Error Handling and Testing

Concepts of Programming Languages
Lecture 9

CAS CS 320

Outline

» Look more carefully at **options** and **results**

» See how **monads** (i.e., **option chaining**) can make working with options more convenient

» Introduce **exceptions** as a way of handling errors unsafely

» Give a short tutorial on **ounit** a unit test framework for OCaml

Practice Problem

$$\Gamma \vdash \texttt{match p with | (x, y) ->} \big(\texttt{x + y}\big) \texttt{+ z} : \tau$$

Determine the smallest context Γ and the type τ such that the above judgment is derivable. Then give the derivation

$$\{ \emptyset, x : \tau \}$$ (crossed out)

don't do this on exam (in red, pointing to $\{\cdots\} \vdash q : int$)

$$\frac{\{p : int \ast int, z : int, q : int, r : int\} \vdash z : int}{} \text{(var)}$$

$$\frac{\{\cdots\} \vdash q : int \text{ (var)} \qquad \frac{}{\{\cdots\} \vdash r : int} \text{(var)}}{\{p : int \ast int, z : int, q : int, r : int\} \vdash q + r : int} \text{(intAdd)}$$

$$\frac{}{\{p : int \ast int, z : int\} \vdash p : \text{int} \ast \text{int}} \text{(var)} \qquad \frac{\{p : int \ast int, z : int, q : int, r : int\} \vdash (q + r) + z : int}{} \text{(intAdd)}$$

$$\frac{}{\{p : int \ast int, z : int\} \vdash \text{match } p \text{ with } | (q, r) \rightarrow (q + r) + z : int} \text{(tuple Match)}$$

$$\dfrac{}{\{l: \alpha\ list\} \vdash l : \alpha\ list}\ (var) \qquad \dfrac{}{\{l: \alpha\ list\} \vdash true : bool}\ (trueLit) \qquad \dfrac{}{\{l: \alpha\ list,\ x:\alpha,\ xs:\alpha\ list\} \vdash false : bool}\ (falseLit)$$

$$\dfrac{}{\{l: \alpha\ list\} \vdash match\ l\ with\ |\ [\ ] \to true\ |\ x::xs \to false : bool}\ (listMatch)$$

$$\dfrac{}{\emptyset \vdash fun\ l \to match\ l\ with\ |\ [\ ] \to true\ |\ x::xs \to false : \alpha\ list \to bool}\ (fun)$$

Options and Results

Recall: Options

```
type 'a option =
    | None
    | Some of 'a
```

option is a polymorphic (parametrized) variant type with two constructors

An option is like a "box" that may or may not contain a value

This is useful for defining **partial functions**

Example

```ocaml
let rec first_such_that (p : 'a -> bool) (l : 'a list) : 'a option =
  match l with
  | [] -> None
  | x :: xs -> if p x then Some x else first_such_that p xs
```

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It's not guaranteed that *any* element in a list satisfies the predicate. *What should we return in this case?*

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Suppose we want to determine the first element in a list which satisfies a given predicate

It's not guaranteed that *any* element in a list satisfies the predicate. *What should we return in this case?*

If we return an option we can return **None**.

Important (Again)

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This means the type-checker *forces* us to handle the undefined case of partial functions

No Remembering Null Checks

```c
void fill_foo(int* foo) {
    if (!foo) { // this is the NULL check
        printf("This is wrong\n");
        return;
    }
    *foo = 23;
}
```

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We don't have to *remember* to check in our value is null before doing our computation

If we don't do a "none check", then our code won't even pass the type checker

Recall: Results

```
type ('a, 'b) result =
    | Ok of 'a
    | Error of 'b
```

A **result** is the same as an option, except that we carry data in the **"None"** case

Results play the same role as options, except they may help with things like error messages

Example

```
type error = LessThanOne | MoreThanOne

let exactly_one (f : 'a -> bool) (l : 'a list) : ('a, error) result =
...
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But we also want to know why we failed...

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But we also want to know why we failed...

Results allow use to return more information in the failed case

Practice Problem

Implement the function

```
val exactly_one : ('a –> bool)
                  -> 'a list
                  -> ('a, error) result
```

according to the idea from the previous slide

Higher Order Functions and Options/Results

