Programming Languages and Compilers (CS 421)

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https://courses.engr.illinois.edu/cs421/sp2024

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

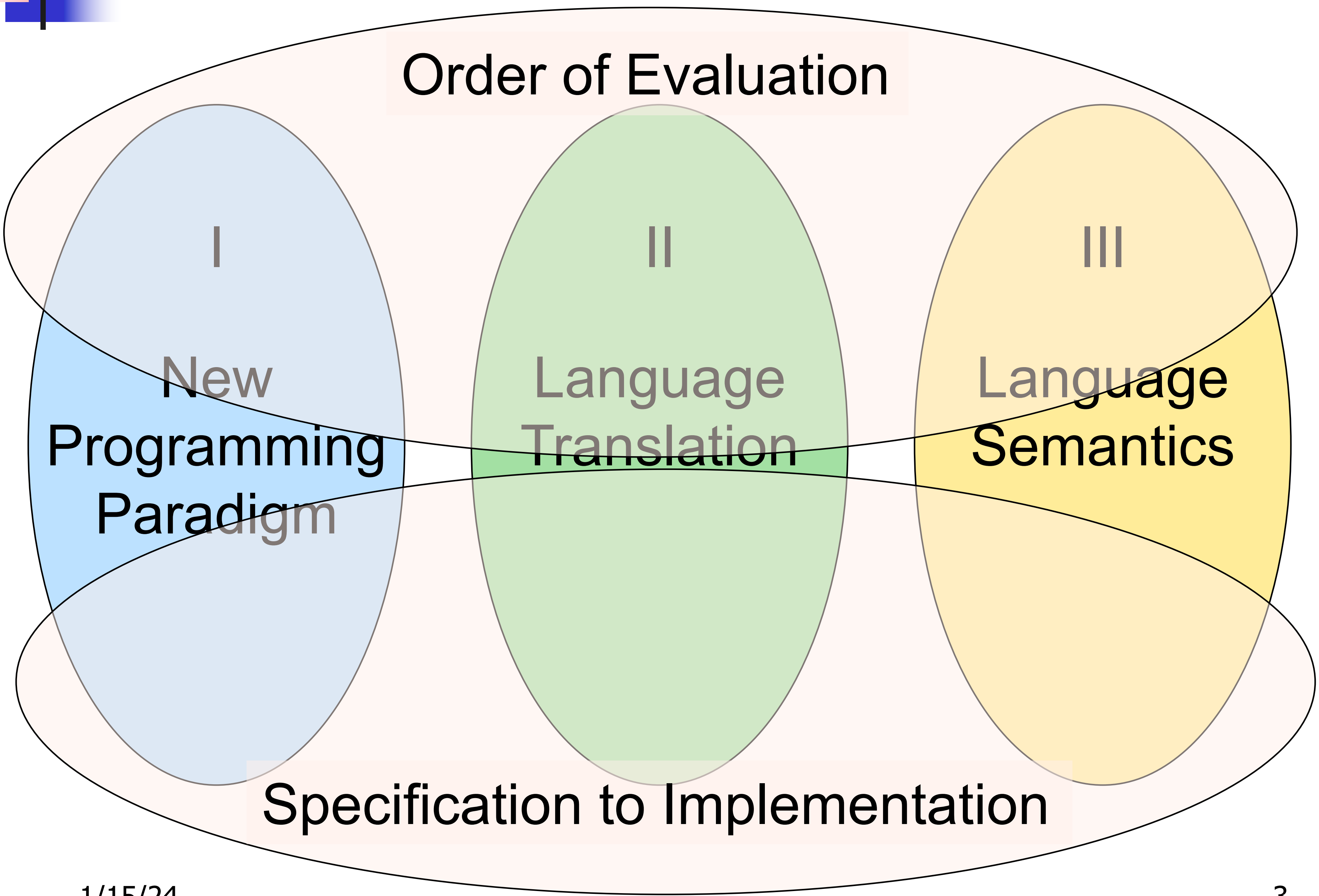
II

