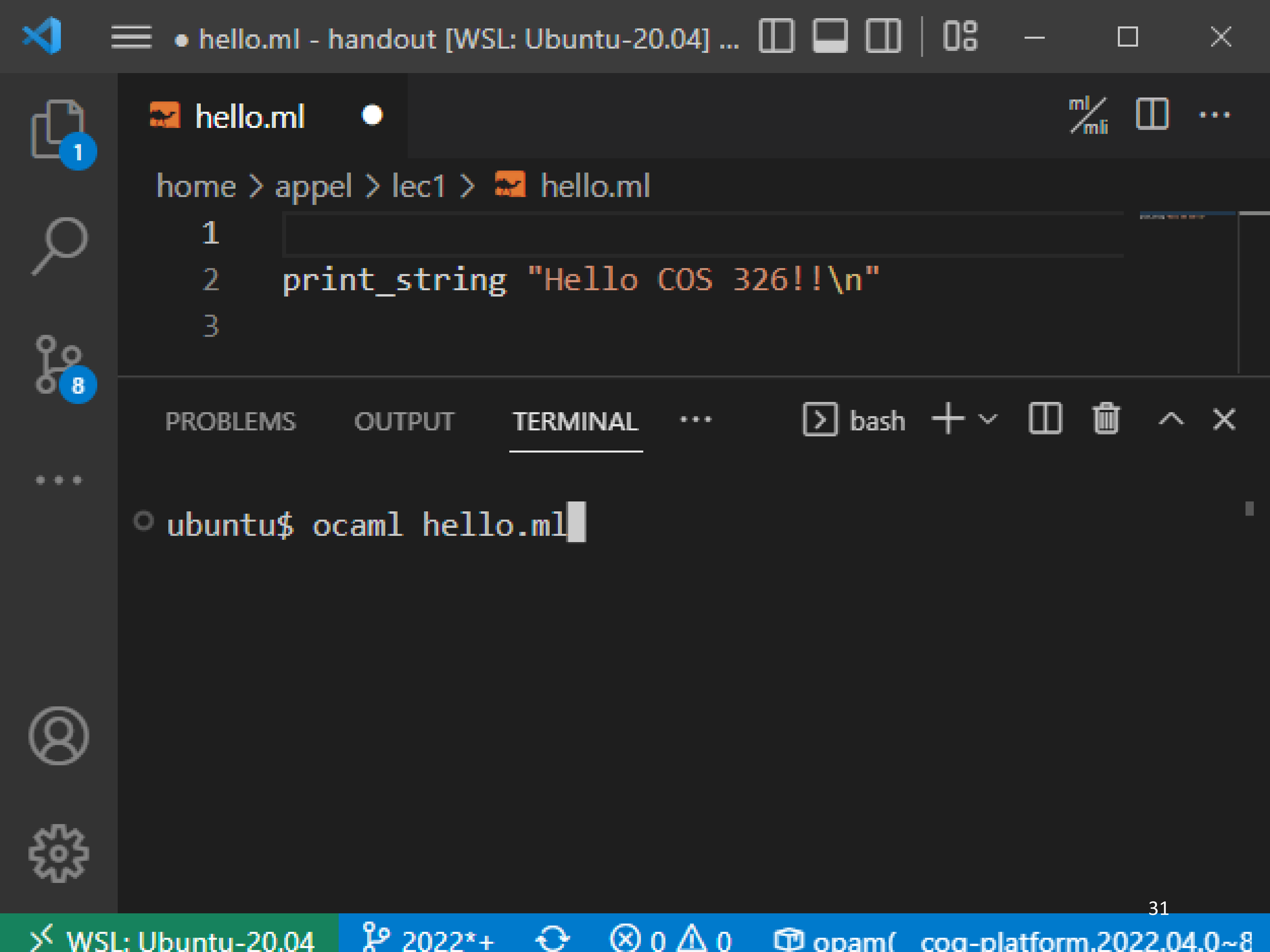
```
print_string "Hello COS 326!!\n"
```

