Programming Languages and Compilers (CS 421)

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https://courses.engr.illinois.edu/cs421/fa2021

Based in part on slides by Mattox Beckman, as updated by Vikram Adve and Gul Agha

Programming Languages & Compilers

Three Main Topics of the Course

I

New Programming Paradigm

II

Language Translation

III

Language Semantics

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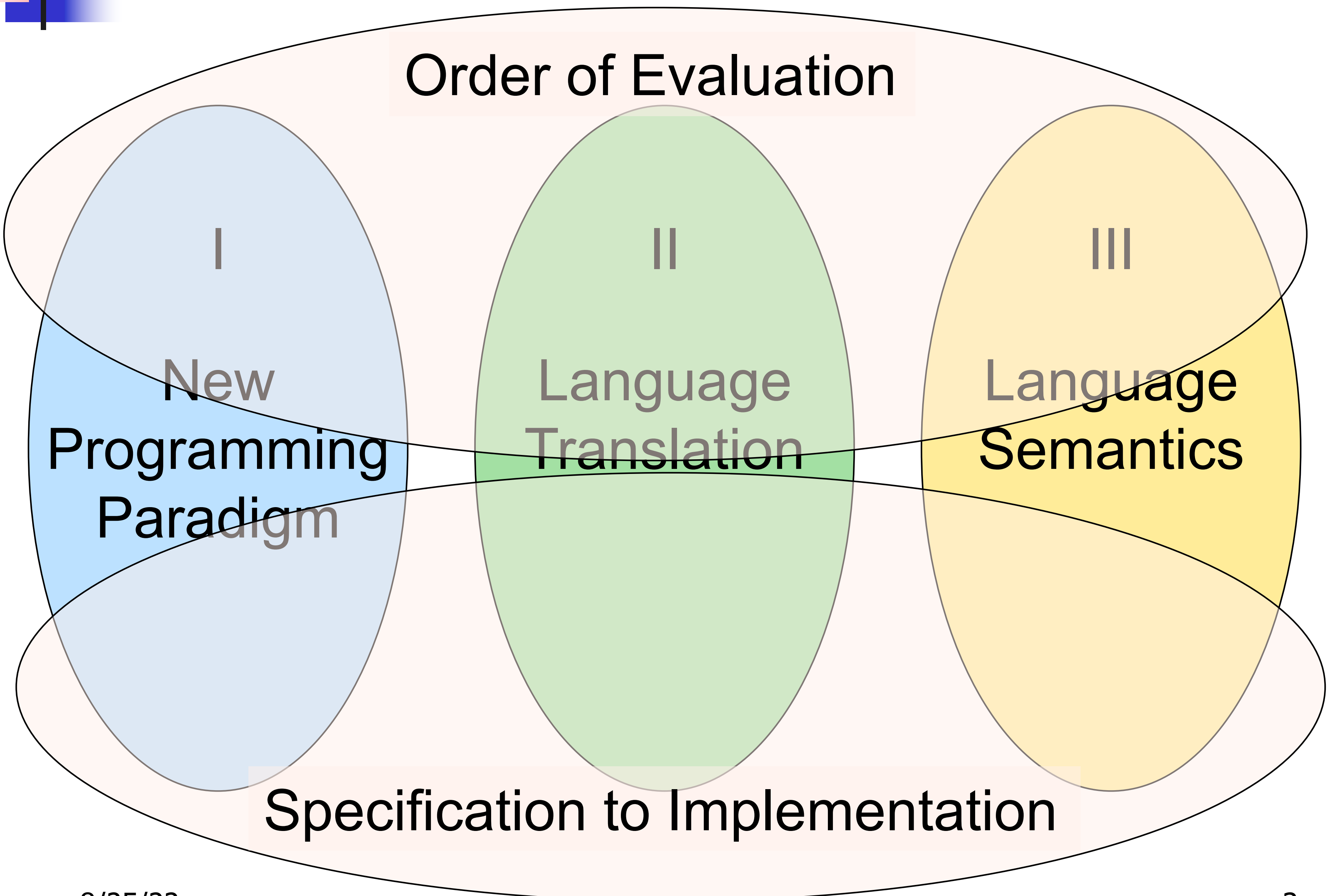

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I : New Programming Paradigm