Language Translation

III

Language Semantics

Programming Languages & Compilers



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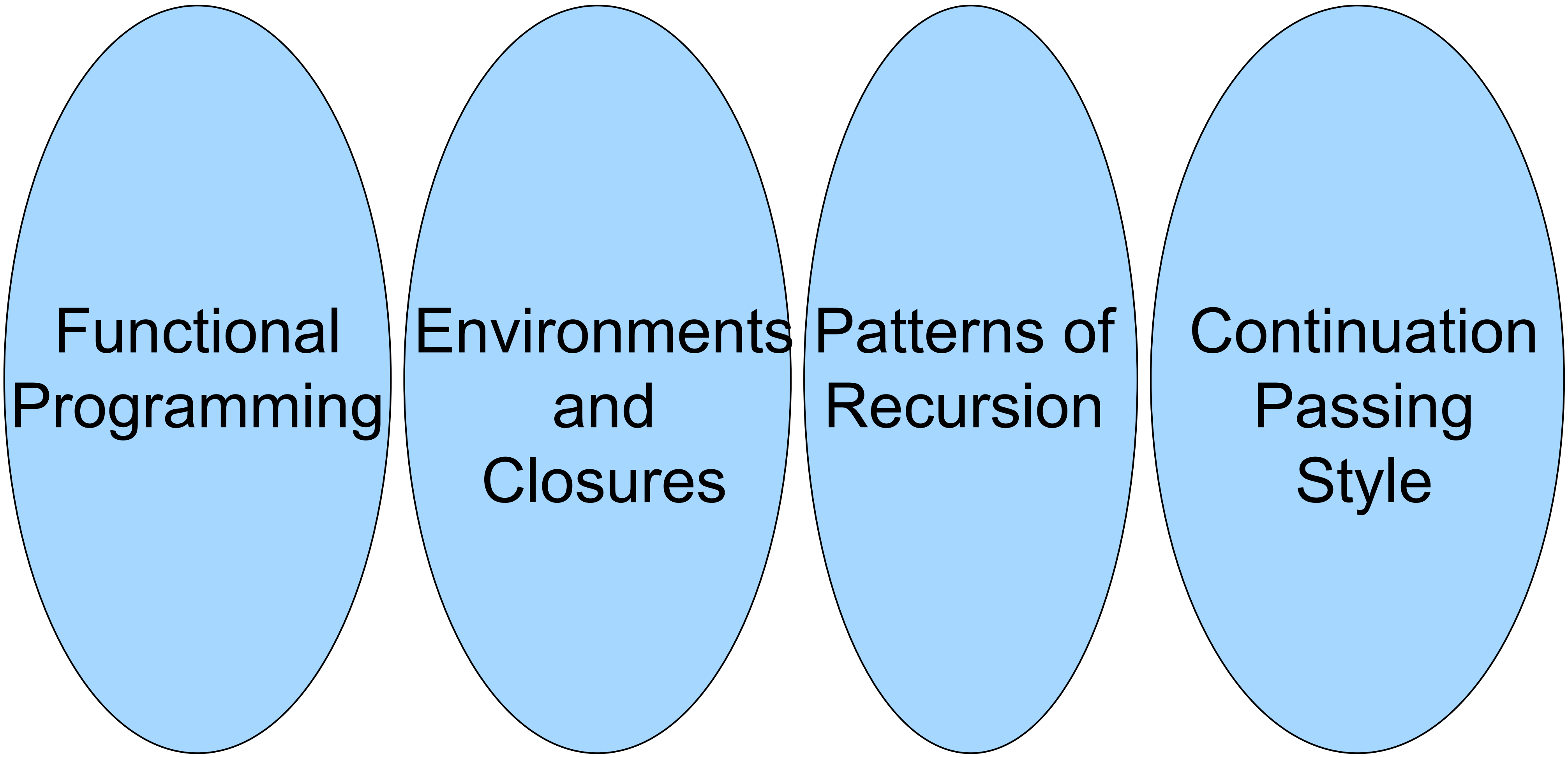
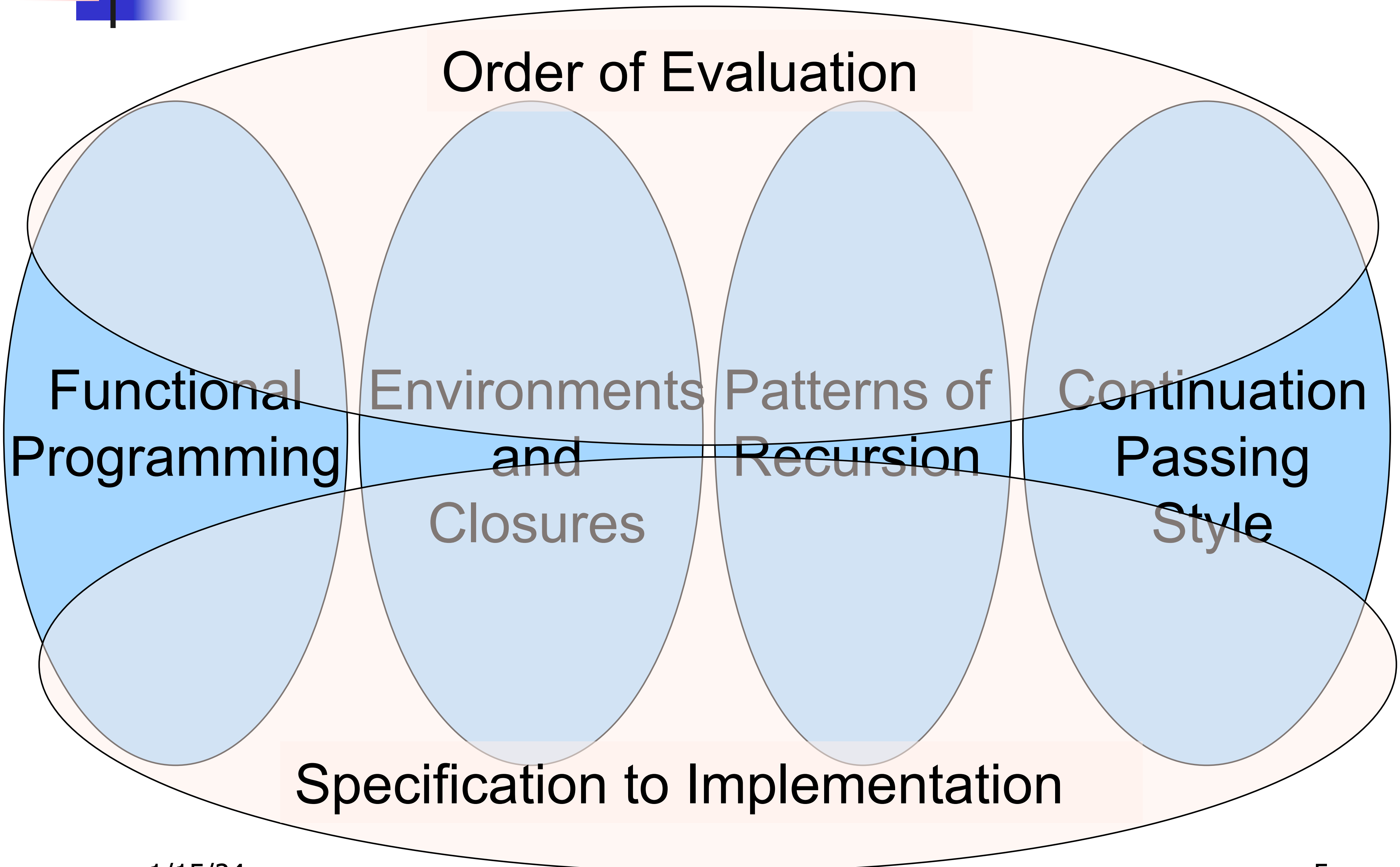
I : New Programming Paradigm