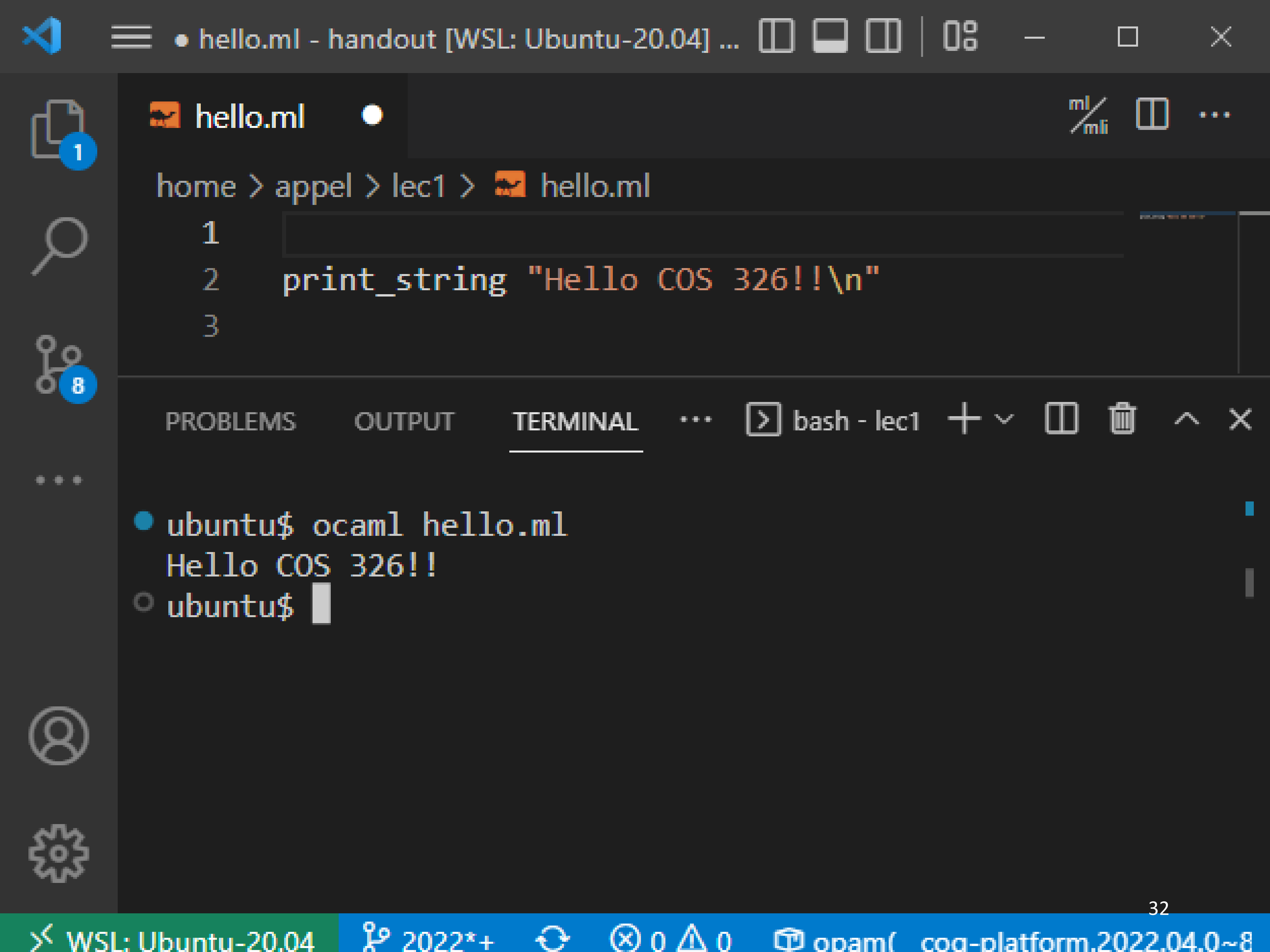

File Edit Selection View Go Run ···
Get Started - lec1 [WSL: Ubuntu-20.04] - Visual Stu...
EXPLORER
Get Started
LEC1 [WSL: UBUNTU-20....
assert.ml
broken.ml
countn.ml
hello.ml
hello2.ml
Makefile
sum_test.ml
sum.ml
Visual Studio Code
Editing evolved
Start
New File...
Open File...
Open Folder...
Clone Git Repository...
Recent
test [WSL: Ubuntu-20.04] /home/a...
Walkthroughs
Get Started with VS Code
Discover the best customizations to make VS Code yours.
Learn the Fundamentals
Jump right into VS Code and get an overview of the must-have features.
Boost your Productivity
More...
Show welcome page on startup
OUTLINE
TIMELINE
WSL: Ubuntu-20.04
0 0
opam(__coq-platform.2022.04.0~8.15~2022.04)


● hello.ml - handout [WSL: Ubuntu-20.04] ...
hello.ml
home > appel > lec1 > hello.ml
1
2 print_string "Hello COS 326!!\n"
3
WSL: Ubuntu-20.04
2022*+
0 0
opam(coq-platform.2022.04.0~8


hello.ml - handout [WSL: Ubuntu-20.04] ...
File
Edit
Selection
View
Go
Run
Terminal
Help
New Terminal Ctrl+Shift+`
Split Terminal Ctrl+Shift+5
Run Task...
Run Build Task... Ctrl+Shift+B
Run Active File
Run Selected Text
Show Running Tasks...
Restart Running Task...
Terminate Task...
Configure Tasks...
Configure Default Build Task...
WSL: Ubuntu-20.04
2022*+
04.0~8


hello.ml - handout [WSL: Ubuntu-20.04] ...
hello.ml
home > appel > lec1 > hello.ml
1
2 print_string "Hello COS 326!!\n"
3
PROBLEMS
OUTPUT
TERMINAL
bash
ubuntu$
WSL: Ubuntu-20.04
2022*+
0 0
opam(coq-platform.2022.04.0~8


hello.ml - handout [WSL: Ubuntu-20.04] ...
hello.ml
home > appel > lec1 > hello.ml
1
2 print_string "Hello COS 326!!\n"
3
PROBLEMS
OUTPUT
TERMINAL
bash
ubuntu$ ocaml hello.ml
WSL: Ubuntu-20.04
2022*+
0
0
opam(coq-platform.2022.04.0~8


hello.ml - handout [WSL: Ubuntu-20.04] ...
hello.ml
home > appel > lec1 > hello.ml
1
2 print_string "Hello COS 326!!\n"
3
PROBLEMS
OUTPUT
TERMINAL
bash - lec1
ubuntu$ ocaml hello.ml
Hello COS 326!!
ubuntu$
WSL: Ubuntu-20.04
2022*+
0 0
opam(coq-platform.2022.04.0~8

A First OCaml Program

`hello.ml:`

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

A First OCaml Program

```
hello.ml:
```

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

a function

its string argument enclosed in `"..."`

a program can be nothing more than just a single expression (but that is uncommon)

no parens. normally call a function f like this:

```
f arg
```

(parens are used for grouping, precedence only when necessary)

A Second OCaml Program

a comment
(* … *)

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)

let _ =
  print_int (sumTo 8);
  print_newline()
```

A Second OCaml Program

the name of the function being defined

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)

let _ =
  print_int (sumTo 8);
  print_newline()
```

the keyword “let” begins a definition; keyword “rec” indicates recursion

A Second OCaml 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)

let _ =
  print_int (sumTo 8);
  print_newline()
```

result type int

argument
named n
with type int

A Second OCaml Program

deconstruct the value n
using pattern matching

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)

let _ =
  print_int (sumTo 8);
  print_newline()
```

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

A Second OCaml Program

vertical bar "|" separates the alternative patterns

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)

let _ =
  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 OCaml Program

Each branch of the match statement constructs a result

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)

let _ =
  print_int (sumTo 8);
  print_newline()
```

construct the result 0

construct a result using a recursive call to sumTo

A Second OCaml 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)

let _ =
  print_int (sumTo 8);
  print_newline()
```

print the result of calling sumTo on 8

print a new line

sum.ml - handout [WSL: Ubuntu-20.04] -...