```
let rec exactly n f l =
  match n, l with
  | 0, [] -> Some []
  | n, [] -> None
  | n, x :: xs ->
    if n < 0
    then None
    else if f x
    then Option.map (fun xs -> x :: xs) (exactly (n - 1) f xs)
    else exactly n f xs
```

A reminder that **map** is a very useful function for error handling

It allows us to work with the output of a recursive call as if it was an "actual" value

demo
(matrices)

Advanced: Monads

$$
\begin{array}{ccc}
T & \xrightarrow{\eta T} & T^2 \\
{\scriptstyle T\eta}\downarrow & \searrow & \downarrow{\scriptstyle \mu} \\
T^2 & \xrightarrow{\mu} & T
\end{array}
$$

Advanced: Monads

$$T \xrightarrow{\eta T} T^2$$

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Roughly speaking, a **monad** is a structure that "holds a thing".
This includes **options** and **results,** but also **lists**

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The key feature of a monad is the ability to **sequence** operations

Advanced: Monads

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$$T^2 \xrightarrow{\mu} T$$

Roughly speaking, a **monad** is a structure that "holds a thing". This includes **options** and **results**, but also **lists**

The key feature of a monad is the ability to **sequence** operations

(see the textbook for more details, this is an idea that comes from a field of mathematics called *category theory*)

Aside: Option Chaining

```
let user = {}; // user has no address
alert( user?.address?.street ); // undefined (no error)
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Option chaining is a feature used in languages like javascript for *sequencing* functions on a possibly nonexistent object without having to explicitly check

This is a pattern based on monads (taken from FP)

Bind a.k.a. "And Then"

```
let bind (x : 'a option) (f : 'a -> 'b option) : 'b option =
  match x with
  | None -> None
  | Some x -> f x
```

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(We have an analogous version for results as well)

demo
(assoc. lists w/ unique keys)

let* Syntax

```
let foo =
  let ( let* ) = Option.bind in
  let* x = ox in
  let* y = oy in
  let* z = oz in
  Some (x + y + z)
```

```
let bar =
  bind ox (fun x ->
  bind oy (fun y ->
  bind oz (fun z ->
  Some (x + y + z))))
```

```
let baz =
  match ox with
  | None -> None
  | Some x -> (
    match oy with
    | None -> None
    | Some y -> (
      match oz with
      | None -> None
      | Some z -> Some (x + y + z)
    )
  )
```

let* syntax allows use to shorthand the use of the **bind** function, which allows us to avoid sequences of (annoying) pattern matches

Again, this is exactly option chaining

Disclaimer: It is never required
that you use monads in this course.
That said, they're very cool

demo

(interpreters)

Important: Eager evaluation

```
let foo =
  match ox, oy with
  | Some x, Some y -> Some (x + y)
  | _ -> None
```

≠

```
let foo =
  match ox with
  | None -> None
  | Some x -> (
    match oy with
    | None -> None
    | Some y -> Some (x + y)
  )
```

OCaml is **eagerly evaluated**

This means that arguments to functions/match expressions are *completely* evaluated before the function is called/match is checked

Exceptions

Raising Exceptions

```python
if f x:
  raise Exception("error message")
else:
  return 2
```
Python

```ocaml
exception MyError

let foo x =
  if f x
  then raise MyError
  else 2
```
OCaml

Like most languages, OCaml has a mechanism for programmatically *crashing* the program

Sometimes, we want this to happen. *Not all errors should be handled gracefully*

Data-Carrying Exceptions

```
exception A
exception B
exception Code of int
exception Details of string
```

Exceptions can carry data, just like constructors of a variant type

This data may be useful when trying to *handle* the exception instead of letting it crash the program

Exceptions and Pattern Matching

```ocaml
let hd l =
  match l with
  | [] -> Failure "hd called on empty list"
  | x :: _ -> x
```

raise

```ocaml
let hd_opt l =
  match hd l with
  | x -> Some x
  | exception (Failure _) -> None
```

OCaml has **try-style error-handling** (see the textbook for details) but it is far common in modern OCaml to **pattern match** on exceptions

Exceptions and Evaluation Order

```
(raise A, raise B)
```

$\neq$

```
let a = raise A in
let b = raise B in
(a, b)
```

One issue with exceptions is that understanding their behavior requires understanding the *order* in which arguments are evaluated