Programming Languages & Compilers



Programming Languages & Compilers

II : Language Translation

Lexing and Parsing

Type Systems

Interpretation

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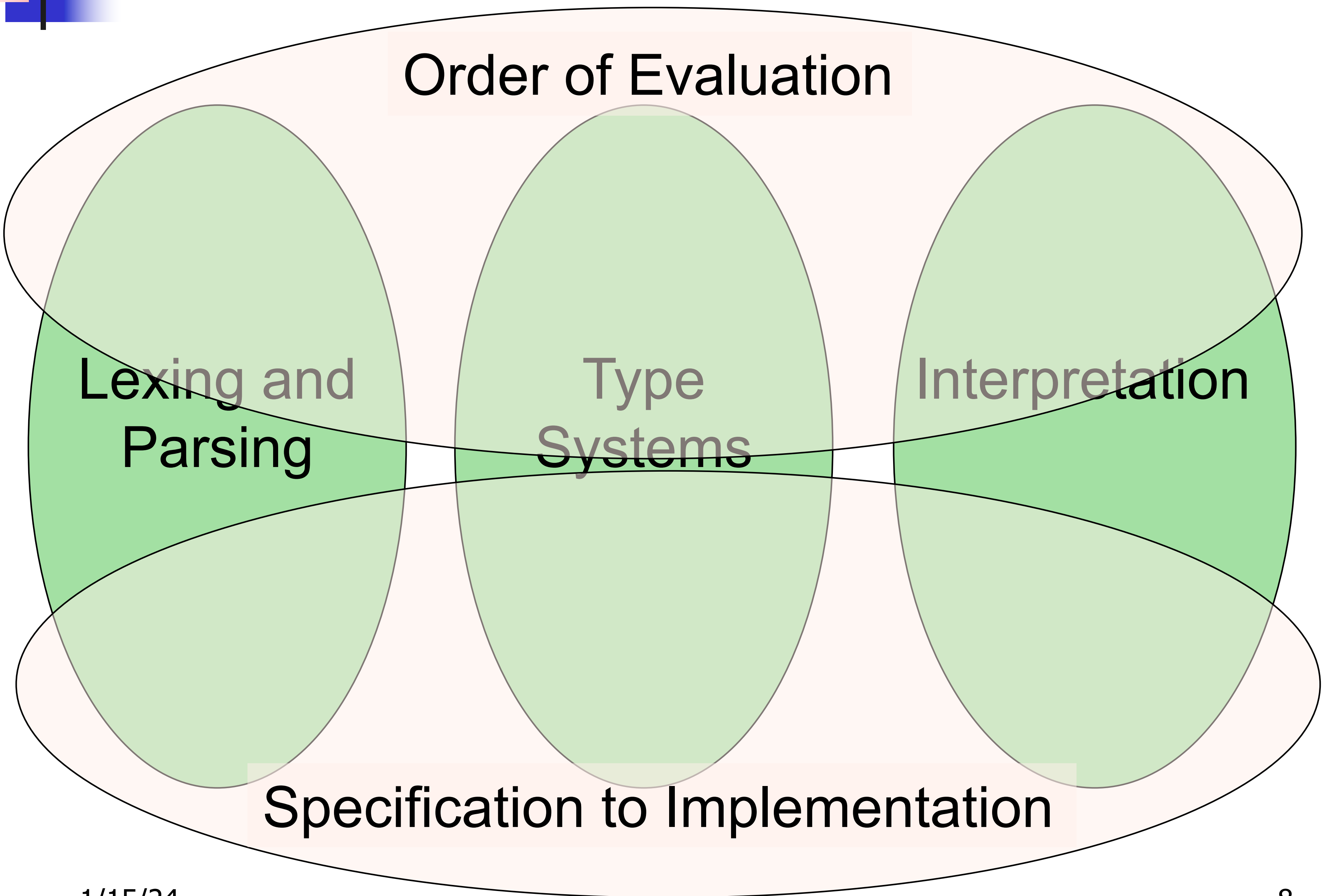

Programming Languages & Compilers

III : Language Semantics

Operational Semantics

Lambda Calculus

Axiomatic Semantics

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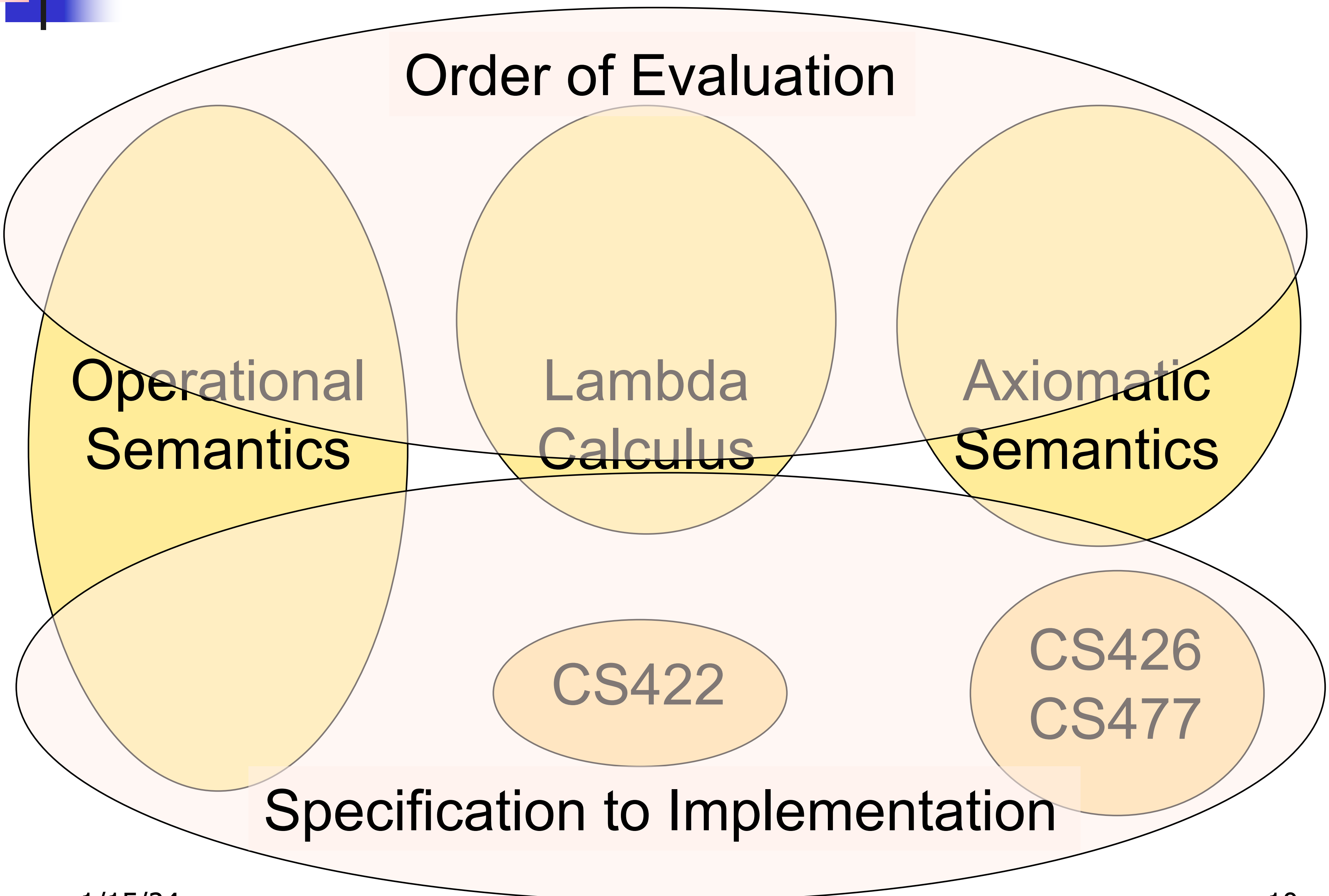