hello.ml | sum.ml

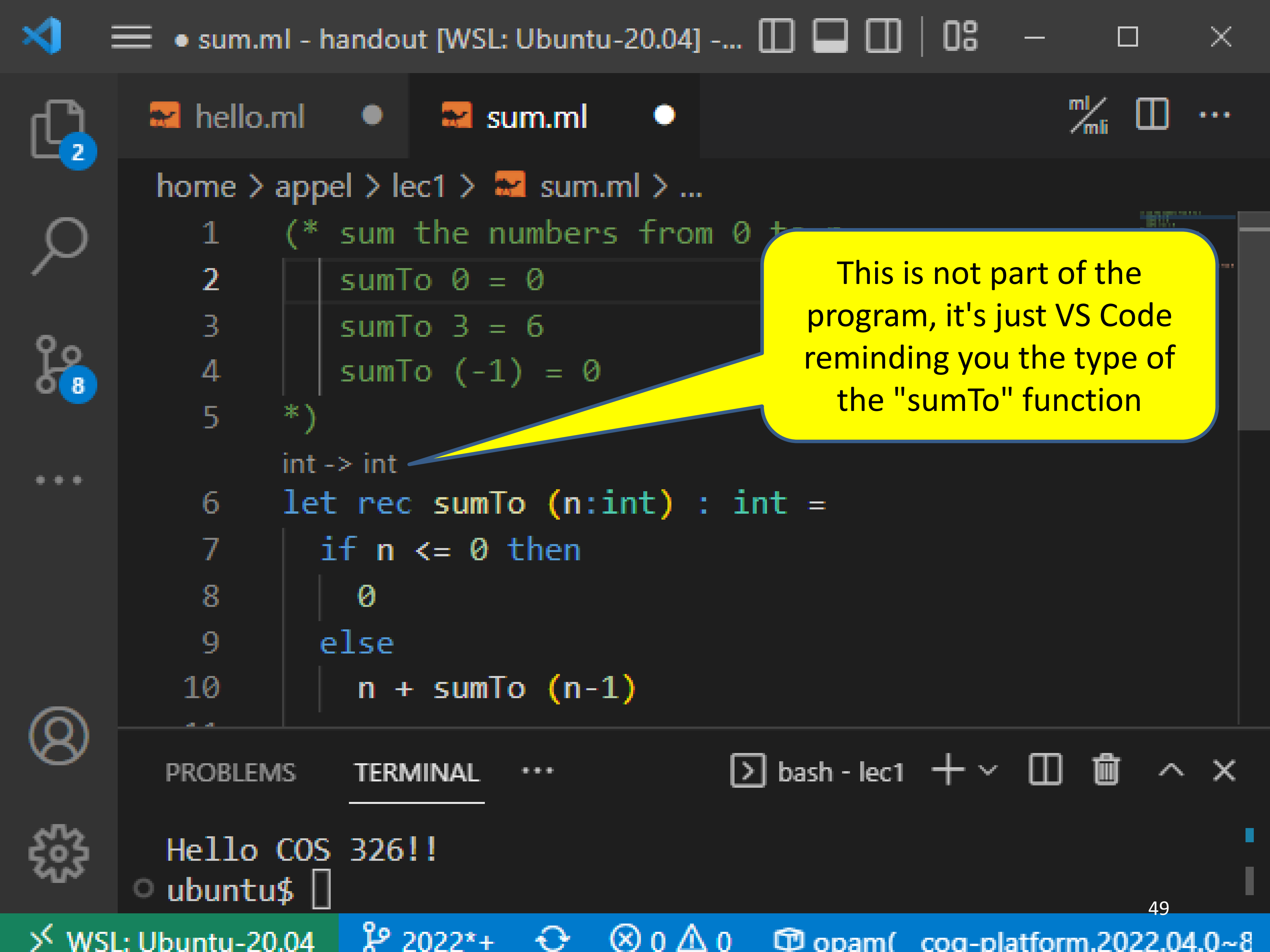
home > appel > lec1 > sum.ml > ...

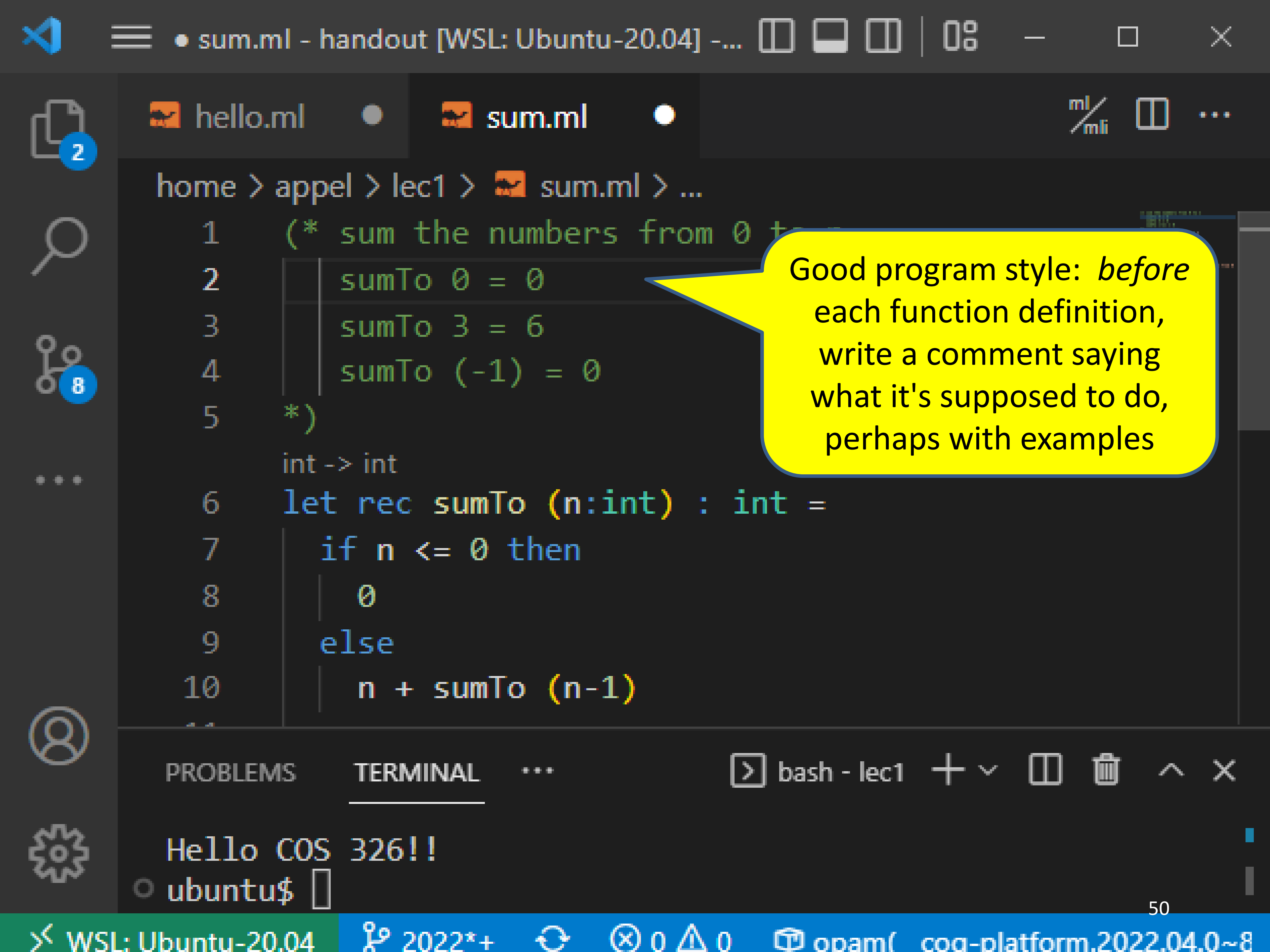
```ocaml
(* sum the numbers from 0 to n
    sumTo 0 = 0
    sumTo 3 = 6
    sumTo (-1) = 0
*)
int -> int
let rec sumTo (n:int) : int =
  if n <= 0 then
    0
  else
    n + sumTo (n-1)
```