Functional Programming

Environments and Closures

Patterns of Recursion

Continuation Passing Style

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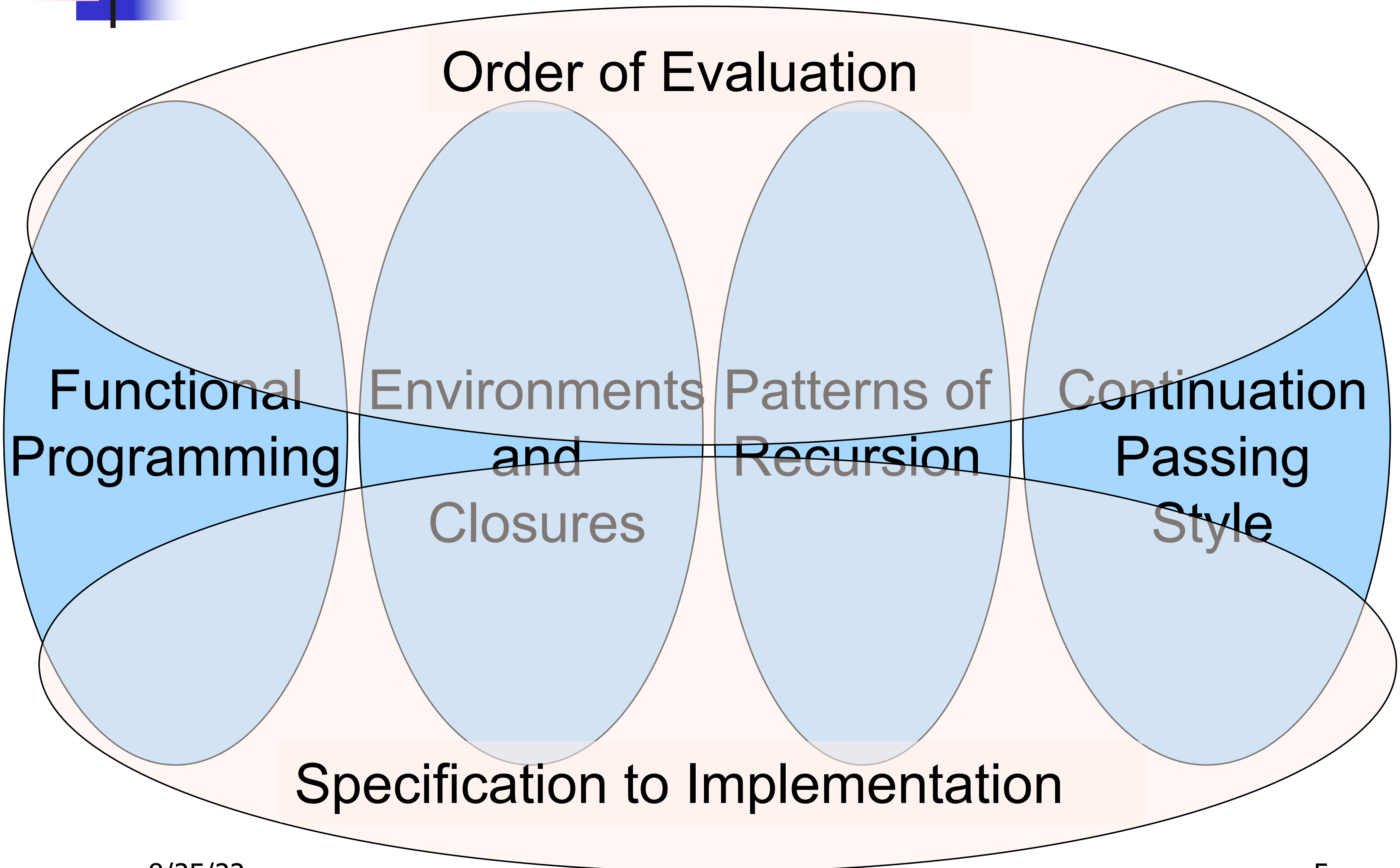

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II : Language Translation

Lexing and Parsing

Type Systems

Interpretation

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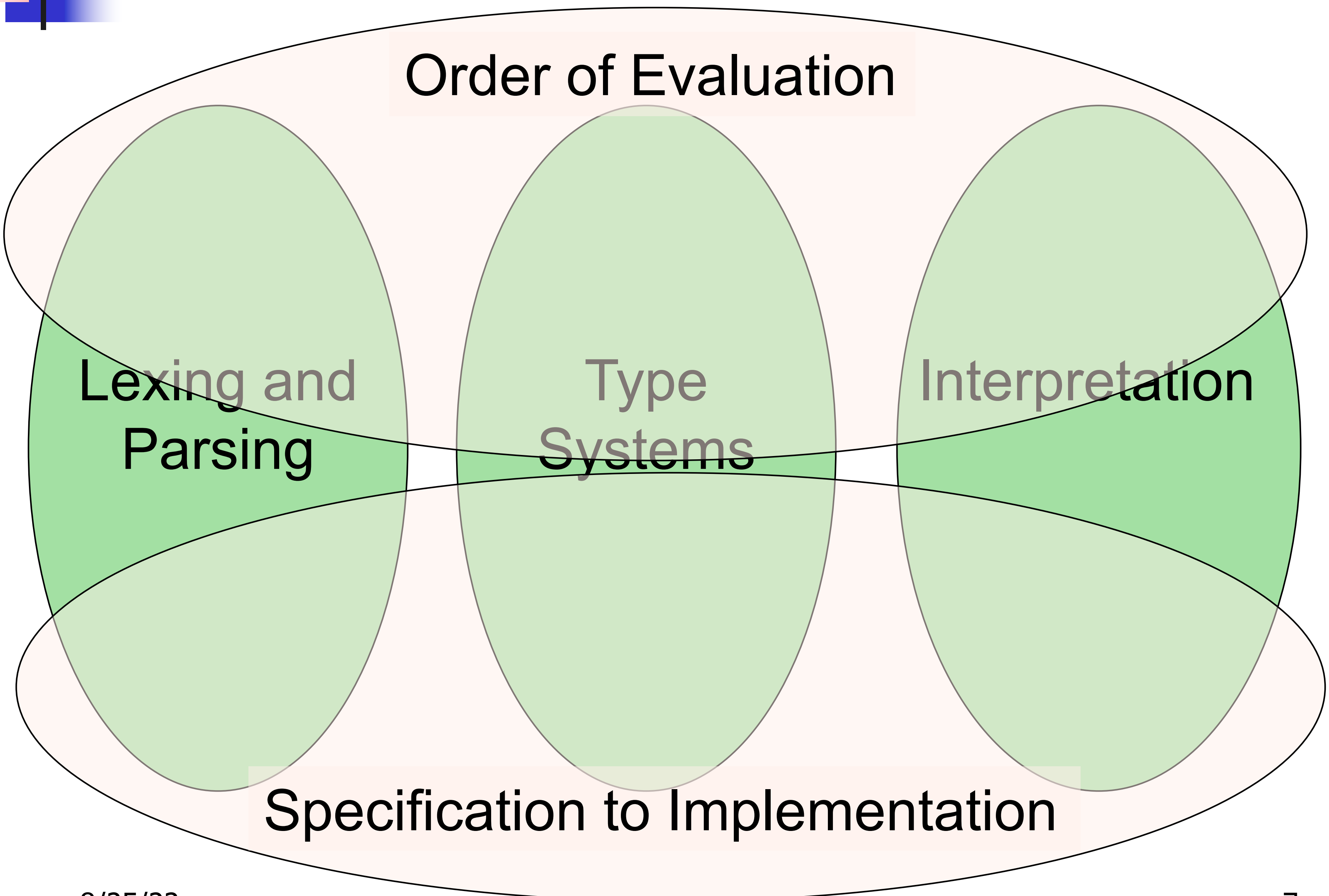