Contact Information - Elsa L Gunter

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  - TBD
    - Can attend in zoom
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Course TAs


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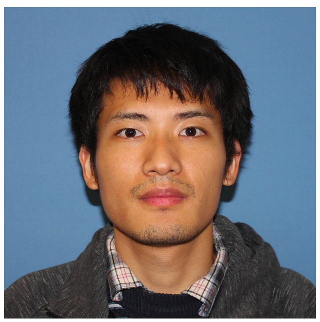
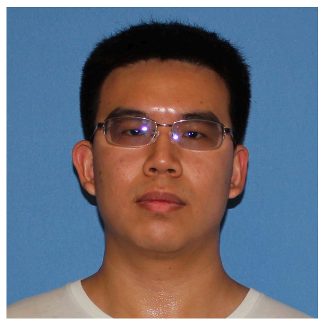

Yerong Li


James Luo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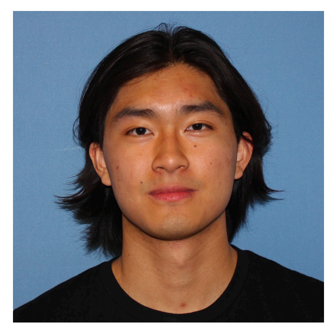
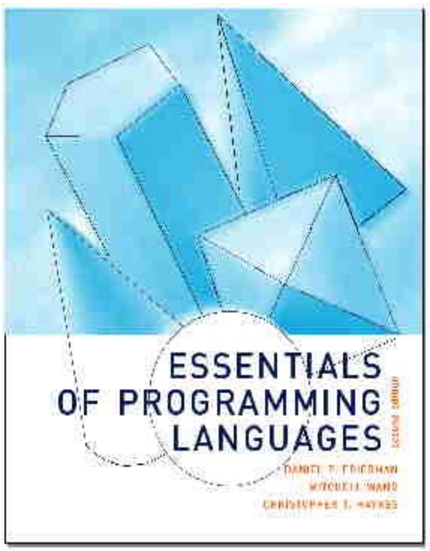

Alan Yao

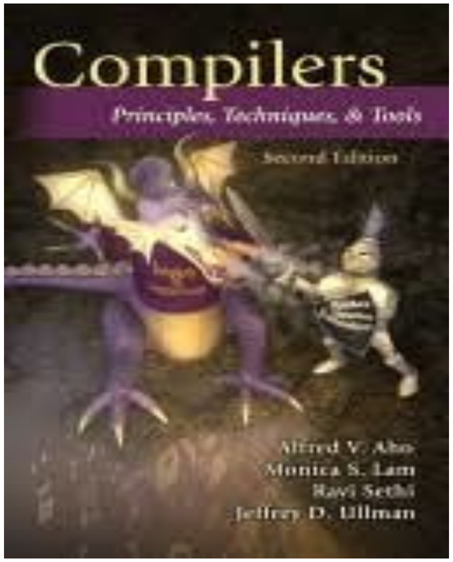
Course Website

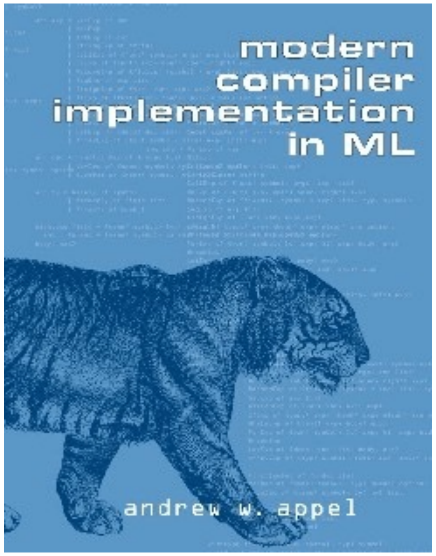
- https://courses.engr.illinois.edu/cs421/sp2024
- Main page - summary of news items
- Policy - rules governing course
- Lectures - syllabus and slides
- MPs - information about assignments
- Exams – Syllabi and review material for Midterms and finals
- Unit Projects - for 4 credit students
- Resources - 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) (~3-6%)
  - MPs (in Ocaml) (~4-7%)
  - All WAs and MPs Submitted by **PrairieLearn**
  - Late submission penalty:
    score capped at 80% of total