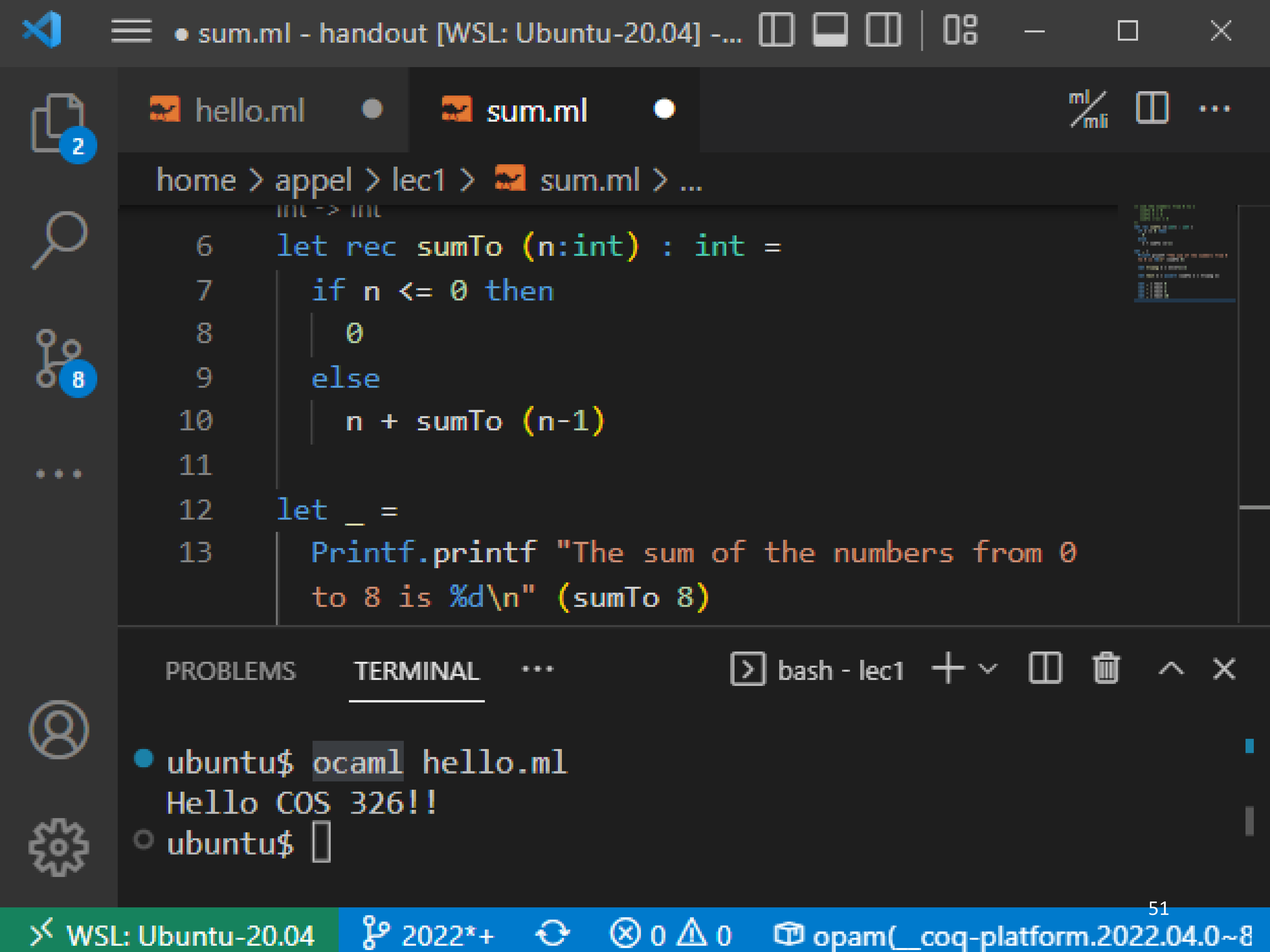
PROBLEMS TERMINAL ··· bash - lec1

```
Hello COS 326!!
ubuntu$
```


WSL: Ubuntu-20.04 | 2022*+ | 0 0 | opam(coq-platform.2022.04.0~8


sum.ml - handout [WSL: Ubuntu-20.04] -...
hello.ml
sum.ml
home > appel > lec1 > sum.ml > ...
(* sum the numbers from 0
sumTo 0 = 0
sumTo 3 = 6
sumTo (-1) = 0
*)
int -> int
let rec sumTo (n:int) : int =
if n <= 0 then
0
else
n + sumTo (n-1)
This is not part of the program, it's just VS Code reminding you the type of the "sumTo" function
PROBLEMS
TERMINAL
bash - lec1
Hello COS 326!!
ubuntu$
WSL: Ubuntu-20.04
2022*+
0
0
opam(coq-platform.2022.04.0~8


sum.ml - handout [WSL: Ubuntu-20.04] -...
hello.ml
sum.ml
home > appel > lec1 > sum.ml > ...
(* sum the numbers from 0
sumTo 0 = 0
sumTo 3 = 6
sumTo (-1) = 0
*)
int -> int
let rec sumTo (n:int) : int =
if n <= 0 then
0
else
n + sumTo (n-1)
Good program style: *before* each function definition, write a comment saying what it's supposed to do, perhaps with examples
PROBLEMS
TERMINAL
bash - lec1
Hello COS 326!!
ubuntu$
WSL: Ubuntu-20.04
2022*+
0
0
opam(
coq-platform.2022.04.0~8



sum.ml - handout [WSL: Ubuntu-20.04] -...
hello.ml
sum.ml
home > appel > lec1 > sum.ml > ...
int -> int
let rec sumTo (n:int) : int =
if n <= 0 then
0
else
n + sumTo (n-1)
let _ =
Printf.printf "The sum of the numbers from 0 to 8 is %d\n" (sumTo 8)
PROBLEMS
TERMINAL
bash - lec1
ubuntu$ ocaml hello.ml
Hello COS 326!!
ubuntu$
WSL: Ubuntu-20.04
2022*+
0 0
opam(__coq-platform.2022.04.0~8