The order in which elements in a tuple are **is not specified by OCaml**
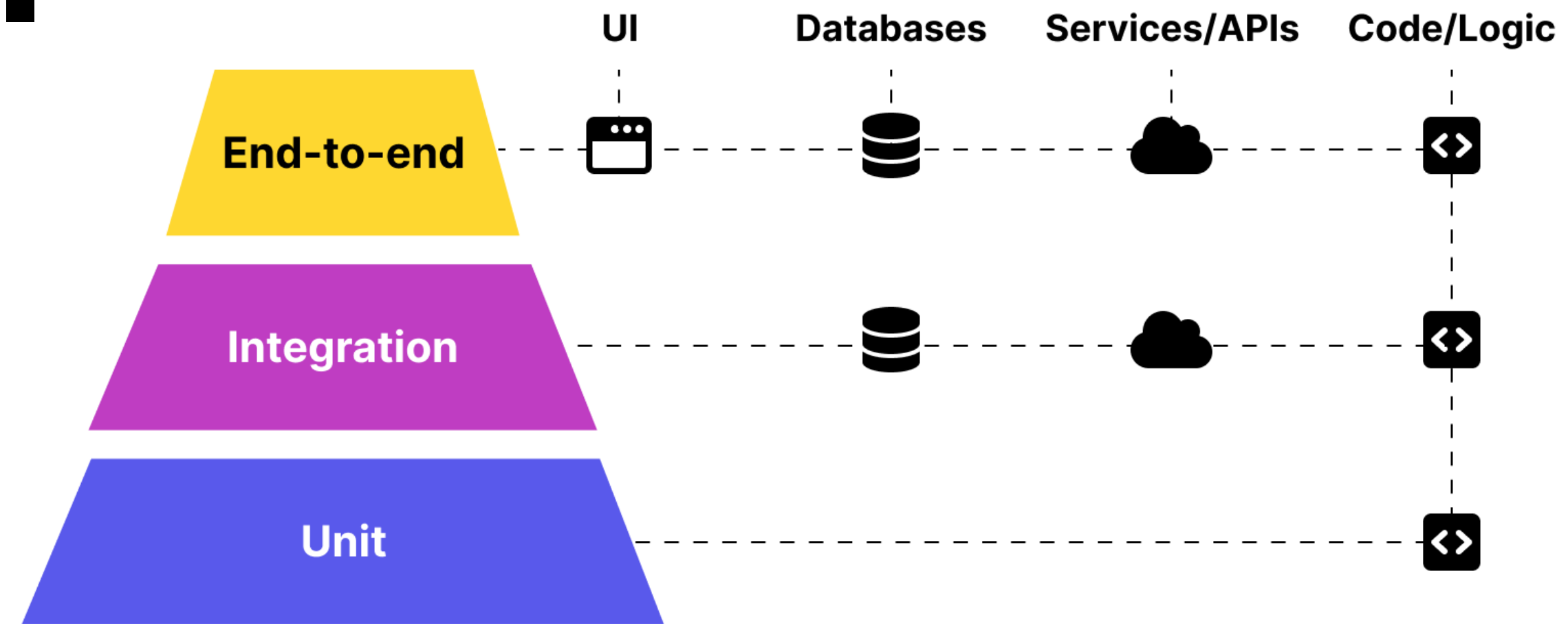
Practice Problem