Course Grading

- Five quizzes - 10% (2% each)
  - In class, BYOD
  - Tentatively Jan 23, Feb 6, Feb 27, Mar 26, Apr 23
- 3 Midterms - 15% each
  - **Feb 12-14, Mar 6-8, Apr 11-13**
  - **BE AVAILABLE FOR THESE DATES!**
- Final 35%
- Tuesday May 7, 7:00pm – 10:00pm
- Percentages based on 3 cr, 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 detailed 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 course staff

OCAML

- Locally:
  - Will use ocaml inside VSCode inside PrairieLearn problems this semester
- Globally:
  - Main OCAML 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

Features of OCAML

- Higher order applicative language
- Call-by-value parameter passing
- Modern syntax
- Parametric polymorphism
  - Aka structural polymorphism
- Automatic garbage collection
- User-defined algebraic data types

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
```

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
```

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
```

Environments

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

$$\rho = \{\text{name}_1 \rightarrow \text{value}_1, \text{name}_2 \rightarrow \text{value}_2, \ldots\}$$

  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

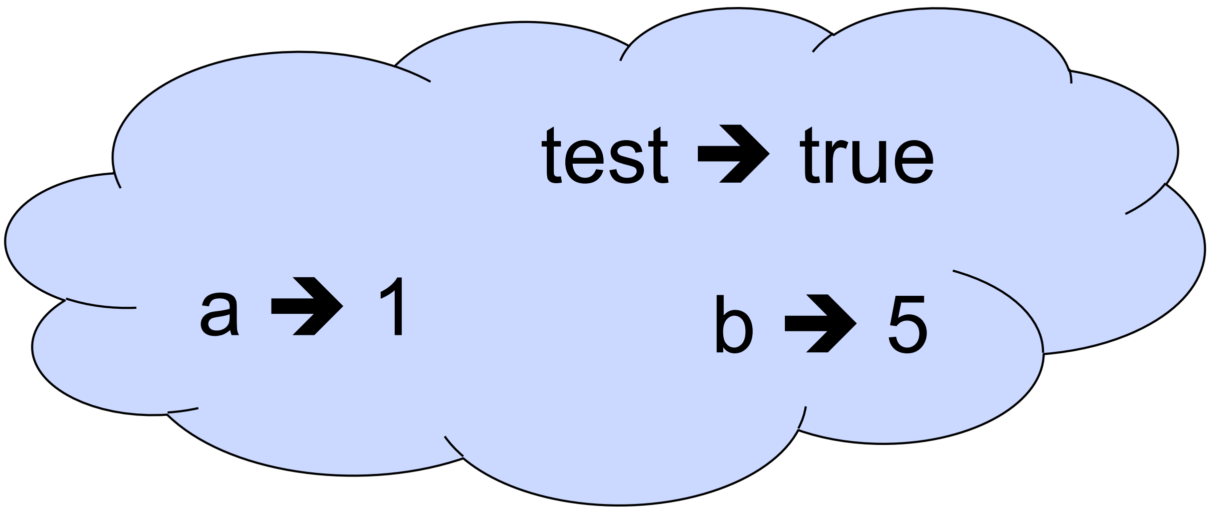
```
# 2 + 3;;     (* Expression *)
// doesn't affect the environment
# let test = 3 < 2;;     (* Declaration *)
val test : bool = false
```

// 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

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

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

- What is the environment after this declaration?

New Bindings Hide Old

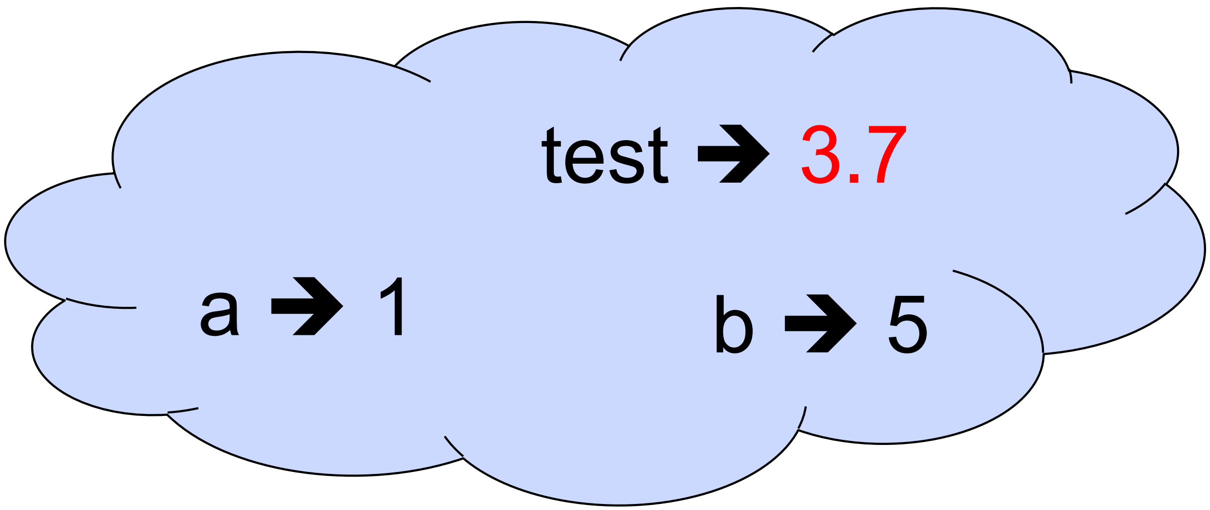
// $\rho_2 = \{b \to 5, a \to 1, test \to false\}$