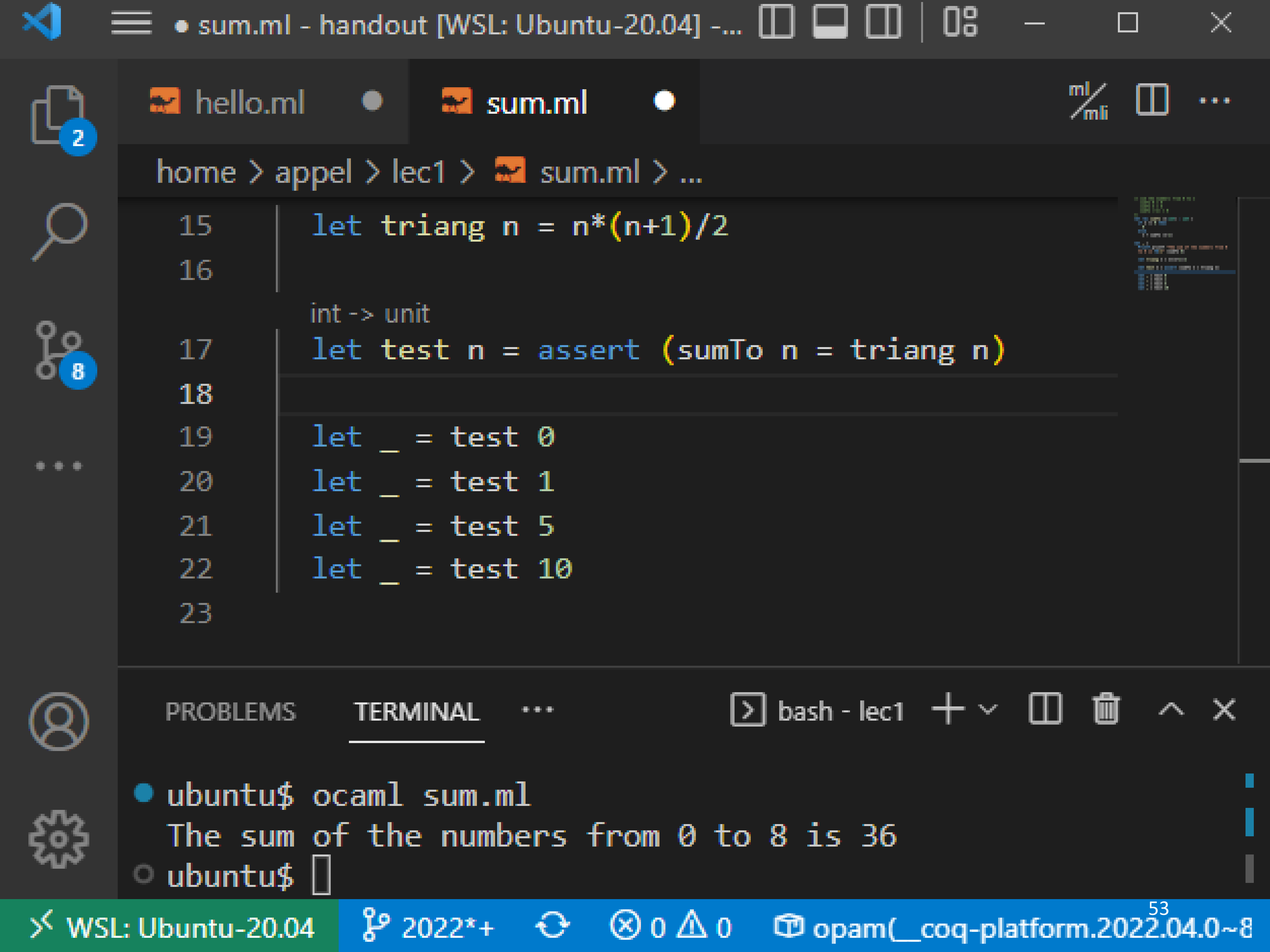
sum.ml - handout [WSL: Ubuntu-20.04]

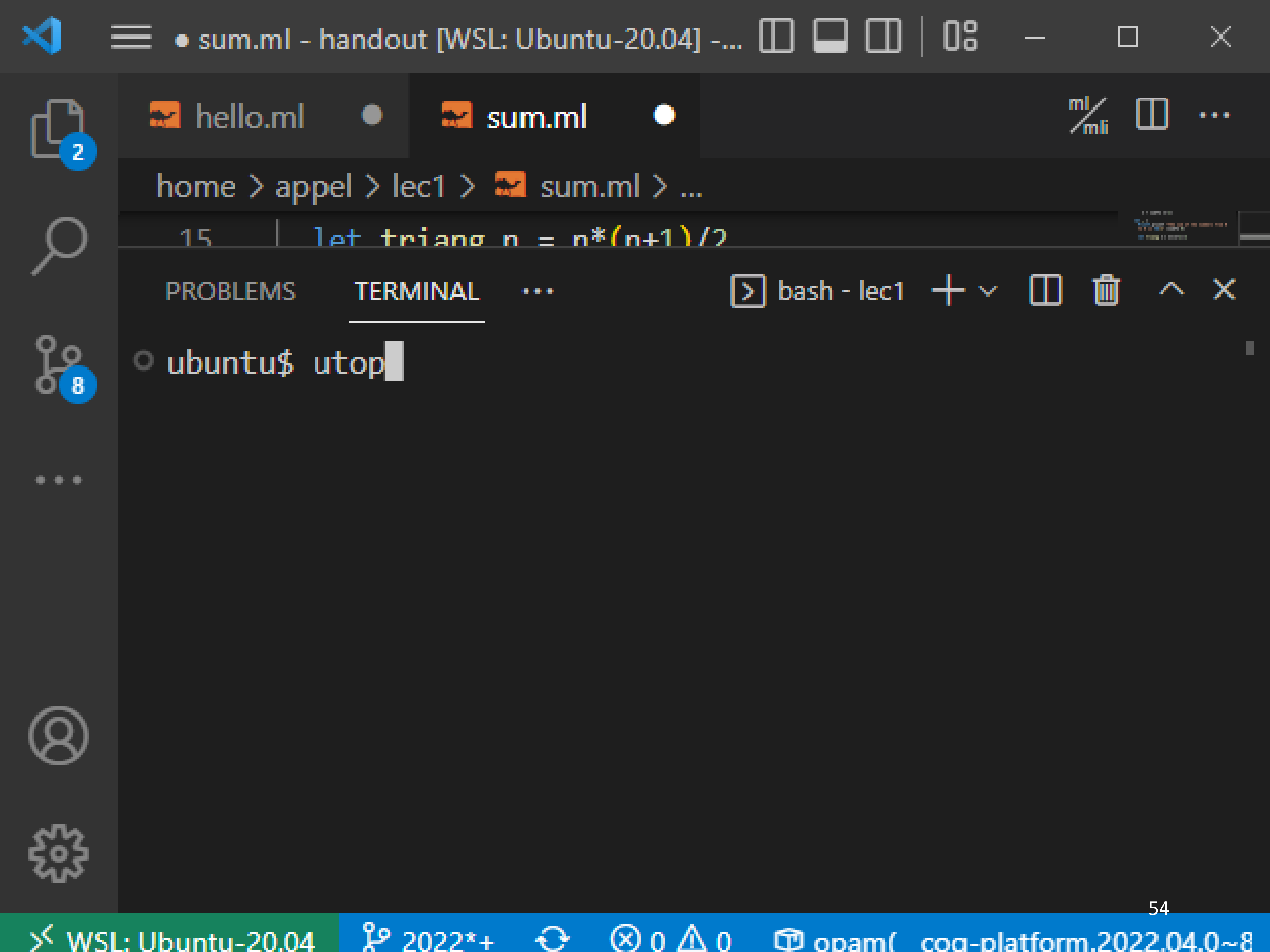
home > appel > lec1 > sum.ml > ...