Reimplement the function

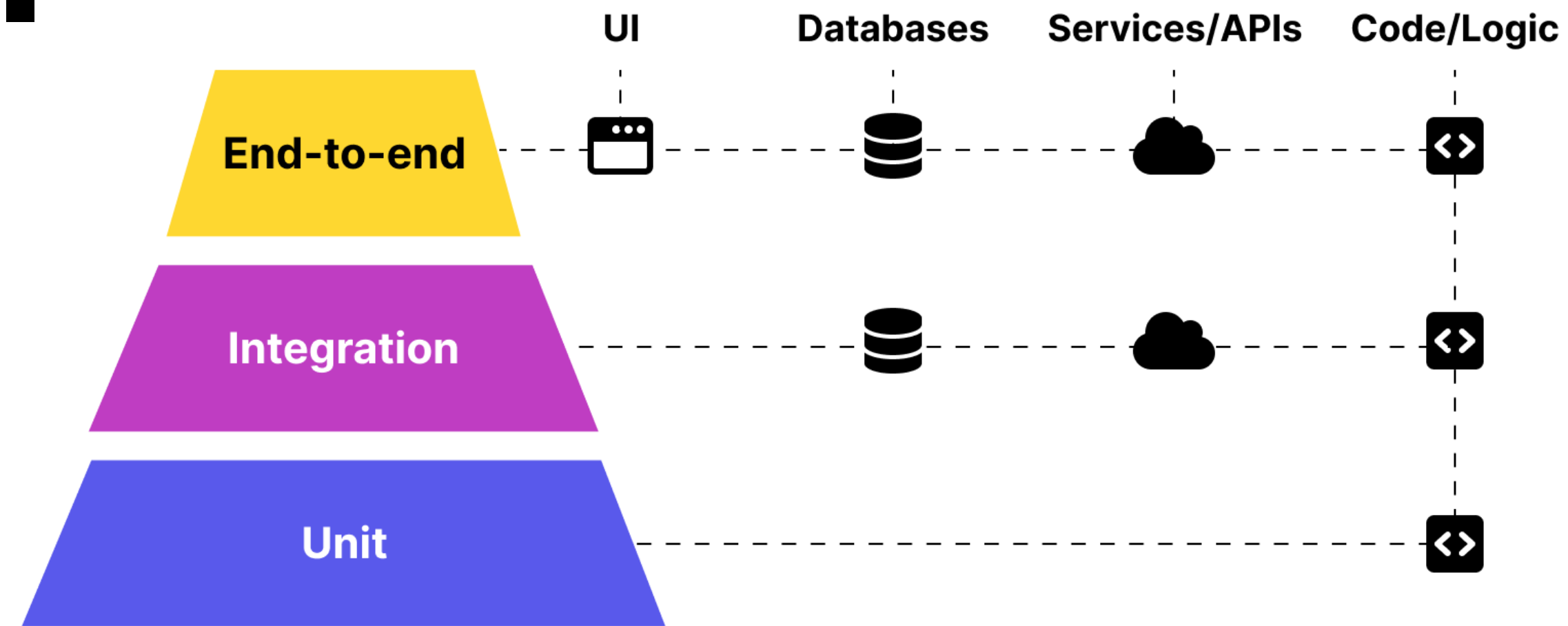**val exactly_one : ('a –> bool)**
**   –> 'a list**
**   –> 'a**

so that it raises an exception if there is no element in the list satisfied by the given predicate
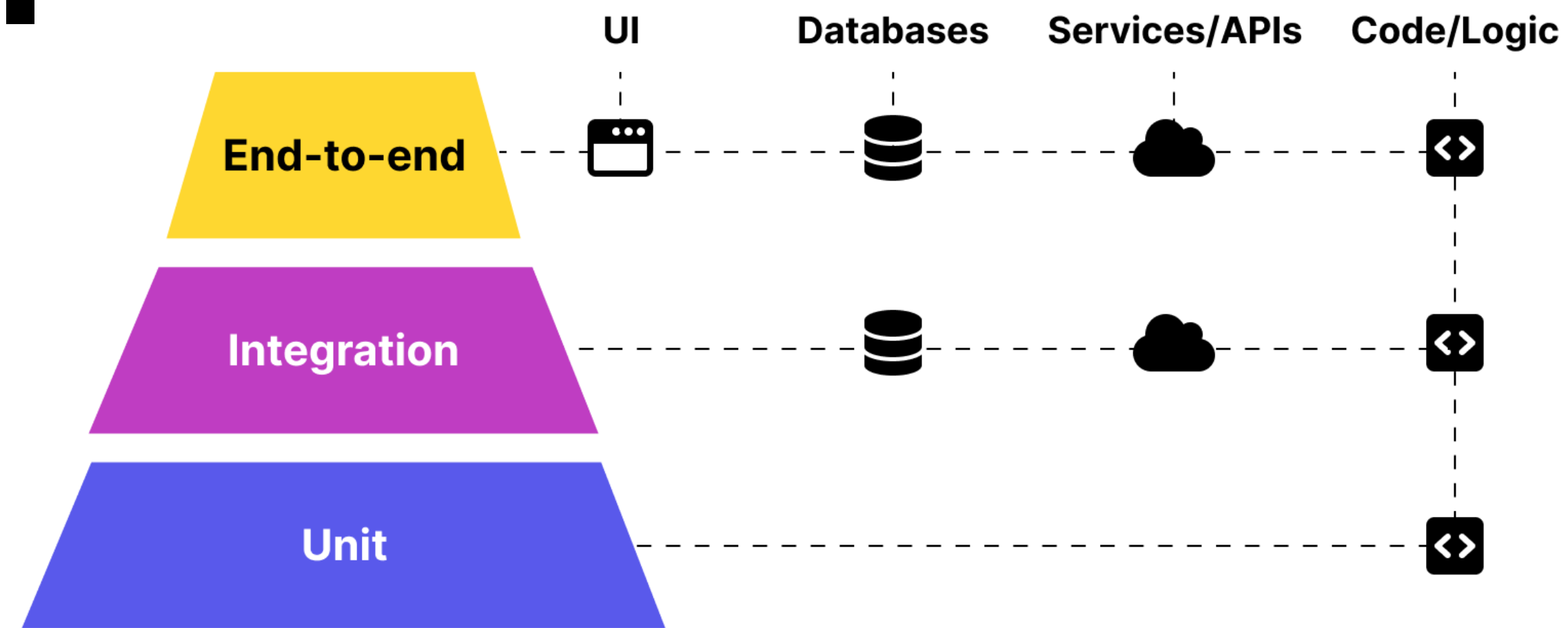
Unit Testing