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III : Language Semantics

Operational Semantics

Lambda Calculus

Axiomatic Semantics

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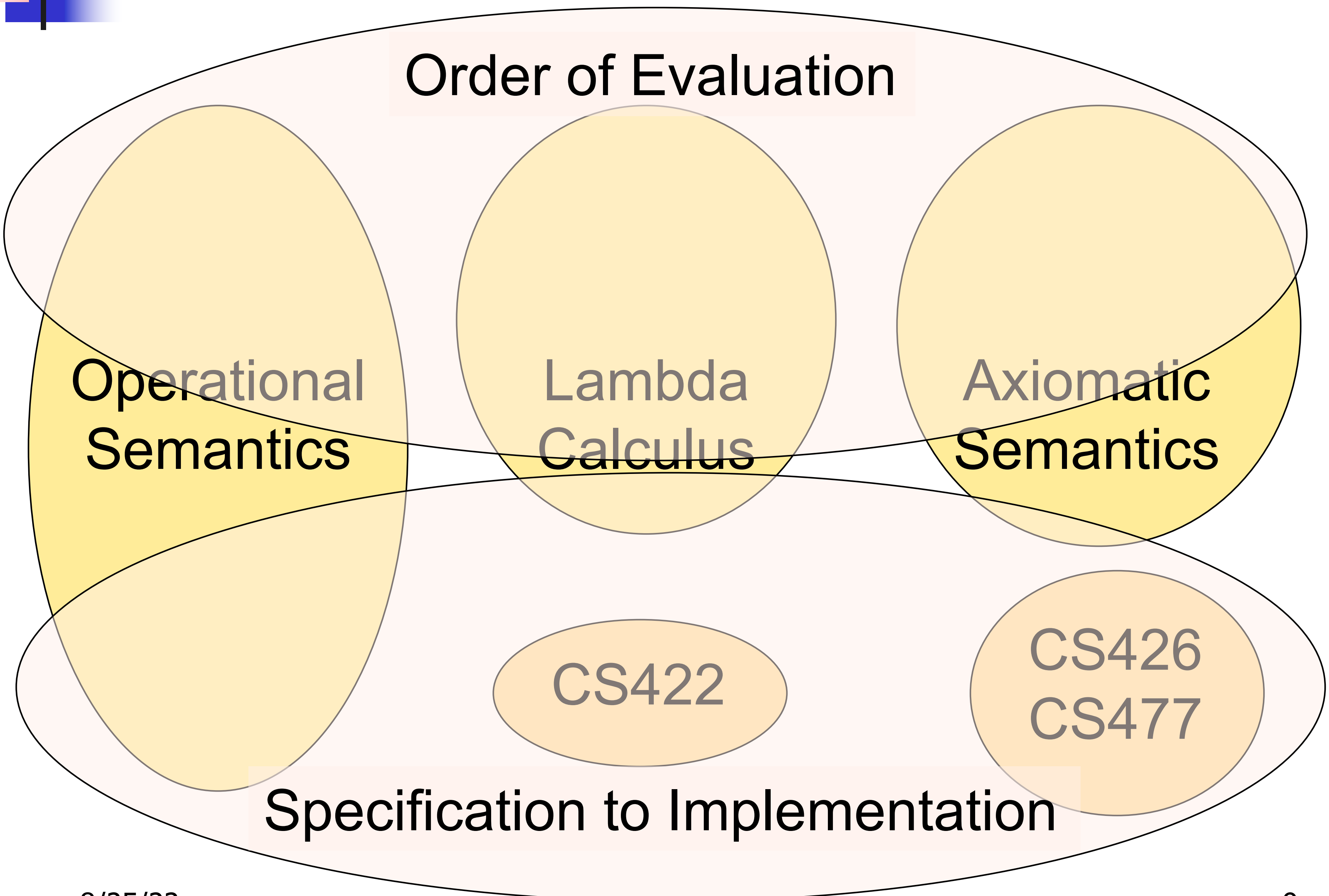