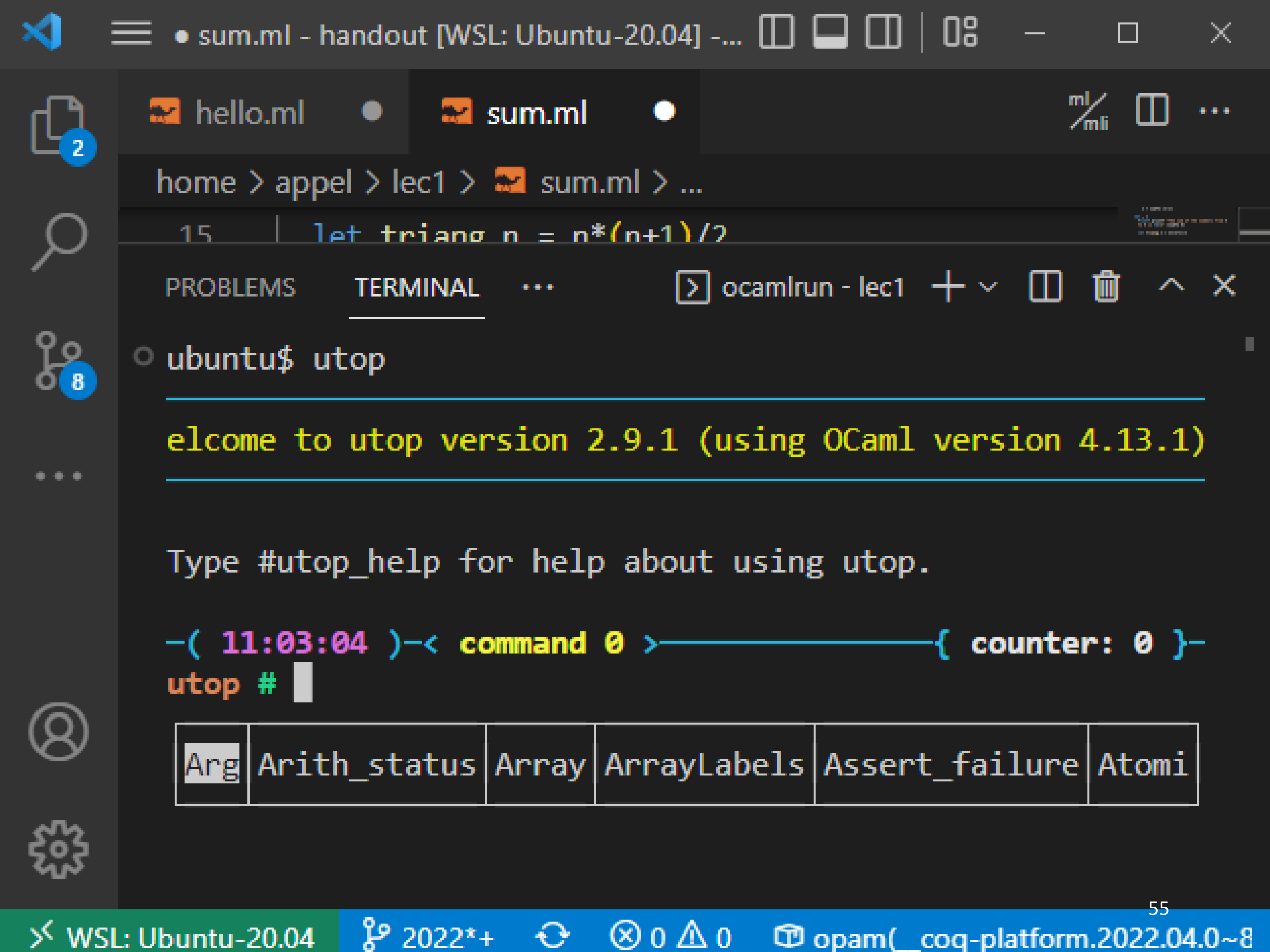
```ocaml
let rec sumTo (n:int) : int =
  if n <= 0 then
    0
  else
    n + sumTo (n-1)

let _ =
  Printf.printf "The sum of the numbers from 0 to 8 is %d\n" (sumTo 8)
```

TERMINAL

```
ubuntu$ ocaml sum.ml
The sum of the numbers from 0 to 8 is 36
ubuntu$
```


sum.ml - handout [WSL: Ubuntu-20.04] -...
hello.ml
sum.ml
home > appel > lec1 > sum.ml > ...
let triang n = n*(n+1)/2
int -> unit
let test n = assert (sumTo n = triang n)
let _ = test 0
let _ = test 1
let _ = test 5
let _ = test 10
PROBLEMS
TERMINAL
bash - lec1
ubuntu$ ocaml sum.ml
The sum of the numbers from 0 to 8 is 36
ubuntu$
WSL: Ubuntu-20.04
2022*+
0 0
opam(_coq-platform.2022.04.0~8


sum.ml - handout [WSL: Ubuntu-20.04] -...
hello.ml
sum.ml
home > appel > lec1 > sum.ml > ...
15 let triang n = n*(n+1)/2
PROBLEMS
TERMINAL
bash - lec1
ubuntu$ utop
WSL: Ubuntu-20.04
2022*+
0 0
opam(coq-platform.2022.04.0~8


sum.ml - handout [WSL: Ubuntu-20.04] -...
hello.ml
sum.ml
home > appel > lec1 > sum.ml > ...
15 let triang n = n*(n+1)/2
PROBLEMS
TERMINAL
ocamlrun - lec1
ubuntu$ utop
elcome to utop version 2.9.1 (using OCaml version 4.13.1)
Type #utop_help for help about using utop.
─(11:03:04)─< command 0 >──{ counter: 0 }─
utop #
Arg
Arith_status
Array
ArrayLabels
Assert_failure
Atomi
WSL: Ubuntu-20.04
2022*+
0
0
opam(_coq-platform.2022.04.0~8

● sum.ml - handout [WSL: Ubuntu-20.04] -...

hello.ml ● sum.ml ●

home > appel > lec1 > sum.ml > ...