High Level

UI Databases Services/APIs Code/Logic

End-to-end

Integration

Unit

High Level

unit tests verify our code on a collection of hand-chosen inputs
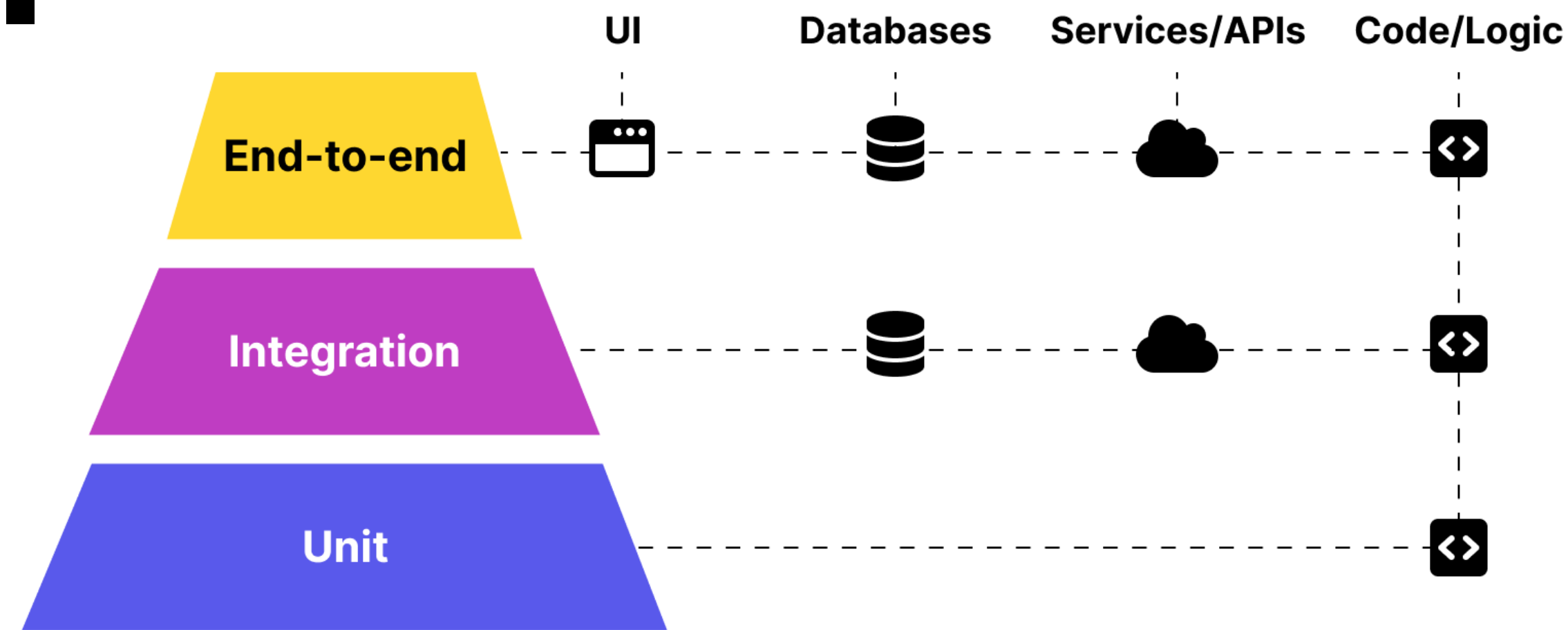
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It's the easiest kind of testing and the "first line of defense"
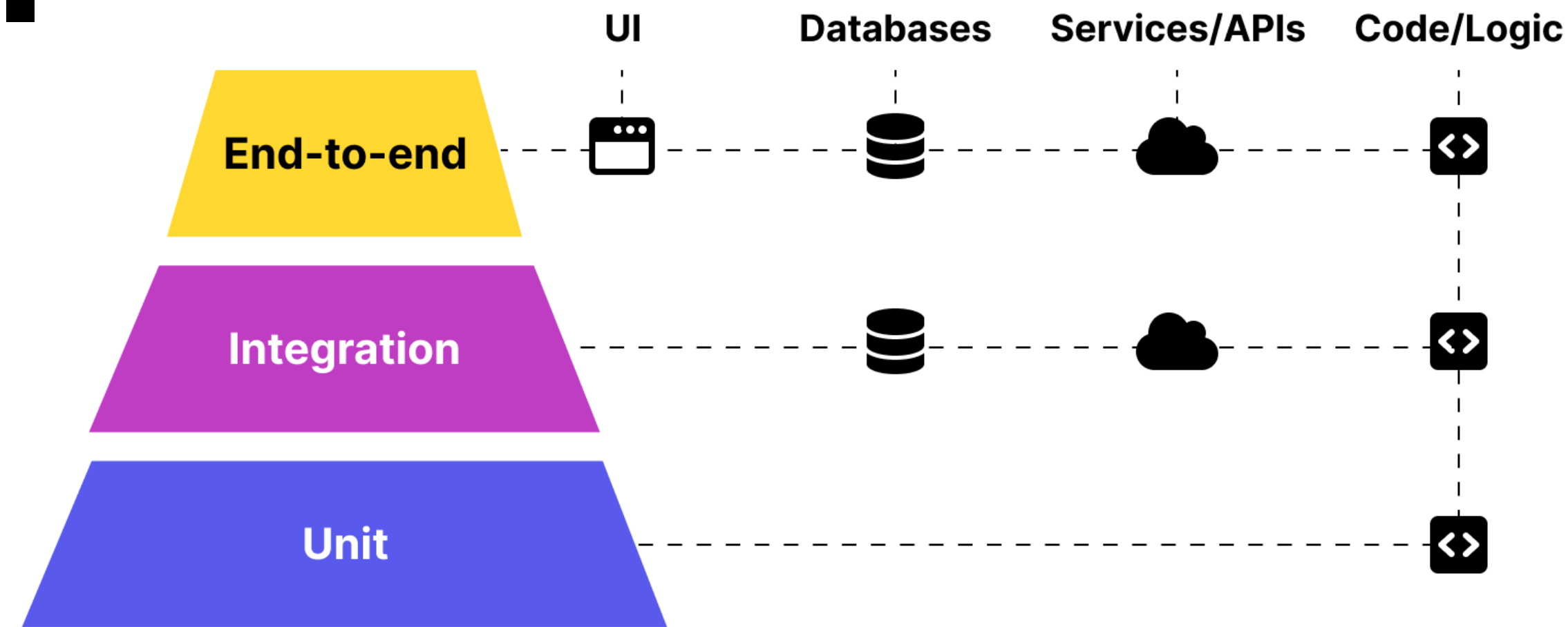
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It's distinct from **fuzz testing** or **randomized testing** in which random inputs are checked