Contact Information - Elsa L Gunter

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  - Thursday 10:30am – 11:20am
  - Thursday 3:45pm – 2:20pm
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Course TAs

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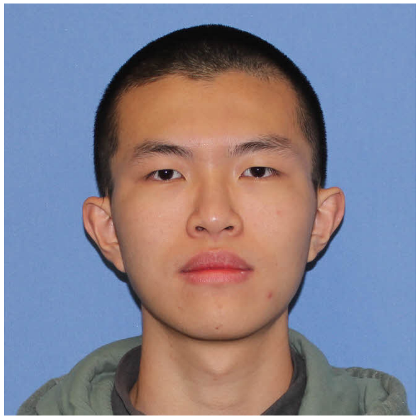


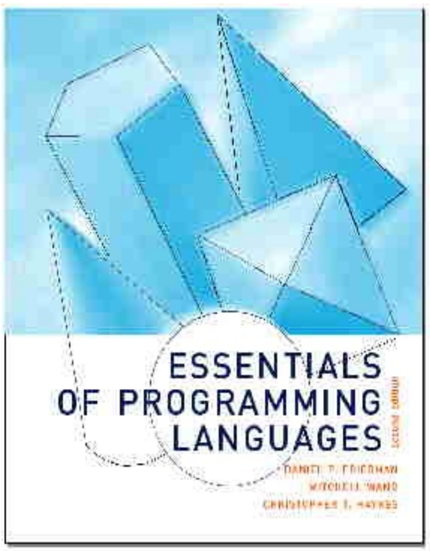
Haoqing Zhu

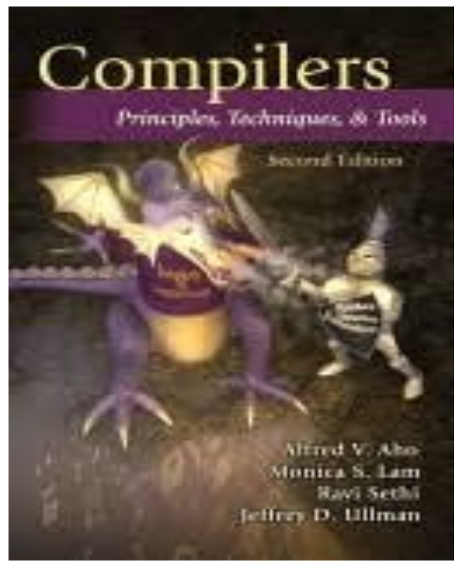
Course Website

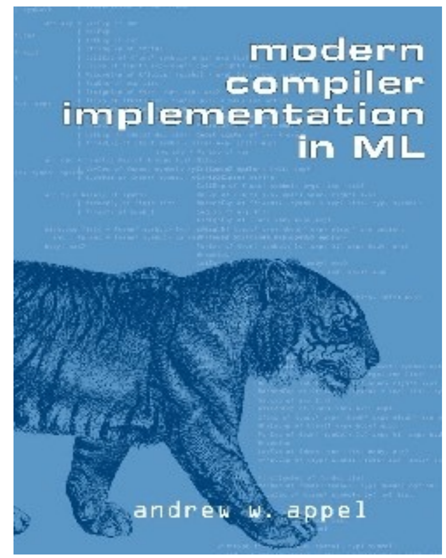
- https://courses.engr.illinois.edu/cs421/fa2022
- Main page - summary of news items
- Policy - rules governing course
- Lectures - syllabus and slides
- MPs - information about assignments
- Exams
- Unit Projects - for 4 credit students
- Resources - tools and helpful info
- FAQ

Some Course References

- No required textbook
- Some suggested references







Some Course References

- No required textbook.
- Pictures of the books on previous slide
- Essentials of Programming Languages (2nd Edition) by Daniel P. Friedman, Mitchell Wand and Christopher T. Haynes, MIT Press 2001.
- Compilers: Principles, Techniques, and Tools, (also known as "The Dragon Book"); by Aho, Sethi, and Ullman. Published by Addison-Wesley. ISBN: 0-201-10088-6.
- Modern Compiler Implementation in ML by Andrew W. Appel, Cambridge University Press 1998
- Additional ones for Ocaml given separately

Course Grading

- Assignments 10%
  - Web Assignments (WA) (~5%)
  - MPs (in Ocaml) (5~%)
  - All WAs and MPs Submitted by **PrairieLearn**
  - Late submission penalty: 20% to total

Course Grading

- 2 Midterms - 25% each
  - **Sep 29, Nov 10**
  - **BE AVAILABLE FOR THESE DATES!**
- Final 40%
- Fall back: 7:00pm-10:00pm., Tuesday Dec. 13
- Percentages are approximate