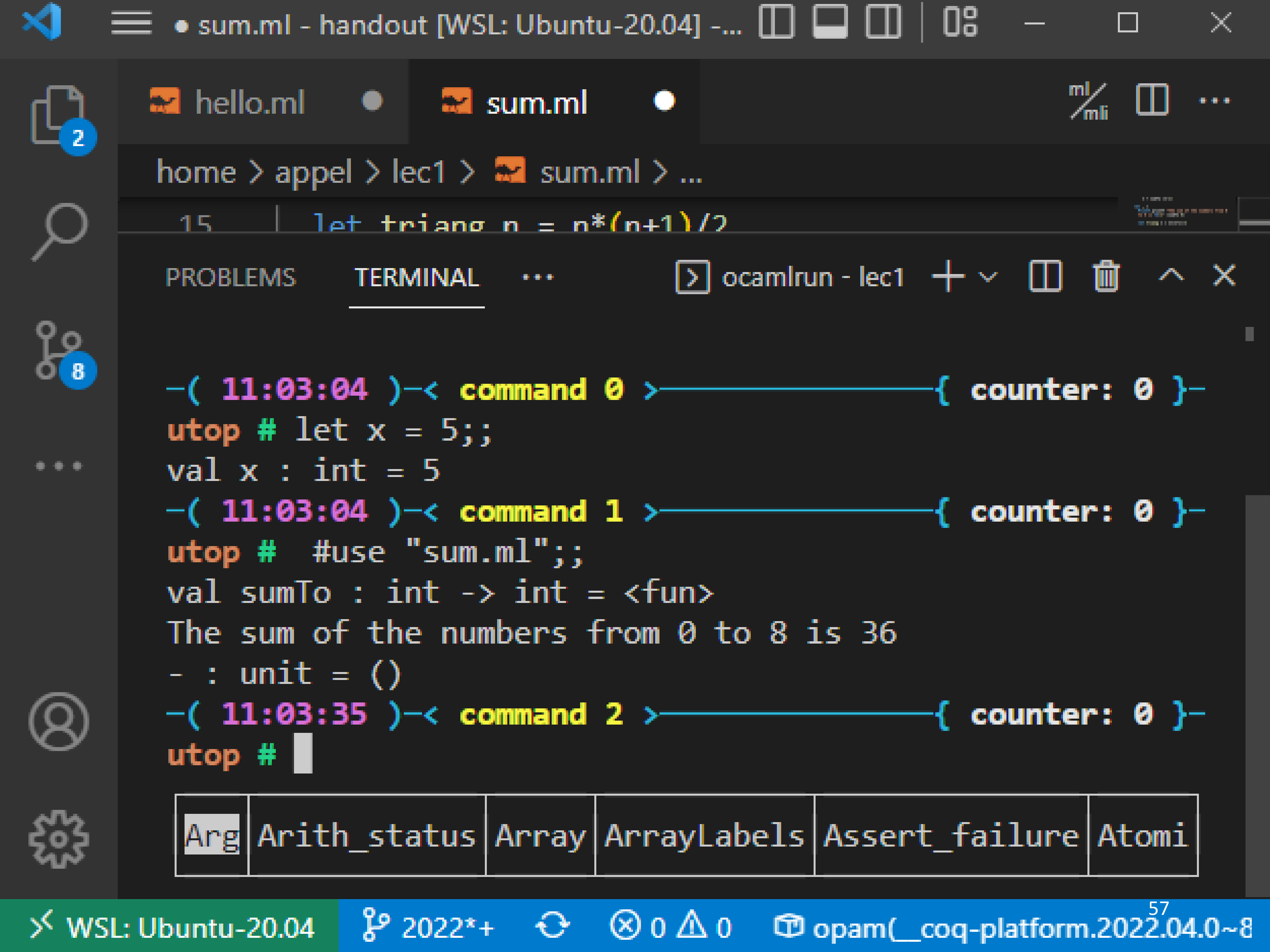
```
15   let triang n = n*(n+1)/2
```

PROBLEMS TERMINAL ··· ocamlrun - lec1

```
elcome to utop version 2.9.1 (using OCaml version 4.13.1)

Type #utop_help for help about using utop.

─( 11:03:04 )─< command 0 >──────────────{ counter: 0 }─
utop # let x = 5;;
val x : int = 5
─( 11:03:04 )─< command 1 >──────────────{ counter: 0 }─
utop #
```

Arg	Arith_status	Array	ArrayLabels	Assert_failure	Atomi

WSL: Ubuntu-20.04 2022*+ ⊗ 0 ⚠ 0 opam(__coq-platform.2022.04.0~8


sum.ml - handout [WSL: Ubuntu-20.04] -...
hello.ml
sum.ml
home > appel > lec1 > sum.ml > ...
15 let triang n = n*(n+1)/2
PROBLEMS
TERMINAL
ocamlrun - lec1
─(11:03:04)─< command 0 >──────{ counter: 0 }─
utop # let x = 5;;
val x : int = 5
─(11:03:04)─< command 1 >──────{ counter: 0 }─
utop # #use "sum.ml";;
val sumTo : int -> int = <fun>
The sum of the numbers from 0 to 8 is 36
- : unit = ()
─(11:03:35)─< command 2 >──────{ counter: 0 }─
utop #
Arg
Arith_status
Array
ArrayLabels
Assert_failure
Atomi
WSL: Ubuntu-20.04
2022*+
0 0
opam(__coq-platform.2022.04.0~8

sum.ml - handout [WSL: Ubuntu-20.04] -...

hello.ml | sum.ml

home > appel > lec1 > sum.ml > ...

```
15    let triang n = n*(n+1)/2
```

PROBLEMS | TERMINAL | ... | ocamlrun - lec1

```
─( 11:03:04 )─< command 0 >──────────────────{ counter: 0 }─
utop # let x = 5;;
val x : int = 5
─( 11:03:04 )─< command 1 >──────────────────{ counter: 0 }─
utop #  #use "sum.ml";;
val sumTo : int -> int = <fun>
The sum of the numbers from 0 to 8 is 36
- : unit = ()
─( 11:03:35 )─< command 2 >──────────────────{ counter: 0 }─
utop # sumTo 6;;
```

Arg	Arith_status	Array	ArrayLabels	Assert_failure	Atomi

WSL: Ubuntu-20.04 | 2022*+ | 0 0 | opam(_coq-platform.2022.04.0~8

sum.ml - handout [WSL: Ubuntu-20.04] -...

hello.ml | sum.ml

home > appel > lec1 > sum.ml > ...

```
15    let triang n = n*(n+1)/2
```

PROBLEMS | TERMINAL | ... | ocamlrun - lec1

```
val x : int = 5
─( 11:03:04 )─< command 1 >────────────────────{ counter: 0 }─
utop #  #use "sum.ml";;
val sumTo : int -> int = <fun>
The sum of the numbers from 0 to 8 is 36
- : unit = ()
─( 11:03:35 )─< command 2 >────────────────────{ counter: 0 }─
utop # sumTo 6;;
- : int = 21
─( 11:04:14 )─< command 3 >────────────────────{ counter: 0 }─
utop # 
```

Arg	Arith_status	Array	ArrayLabels	Assert_failure	Atomi

WSL: Ubuntu-20.04 | 2022*+ | 0 | 0 | opam(__coq-platform.2022.04.0~8

OCAML BASICS: EXPRESSIONS, VALUES, SIMPLE TYPES

Terminology: Expressions, Values, Types

Expressions are computations

- 2 + 3 is a computation

Values (a subset of the expressions) 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

Some simple types, values, expressions

Type:	Values:	Expressions:
`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:

https://ocaml.org/api/Stdlib.html

Evaluation

```
42 * (13 + 1)
```

Evaluation

```
42 * (13 + 1) -->* 588
```

Read like this: “the expression 42 * (13 + 1) evaluates to the value 588”

The “*” is there to say that it does so in 0 or more small steps

Evaluation

$$\underbrace{\texttt{42 * (13 + 1) -->* 588}}$$

Read like this: "the expression 42 * (13 + 1) evaluates to the value 588"

The "*" is there to say that it does so in 0 or more small steps

Here I'm telling you how to execute an OCaml expression --- i.e., I'm telling you something about the *operational semantics* of OCaml

More on semantics later.

