Programming Languages and Compilers (CS 421)

Sasa Misailovic

4110 SC, UIUC

https://courses.engr.illinois.edu/cs421/fa2017/CS421A

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

Contact Information – Sasa Misailovic

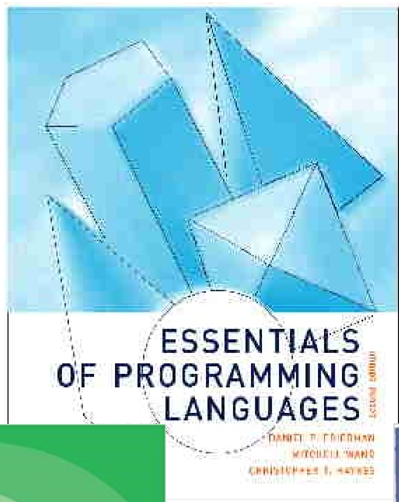
- Office: 4110 SC
- Office hours:
  - Tuesday, Thursday 8:30am – 9:30am
  - Also by appointment
- Email: misailo@illinois.edu

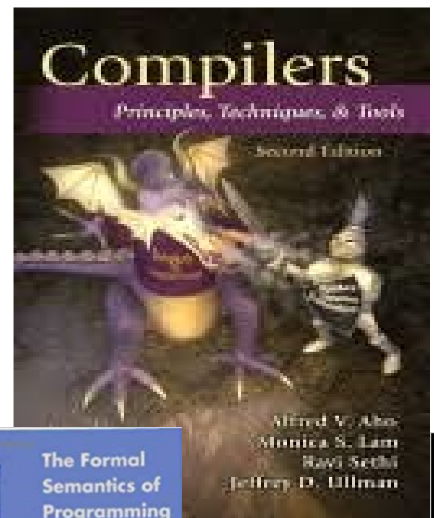
Course Website

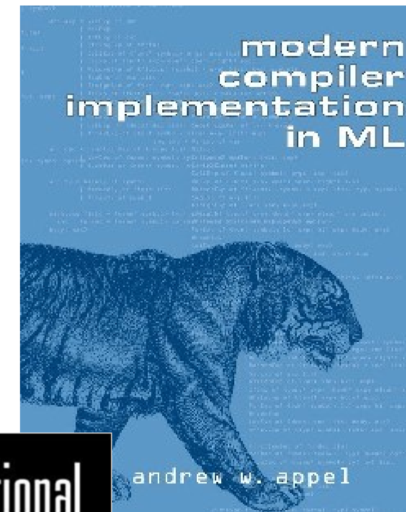
- https://courses.engr.illinois.edu/cs421/fa2018/CS421A
- Main page - summary of news items
- Policy - rules governing course
- Lectures - syllabus and slides
- MPs - information about assignments
- Exams
- Unit Projects - for 4 credit students
- Resources - tools and helpful info
- FAQ

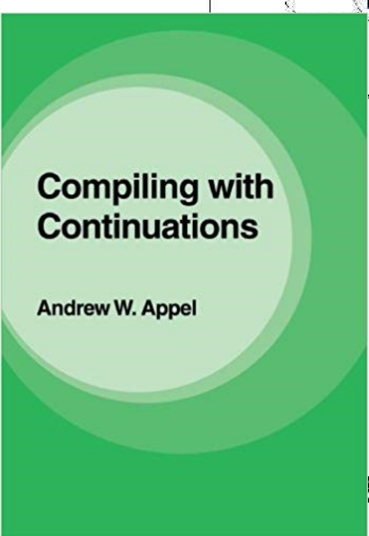
Some Course References

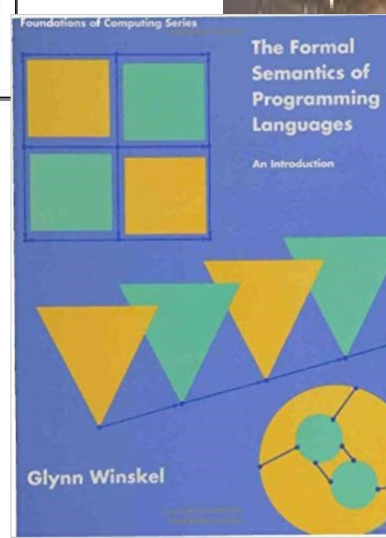
- No required textbook
- Some suggested references