Course Assingments – WA & MP

- You may discuss assignments and their solutions with others
- You may work in groups, but you must **list members with whom you worked** if you share solutions or solution outlines
- **Each student must write up and turn in their own solution separately**
- You may look at examples from class and other similar examples from any source – **cite appropriately**
  - Note: University policy on plagiarism still holds - cite your sources if you are not the sole author of your solution
  - Do not have to cite course notes or me

OCAML

- Locally:
  - Will use ocaml inside VSCode inside PrairieLearn problems this semester
- Globally:
  - Main CAML home: http://ocaml.org
  - To install OCAML on your computer see: http://ocaml.org/docs/install.html
  - To try on the web: https://try.ocamlpro.com
  - More notes on this later

References for OCaml

- Supplemental texts (not required):
- The Objective Caml system release 4.05, by Xavier Leroy, online manual
- Introduction to the Objective Caml Programming Language, by Jason Hickey
- Developing Applications With Objective Caml, by Emmanuel Chailloux, Pascal Manoury, and Bruno Pagano, on O'Reilly
  - Available online from course resources

Why learn OCAML?

- Many features not clearly in languages you have already learned
- Assumed basis for much research in programming language research
- OCAML is particularly efficient for programming tasks involving languages (eg parsing, compilers, user interfaces)
- Industrially Relevant:
  - Jane Street trades billions of dollars per day using OCaml programs
  - Major language supported at Bloomberg
- Similar languages: Microsoft F#, SML, Haskell, Scala

Session in OCAML

% ocaml

Objective Caml version 4.07.1

(* Read-eval-print loop; expressions and declarations *)

2 + 3;; (* Expression *)

- : int = 5

3 < 2;;

- : bool = false

No Overloading for Basic Arithmetic Operations

```
# 15 * 2;;
- : int = 30
# 1.35 + 0.23;;  (* Wrong type of addition *)
Characters 0-4:
  1.35 + 0.23;;  (* Wrong type of addition *)
  ^^^^
Error: This expression has type float but an
    expression was expected of type
        int
# 1.35 +. 0.23;;
- : float = 1.58
```

No Implicit Coercion

```
# 1.0 * 2;; (* No Implicit Coercion *)
Characters 0-3:
  1.0 * 2;; (* No Implicit Coercion *)
  ^^^
Error: This expression has type float but an
    expression was expected of type
      int
```

Sequencing Expressions

```
# "Hi there";;  (* has type string *)
- : string = "Hi there"
# print_string "Hello world\n";;  (* has type unit *)
Hello world
- : unit = ()
# (print_string "Bye\n"; 25);;  (* Sequence of exp *)
Bye
- : int = 25
```

Declarations; Sequencing of Declarations

```
# let x = 2 + 3;;   (* declaration *)
val x : int = 5
# let test = 3 < 2;;
val test : bool = false
# let a = 1 let b = a + 4;; (* Sequence of dec *)
val a : int = 1
val b : int = 5
```

Booleans (aka Truth Values)

```
# true;;
- : bool = true
# false;;
- : bool = false
```

// $\rho_7 = \{c \to 4, test \to 3.7, a \to 1, b \to 5\}$

```
# if b > a then 25 else 0;;
- : int = 25
```

Booleans and Short-Circuit Evaluation

```
# 3 > 1 && 4 > 6;;
- : bool = false
# 3 > 1 || 4 > 6;;
- : bool = true
# (print_string "Hi\n"; 3 > 1) || 4 > 6;;
Hi
- : bool = true
# 3 > 1 || (print_string "Bye\n"; 4 > 6);;
- : bool = true
# not (4 > 6);;
- : bool = true
```

Functions

```
# let plus_two n = n + 2;;
val plus_two : int -> int = <fun>
# plus_two 17;;
- : int = 19
```

Functions

```
let plus_two n = n + 2;;

plus_two 17;;
- : int = 19
```

Nameless Functions (aka Lambda Terms)


```
fun n -> n + 2;;

(fun n -> n + 2) 17;;
- : int = 19
```

Functions

```
# let plus_two n = n + 2;;
val plus_two : int -> int = <fun>
# plus_two 17;;
- : int = 19
# let plus_two = fun n -> n + 2;;
val plus_two : int -> int = <fun>
# plus_two 14;;
- : int = 16
```

First definition syntactic sugar for second

Functions with more than one argument

```
# let add_three x y z = x + y + z;;
val add_three : int -> int -> int -> int = <fun>
# let t = add_three 6 3 2;;
val t : int = 11
# let add_three =
   fun x -> (fun y -> (fun z -> x + y + z));;
val add_three : int -> int -> int -> int = <fun>
```

Again, first syntactic sugar for second

Using a nameless function

```
# (fun x -> x * 3) 5;;   (* An application *)
- : int = 15
# ((fun y -> y +. 2.0), (fun z -> z * 3));;
  (* As data *)
- : (float -> float) * (int -> int) = (<fun>,
  <fun>)
```

Note: in fun v -> exp(v), scope of variable is only the body exp(v)

Environments

- *Environments* record what value is associated with a given identifier
- Central to the semantics and implementation of a language
- Notation

$$\rho = \{name_1 \rightarrow value_1,\ name_2 \rightarrow value_2,\ \ldots\}$$

  Using set notation, but describes a partial function
- Often stored as list, or stack
  - To find value start from left and take first match