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

- What is the environment after this declaration?

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

Environments

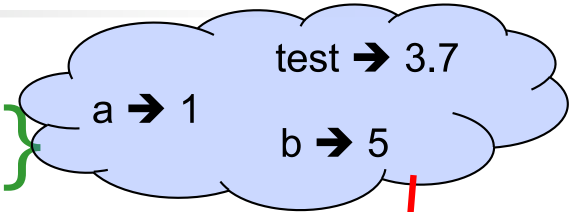


Now it's your turn

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

Local Variable Creation

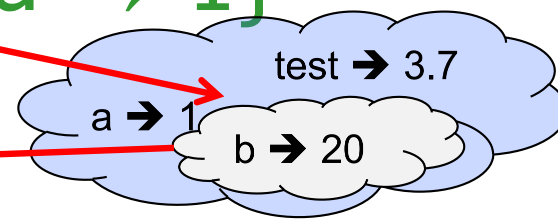
// $\rho_3 = \{test \to 3.7, a \to 1, b \to 5\}$



\# let b = 5 * 4

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

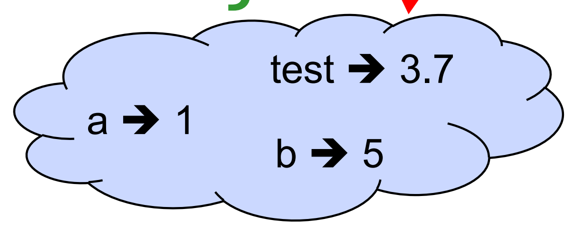
in 2 * b;;



\- : int = 40

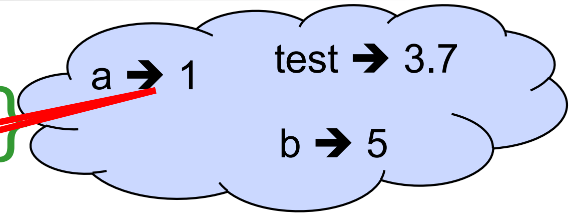
// $\rho_5 = \rho_3 = \{test \to 3.7, a \to 1, b \to 5\}$

\# 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

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

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

    in b * b;;

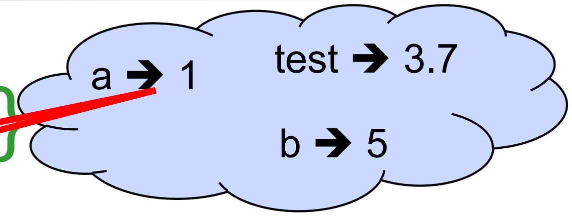
val c : int = 4

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

\# b;;

\- : int = 5

Local let binding



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

let c =

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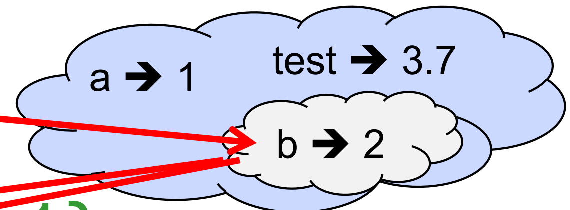


in b * b;;

val c : int = 4

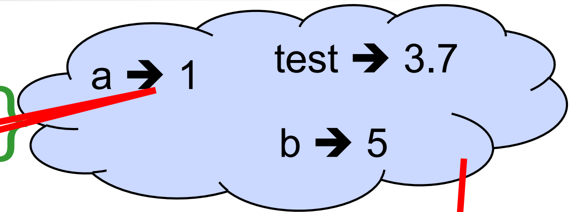
// $\rho_7 = \{c \rightarrow 4, test \rightarrow 3.7, a \rightarrow 1, b \rightarrow 5\}$

b;;

- : int = 5

Local let binding

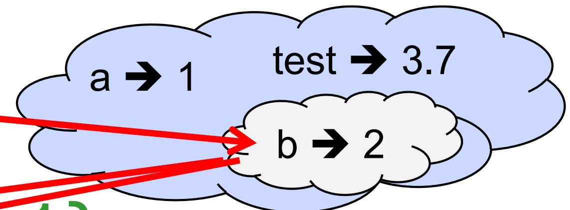
// $\rho_5 = \rho_3 = \{test \rightarrow 3.7, a \rightarrow 1, b \rightarrow 5\}$



\# let c =

    let b = a + a

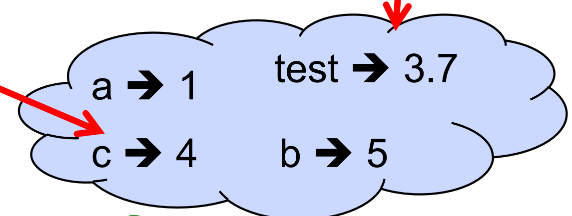
// $\rho_6 = \{b \rightarrow 2\} + \rho_3$



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

    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

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
```