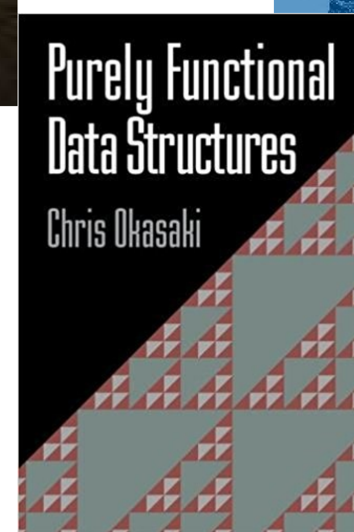












Course Grading

- Assignments 20%
  - About 12 Web Assignments (WA) (~7%)
  - About 6 MPs (in Ocaml) (~7%)
  - About 5 Labs (~6%)
  - All WAs and MPs Submitted through **PrairieLearn**
  - Late submission penalty: 20%
  - Labs in Computer-Based Testing Center (Grainger)
  - Self-scheduled over a three day period
  - No extensions beyond the three day period
  - Fall back: Labs become MPs

Course Grading

- 2 Midterms - 20% each
  - Labs in Computer-Based Testing Center (Grainger)
  - Self-scheduled over a three day period
  - No extensions beyond the three day period
  - Dates: **Oct 2-4 (Midterm 1) Nov 6-8 (Midterm 2)**
  - Fall back: In class backup dates – Oct 9, Nov 13
  - **DO NOT MISS EXAM DATES!**
- Final 40% - Dec 19, 8:00am – 11:00am (nominally)
- Will likely use CBTF for Final (3 day window)
- Percentages are approximate

Course Assignments – 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

Course Objectives

- New programming paradigm
  - Functional programming
  - Environments and Closures
  - Patterns of Recursion
  - Continuation Passing Style
- Phases of an interpreter / compiler
  - Lexing and parsing
  - Type systems
  - Interpretation
- Programming Language Semantics
  - Lambda Calculus
  - Operational Semantics
  - Axiomatic Semantics