Environments

X → 3

name → "Steve"

. . .

region → (5.4, 3.7)

y → 17

id → {Name = "Paul",
Age = 23,
SSN = 999888777}

b → true

Global Variable Creation

\# 2 + 3;;   (* Expression *)

// doesn't affect the environment

\# let test = 3 < 2;;   (* Declaration *)

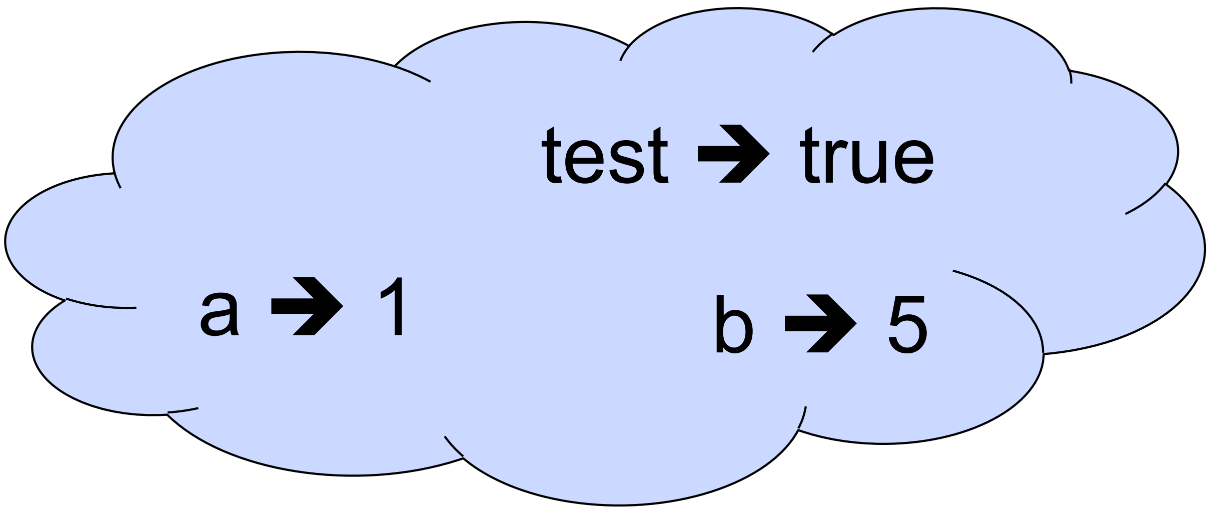
val test : bool = false

// ρ_1 = {test → false}

\# let a = 1 let b = a + 4;; (* Seq of dec *)

// ρ_2 = {b → 5, a → 1, test → false}

Environments



New Bindings Hide Old

// $\rho_2 = \{b \to 5, a \to 1, test \to false\}$

```
let test = 3.7;;
```

- What is the environment after this declaration?

New Bindings Hide Old

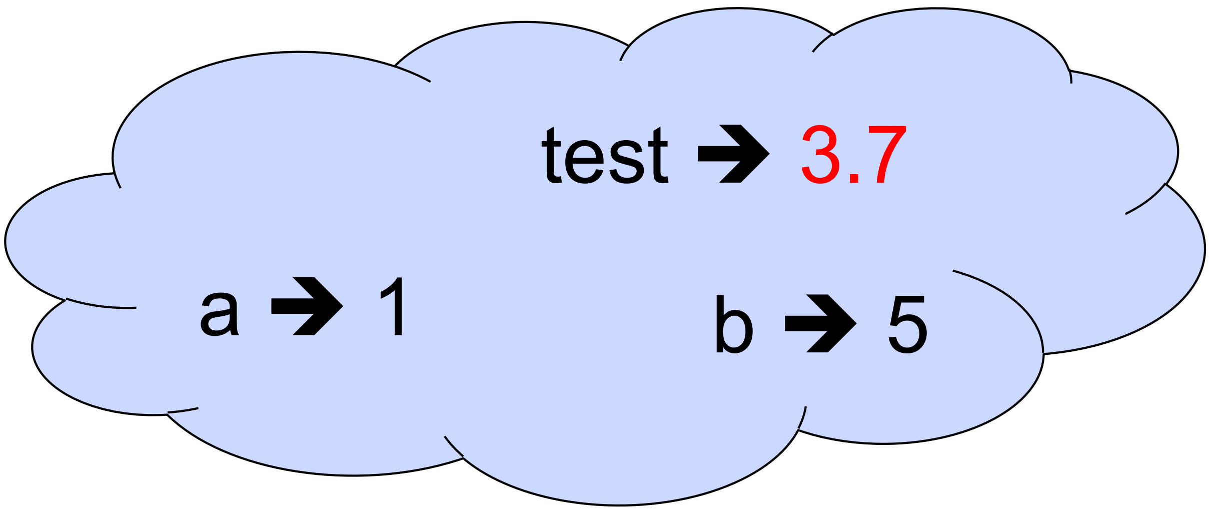
// $\rho_2 = \{b \rightarrow 5, a \rightarrow 1, test \rightarrow false\}$

```
let test = 3.7;;
```

- What is the environment after this declaration?