Evaluation

```
42 * (13 + 1)                 -->*   588

(3.14 +. 12.0) *. 10e6        -->*   151400000.

int_of_char ’a’               -->*   97

"moo" ^ "cow"                 -->*   “moocow”

if true then 3 else 4         -->*   3

print_int 3                   -->*   ()
```

Evaluation

`1 + "hello"    -->*   ???`

Evaluation

`1 + "hello"   -->*   ???`

“+” processes integers
“hello” is not an integer
evaluation is undefined!

Don’t worry! This expression doesn’t type check.

Aside: See this 4-min talk on Javascript:
https://www.destroyallsoftware.com/talks/wat

OCAML BASICS:
CORE EXPRESSION SYNTAX

Core Expression Syntax

The simplest OCaml expressions e are:

- values *numbers, strings, bools, ...*
- id *variables (x, foo, ...)*
- e_1 op e_2 *operators (x+3, ...)*
- id e_1 e_2 … 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.)

OCAML 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

We write (e : t) to say that *expression* e *has type* t. eg:

2 : int

"hello" : string

2 + 2 : int

"I say " ^ "hello" : 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 OCaml 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:

- help us *think* about *how to construct* our programs
- help us *find stupid programming errors*
- help us track down errors quickly when we *edit our code*
- allow us to *enforce powerful invariants* about 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 "…")

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 "…")

(3) if e1 : int and e2 : int
then e1 + e2 : int

(4) if e1 : int and e2 : int
then e1 * e2 : int

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 "…")

(3) if e1 : int and e2 : int
then e1 + e2 : int

(4) if e1 : int and e2 : int
then e1 * e2 : int

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

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

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 "…")

(3) if e1 : int and e2 : int
then e1 + e2 : int

(4) if e1 : int and e2 : int
then e1 * e2 : int

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

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

Using the rules:

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

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 "…")

(3) if e1 : int and e2 : int
then e1 + e2 : int

(4) if e1 : int and e2 : int
then e1 * e2 : int

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

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

Using the rules:

2 : int and 3 : int. (By rule 1)
Therefore, (2 + 3) : int (By rule 3)

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 "…")

(3) if e1 : int and e2 : int
then e1 + e2 : int

(4) if e1 : int and e2 : int
then e1 * e2 : int

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

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

Using the rules:

2 : int and 3 : int. (By rule 1)
Therefore, (2 + 3) : int (By rule 3)
5 : int (By rule 1)

Type Checking Rules

Example rules:

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

(2) "abc" : string (and similarly for a

(3) if e1 : int and e2 : int
then e1 + e2 : int

FYI: This is a ***formal proof*** that the expression is well-typed!

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

tring_of_int e : string

Using the rules:

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

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 "…")

(3) if e1 : int and e2 : int
then e1 + e2 : int

(4) if e1 : int and e2 : int
then e1 * e2 : int

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

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

Another perspective:

???? * ???? : int

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

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 "…")

(3) if e1 : int and e2 : int
then e1 + e2 : int

(4) if e1 : int and e2 : int
then e1 * e2 : int

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

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

Another perspective:

7 * ???? : int

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

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 "…")

(3) if e1 : int and e2 : int
then e1 + e2 : int

(4) if e1 : int and e2 : int
then e1 * e2 : int

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

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

Another perspective:

7 * (add_one 17) : int

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

Type Checking Rules

You can always start up the OCaml interpreter to find out a type of a simple expression:

```
$ ocaml
        OCaml Version 4.13.1
#
```

Type Checking Rules

You can always start up the OCaml interpreter to find out a type of a simple expression:

or utop

```
$ ocaml
        OCaml Version 4.13.1
# 3 + 1;;
```

use ";;" to end a phrase in the top level

(";;" can also end a top-level phrase in a file, but I'm going to avoid using it there because then some of you will confuse it with a ";" ....)

Type Checking Rules

You can always start up the OCaml interpreter to find out a type of a simple expression:

```
$ ocaml
       OCaml Version 4.13.1
# 3 + 1;;
- : int = 4
#
```

press return and you find out the type and the value

Type Checking Rules

You can always start up the OCaml interpreter to find out a type of a simple expression:

```
$ ocaml
       OCaml Version 4.13.1
# 3 + 1;;
- : int = 4
# “hello ” ^ “world”;;
- : string = “hello world”
#
```

press return and you find out the type and the value

Type Checking Rules

You can always start up the OCaml interpreter to find out a type of a simple expression:

```
$ ocaml
      OCaml Version 4.13.1
# 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)

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

(3) if e1 : int and e2 : int
then e1 + e2 : int

(4) if e1 : int and e2 : int
then e1 * e2 : int

(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	(By rule 2)
1 : int	(By rule 1)
1 + "hello" : ??	(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

It is a ***good thing*** that this expression does not type check!

“Well typed programs do not go wrong”

Robin Milner, 1978

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

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

Isn't that cheating?

"Well typed programs do not go wrong"

Robin Milner, 1978

(3 / 0) is well typed. Does it "go wrong?" Answer: No.

"Go wrong" is a technical term meaning, "have no defined semantics." Raising an exception is perfectly well defined semantics, which we can reason about, which we can handle in ML with an exception handler.

So, it's not cheating.

(Discussion: why do we make this distinction, anyway?)

Type Soundness

"Well typed programs do not go wrong"

Programming languages with this property have *sound* type systems. They are called *safe* languages.

Safe languages are generally *immune* to buffer overrun vulnerabilities, uninitialized pointer vulnerabilities, etc., etc. (but not immune to all bugs!)

Safe languages: ML, Java, Python, …

Unsafe languages: C, C++

OVERALL SUMMARY:
A SHORT INTRODUCTION TO FUNCTIONAL PROGRAMMING

OCaml

OCaml is a *functional* programming language

- express control flow and iteration by defining *functions*
- *not by* ***modifying*** *the values of variables and data structures*

Imperative: “do this” Functional: “be this”

OCaml is a *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
- the type system is *sound*; the language is *safe*