It's also distinct from an area of CS call *software verification,* in which we uses computers to *prove* that our programs are correct

Words of Warning

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OUnit, we just want to get familiar with the ideas

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We will use OUnit from now on for assignments and
projects, so you need to know how to read and
write tests in this framework

Set-up

```
(test
 (name test_PROG)
 (libraries ounit2))
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We will always do this for you in your projects, but it's good to know how to do for our own projects*

*I know no one is using OCaml for personal projects, but I can hope...

Important Functions

`(>::)`   creates a labelled test

`(>:::)`   creates a labelled test suite

assert_equal   compares two values in a unit test

assert_raises   checks that an expression raises the right exception

run_test_tt_main runs a test suite

Example Test Suite

```
let tests = "test suite for sum" >::: [
  "empty" >:: (fun _ -> assert_equal 0 (sum []));
  "singleton" >:: (fun _ -> assert_equal 1 (sum [1]));
  "two_elements" >:: (fun _ -> assert_equal 3 (sum [1; 2]));
]

let _ = run_test_tt_main tests
```

test/test_PROG.ml

Each test is given a name, the suite is given a name as well

Each test is wrapped in an anonymous function *(why?)*

Unit Testing with OUnit

Benefits:

» Tests can be run in parallel

» Failed tests don't block!

Downsides:

» More code to read and write

» Output is a bit difficult to read**...**

demo

(testing exactly_one)

Summary

Error handling can be done safely with types and unsafely with exceptions

Either way we can test with unit test frameworks like OUnit

FP has a lot of beautiful mechanisms for working with complex types like options and results