// $\rho_3 = \{test \rightarrow 3.7, a \rightarrow 1, b \rightarrow 5\}$

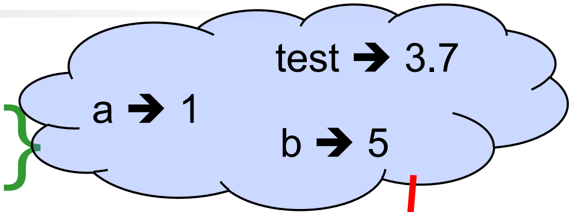
Environments



Now it’s your turn

You should be able to do WA1-IC Problem 1 , parts (* 1 *) - (* 3 *)

Local Variable Creation

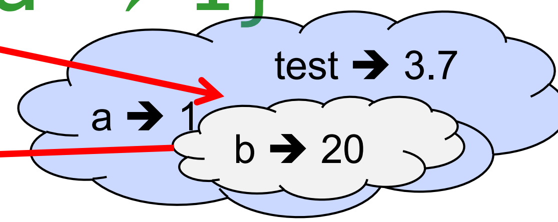


// $\rho_3 = \{test \to 3.7, a \to 1, b \to 5\}$

\# let b = 5 * 4

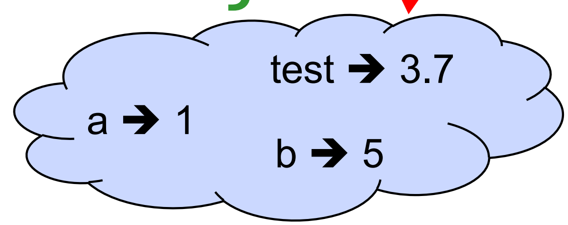
// $\rho_4 = \{b \to 20, test \to 3.7, a \to 1\}$

in 2 * b;;



\- : int = 40

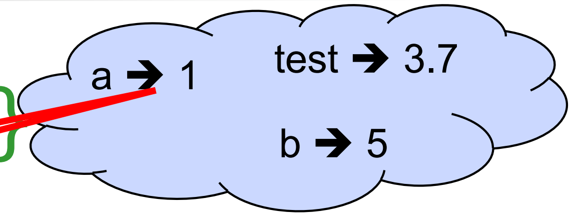
// $\rho_5 = \rho_3 = \{test \to 3.7, a \to 1, b \to 5\}$



\# b;;

\- : int = 5

Local let binding



// $\rho_5 = \rho_3 = \{test \rightarrow 3.7,\ a \rightarrow 1,\ b \rightarrow 5\}$

```
# let c =
    let b = a + a
```

// $\rho_6 = \{b \rightarrow 2\} + \rho_3$

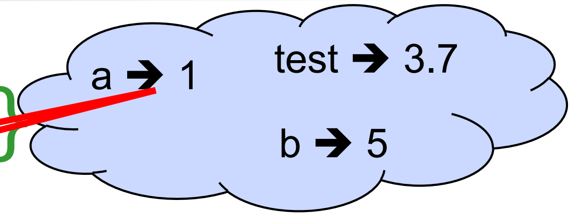
// $\quad\quad = \{b \rightarrow 2,\ test \rightarrow 3.7,\ a \rightarrow 1\}$

```
    in b * b;;
val c : int = 4
```

// $\rho_7 = \{c \rightarrow 4,\ test \rightarrow 3.7,\ a \rightarrow 1,\ b \rightarrow 5\}$

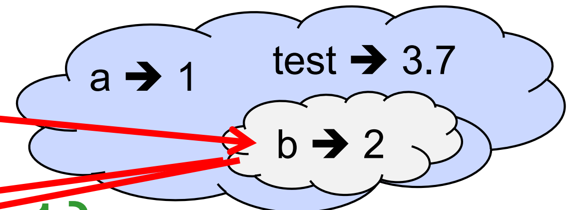
```
# b;;
- : int = 5
```

Local let binding



// $\rho_5 = \rho_3 = \{test \rightarrow 3.7,\ a \rightarrow 1,\ b \rightarrow 5\}$

```
# let c =
    let b = a + a
```



// $\rho_6 = \{b \rightarrow 2\} + \rho_3$

// $\quad = \{b \rightarrow 2,\ test \rightarrow 3.7,\ a \rightarrow 1\}$

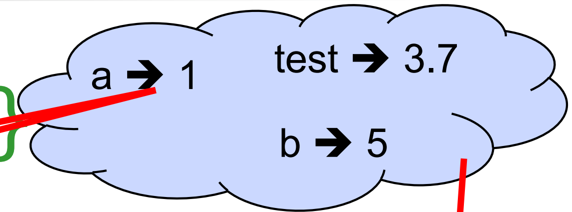
```
    in b * b;;
val c : int = 4
```

// $\rho_7 = \{c \rightarrow 4,\ test \rightarrow 3.7,\ a \rightarrow 1,\ b \rightarrow 5\}$

```
# b;;
- : int = 5
```