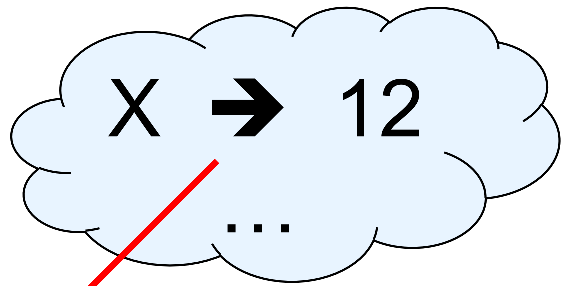
First definition syntactic sugar for second

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)

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

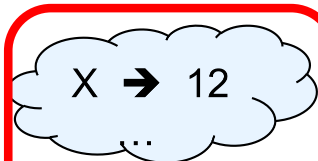
```
# let x = 7;;   (* New declaration, not an update *)
val x : int = 7

# plus_x 3;;
```

What is the result this time?

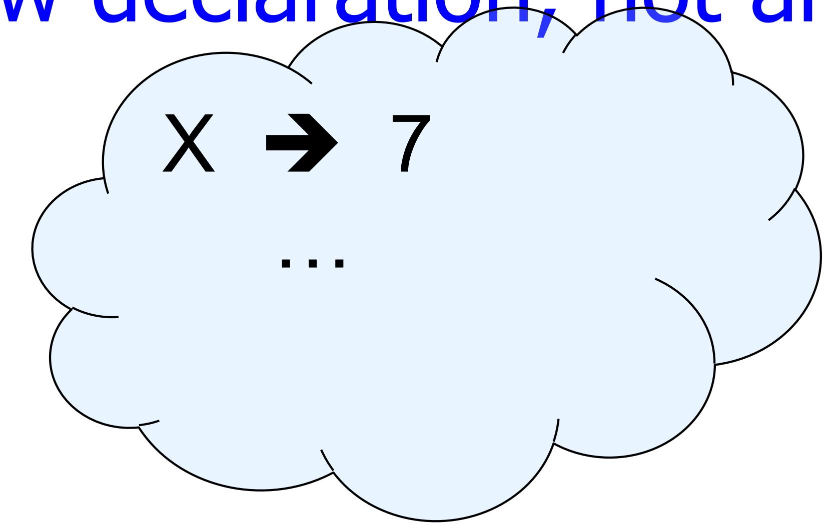
Values fixed at declaration time

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 formal parameter (the input variables)* with an expression (the function body), written:

$$f \rightarrow < (v1,\ldots,vn) \rightarrow exp, \rho_f >$$

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

* Will come back to the "formal parameter"

Closure for plus_x

- When plus_x was defined, had environment:

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

- Recall: let plus_x y = y + x

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

- Closure for fun y -> y + x:

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

- Environment just after plus_x defined:

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

Now it's your turn

You should be able complete ACT1

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

Functions with more than one argument

```
# let add_three x y z = x + y + z;;
val add_three : int -> int -> int -> int = <fun>
```

- What is the value of add_three?
- Let ρ_{add_three} be the environment before the declaration
- Remember:

```
let add_three =
 fun x -> (fun y -> (fun z -> x + y + z));;
```

Value: <x ->fun y -> (fun z -> x + y + z), ρ_{add_three} >

Partial application of functions

```
let add_three x y z = x + y + z;;
```

```
# let h = add_three 5 4;;
val h : int -> int = <fun>
# h 3;;
- : int = 12
# h 7;;
- : int = 16
```

Partial application of functions

```
let add_three x y z = x + y + z;;
```

```
# let h = add_three 5 4;;
val h : int -> int = <fun>
# h 3;;
- : int = 12
# h 7;;
- : int = 16
```

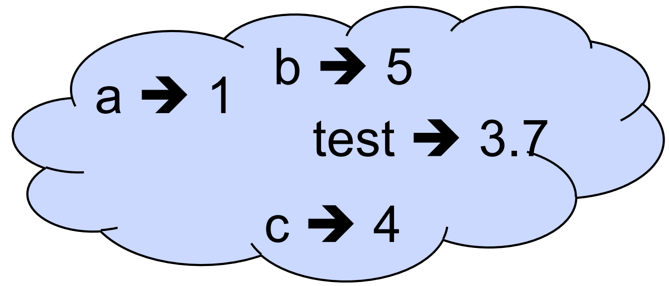
- Partial application also called *sectioning*

Functions as arguments

```
# let thrice f x = f (f (f x));;
val thrice : ('a -> 'a) -> 'a -> 'a = <fun>
# let g = thrice plus_two;;
val g : int -> int = <fun>
# g 4;;
- : int = 10
# thrice (fun s -> "Hi! " ^ s) "Good-bye!";;
- : string = "Hi! Hi! Hi! Good-bye!"
```

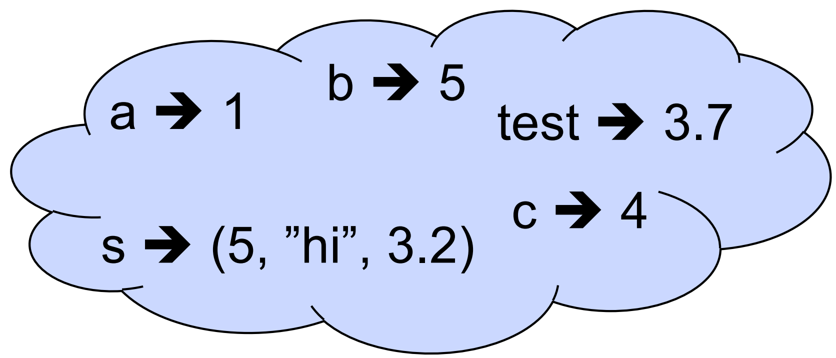
Tuples as Values

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



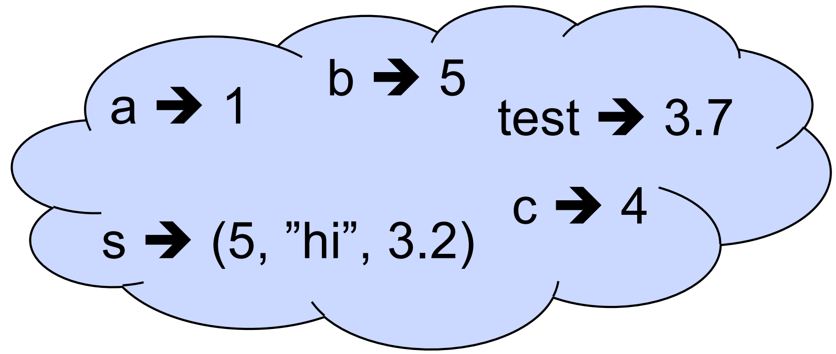

```
# let s = (5,"hi",3.2);;
val s : int * string * float = (5, "hi", 3.2)
```

// $\rho_8 = \{s \rightarrow (5, \text{"hi"}, 3.2),$
$c \rightarrow 4, \text{test} \rightarrow 3.7,$
$a \rightarrow 1, b \rightarrow 5\}$