Local let binding

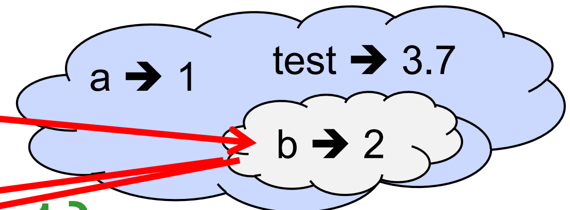
// $\rho_5 = \rho_3 = \{test \rightarrow 3.7,\ a \rightarrow 1,\ b \rightarrow 5\}$




```
# let c =
    let b = a + a
```

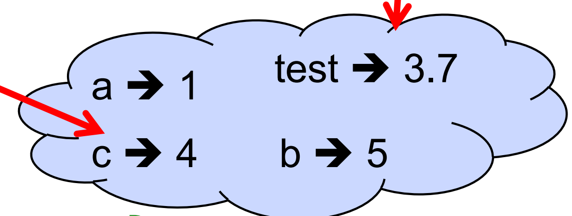
// $\rho_6 = \{b \rightarrow 2\} + \rho_3$

// $\quad = \{b \rightarrow 2,\ test \rightarrow 3.7,\ a \rightarrow 1\}$




```
    in b * b;;
val c : int = 4
```

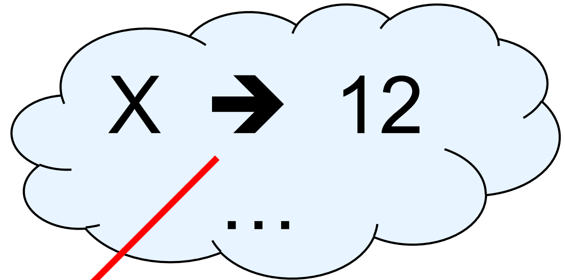
// $\rho_7 = \{c \rightarrow 4,\ test \rightarrow 3.7,\ a \rightarrow 1,\ b \rightarrow 5\}$




```
# b;;
- : int = 5
```

Values fixed at declaration time

```
# let x = 12;;
```




```
val x : int = 12
# let plus_x y = y + x;;
val plus_x : int -> int = <fun>
# plus_x 3;;
```

What is the result?

Values fixed at declaration time

```
# let x = 12;;
val x : int = 12
# let plus_x y = y + x;;
val plus_x : int -> int = <fun>
# plus_x 3;;
- : int = 15
```

Values fixed at declaration time

let x = 7;;   (* New declaration, not an update *)

val x : int = 7

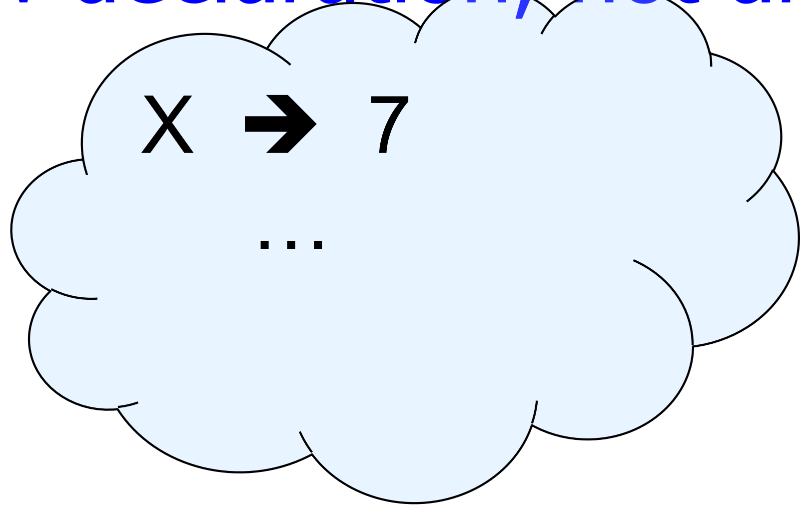
plus_x 3;;

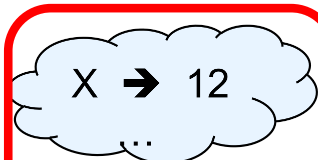
What is the result this time?

Values fixed at declaration time

let x = 7;;   (* New declaration, not an update *)

val x : int = 7





plus_x 3;;

What is the result this time?

Values fixed at declaration time

```
# let x = 7;;   (* New declaration, not an update *)
val x : int = 7

# plus_x 3;;
- : int = 15
```

Question

- Observation: Functions are first-class values in this language

- Question: What value does the environment record for a function variable?

- Answer: a closure

Save the Environment!

- A *closure* is a pair of an environment and an association of a sequence of variables (the input variables) with an expression (the function body), written:

$$f \to < (v1,\dots,vn) \to exp, \rho_f >$$

- Where ρ_f is the environment in effect when f is defined (if f is a simple function)

Closure for plus_x

- When plus_x was defined, had environment:

$$\rho_{plus\_x} = \{\ldots, x \to 12, \ldots\}$$

- Recall: let plus_x y = y + x

  is really let plus_x = fun y -> y + x

- Closure for fun y -> y + x:

$$<y \to y + x, \rho_{plus\_x}>$$

- Environment just after plus_x defined:

$$\{plus\_x \to <y \to y + x, \rho_{plus\_x}>\} + \rho_{plus\_x}$$

Now it's your turn

You should be able to do WA1-IC Problem 1 , parts (* 4 *) - (* 7 *)