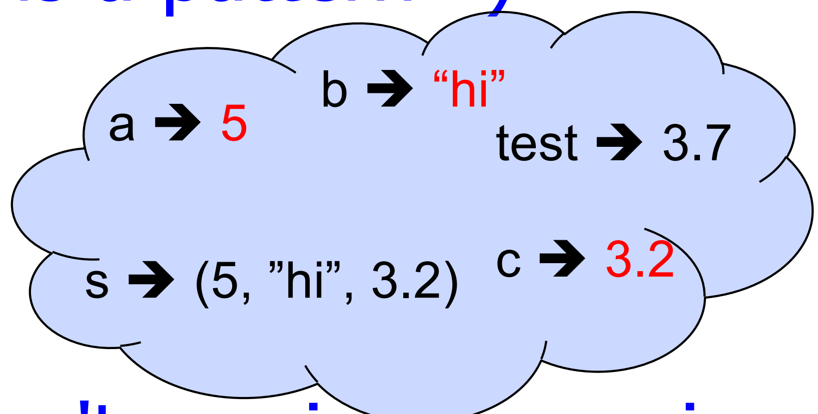


Pattern Matching with Tuples

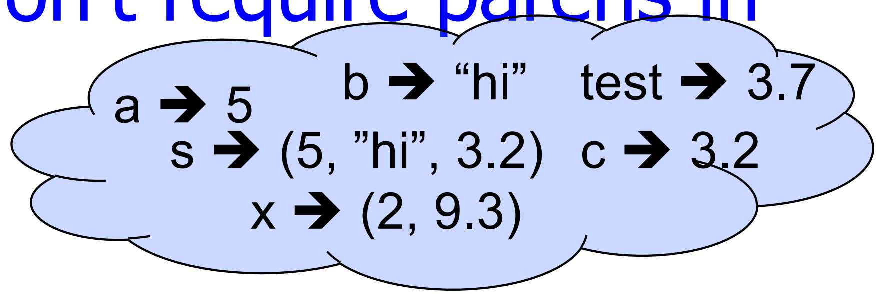
- $\rho_8 = \{s \to (5, \text{"hi"}, 3.2),$
  $c \to 4, test \to 3.7,$
  $a \to 1, b \to 5\}$




```
# let (a,b,c) = s;;  (* (a,b,c) is a pattern *)
val a : int = 5
val b : string = "hi"
val c : float = 3.2
```




```
# let x = 2, 9.3;; (* tuples don't require parens in
   Ocaml *)
val x : int * float = (2, 9.3)
```



Nested Tuples

```
# (*Tuples can be nested *)
let d = ((1,4,62),("bye",15),73.95);;
val d : (int * int * int) * (string * int) * float =
  ((1, 4, 62), ("bye", 15), 73.95)
# (*Patterns can be nested *)
let (p,(st,_),_) = d;; (* _ matches all, binds nothing
   *)
val p : int * int * int = (1, 4, 62)
val st : string = "bye"
```

Functions on tuples

```
# let plus_pair (n,m) = n + m;;
val plus_pair : int * int -> int = <fun>
# plus_pair (3,4);;
- : int = 7
# let double x = (x,x);;
val double : 'a -> 'a * 'a = <fun>
# double 3;;
- : int * int = (3, 3)
# double "hi";;
- : string * string = ("hi", "hi")
```

Match Expressions

```
# let triple_to_pair triple =
  match triple
  with (0, x, y) -> (x, y)
  | (x, 0, y) -> (x, y)
  | (x, y, _) -> (x, y);;
val triple_to_pair : int * int * int -> int * int =
  <fun>
```

- Each clause: pattern on left, expression on right
- Each x, y has scope of only its clause
- Use first matching clause

Closure for plus_pair

- Assume ρ_{plus_pair} was the environment just before plus_pair defined
- Closure for plus_pair:

$$<(n,m) \rightarrow n + m, \rho_{plus\_pair}>$$

- Environment just after plus_pair defined:

$$\{plus\_pair \rightarrow <(n,m) \rightarrow n + m, \rho_{plus\_pair}>\} + \rho_{plus\_pair}$$

Save the Environment!

- A *closure* is a pair of an environment and an association of a pattern (e.g. (v1,…,vn) giving the input variables) with an expression (the function body), written:

$$< (v1,\ldots,vn) \rightarrow exp, \rho >$$

- Where ρ is the environment in effect when the function is defined (for a simple function)

Evaluating declarations

- Evaluation uses an environment ρ
- To evaluate a (simple) declaration let x = e
  - Evaluate expression e in ρ to value v
  - Update ρ with x v: $\{x \to v\} + \rho$
- Update: $\rho_1 + \rho_2$ has all the bindings in ρ_1 and all those in ρ_2 that are not rebound in ρ_1

$\{x \to 2, y \to 3, a \to \text{“hi”}\} + \{y \to 100, b \to 6\}$

$= \{x \to 2, y \to 3, a \to \text{“hi”}, b \to 6\}$

Evaluating expressions in OCaml

- Evaluation uses an environment ρ
- A constant evaluates to itself, including primitive operators like + and =
- To evaluate a variable, look it up in ρ: $\rho(v)$
- To evaluate a tuple $(e_1,\ldots,e_n)$,
  - Evaluate each e_i to v_i, right to left for Ocaml
  - Then make value $(v_1,\ldots,v_n)$

Evaluating expressions in OCaml

- To evaluate uses of +, _ , etc, eval args, then do operation
- Function expression evaluates to its closure
- To evaluate a local dec: let x = e1 in e2
  - Eval e1 to v, then eval e2 using $\{x \to v\} + \rho$
- To evaluate a conditional expression: if b then e1 else e2
  - Evaluate b to a value v
  - If v is True, evaluate e1
  - If v is False, evaluate e2

Evaluation of Application with Closures

- Given application expression $f\ e$
- In Ocaml, evaluate e to value v
- In environment ρ, evaluate left term to closure, $c = <(x_1,\ldots,x_n) \to b, \rho'>$
  - $(x_1,\ldots,x_n)$ variables in (first) argument
  - v must have form $(v_1,\ldots,v_n)$
- Update the environment ρ' to

  $\rho'' = \{x_1 \to v_1,\ldots, x_n \to v_n\} + \rho'$
- Evaluate body b in environment ρ''