Programming Languages & Compilers

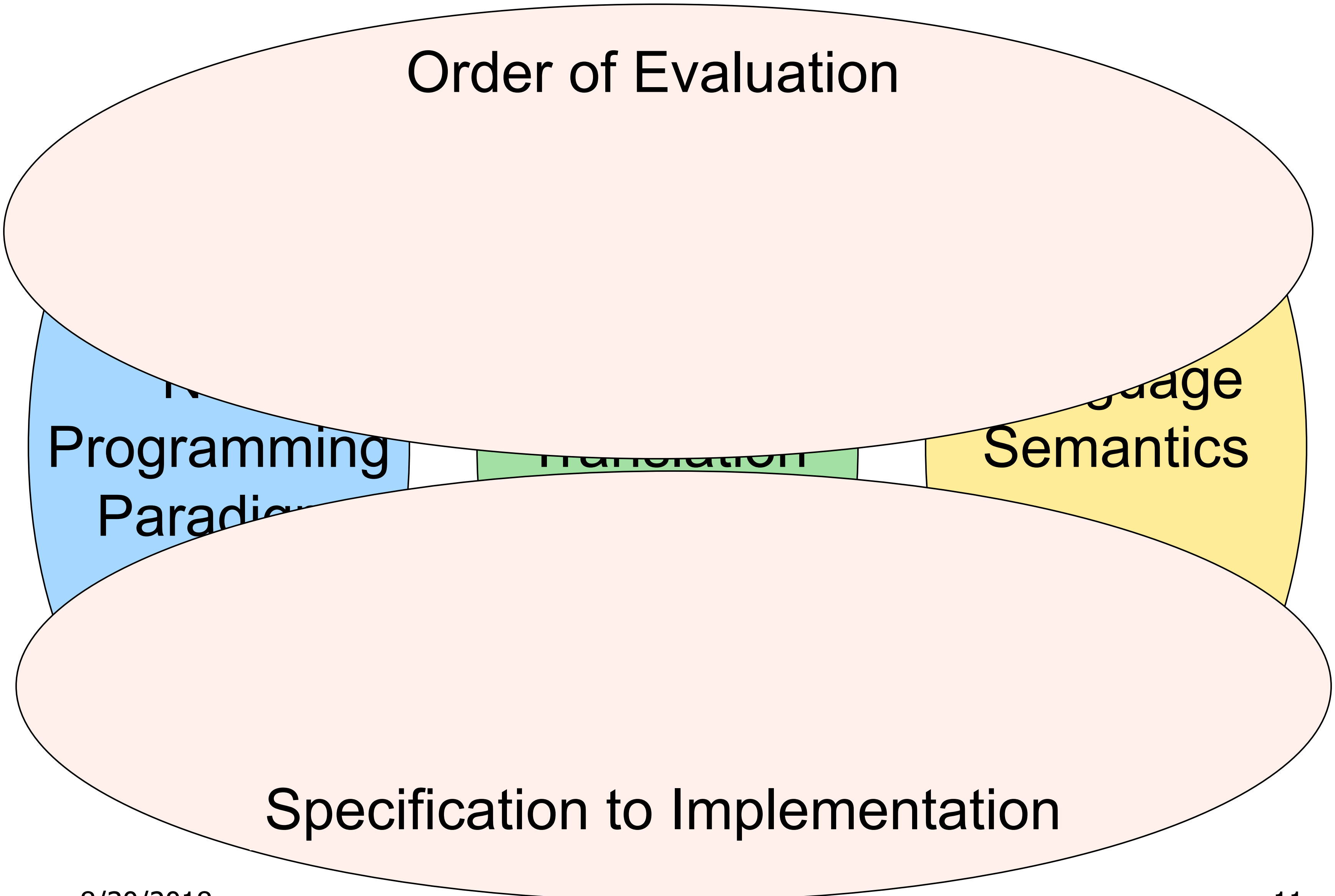
Three Main Topics of the Course

I
New Programming Paradigm

II
Language Translation

III
Language Semantics

Programming Languages & Compilers



Programming Languages & Compilers

I : New Programming Paradigm

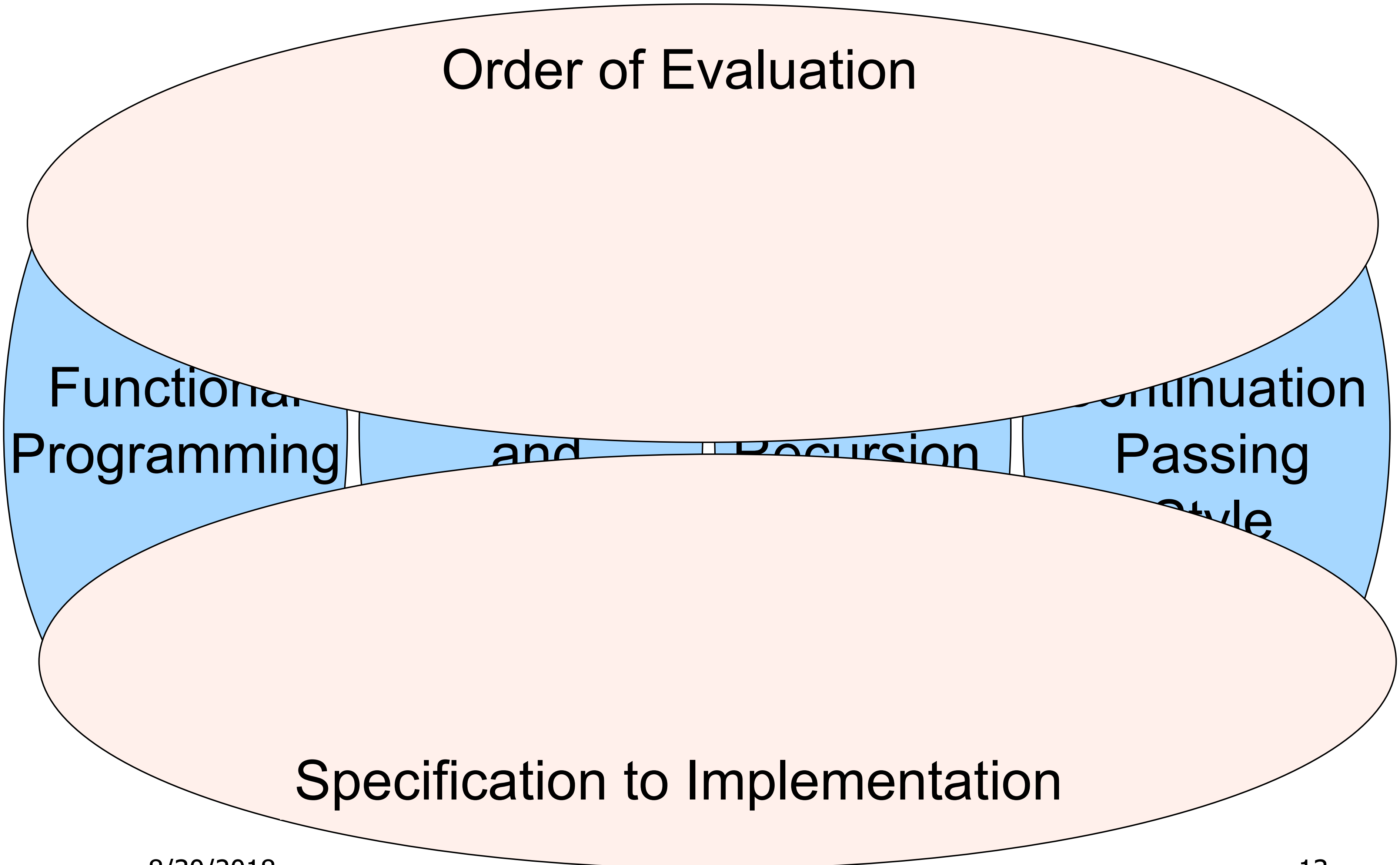
Functional Programming

Environments and Closures

Patterns of Recursion

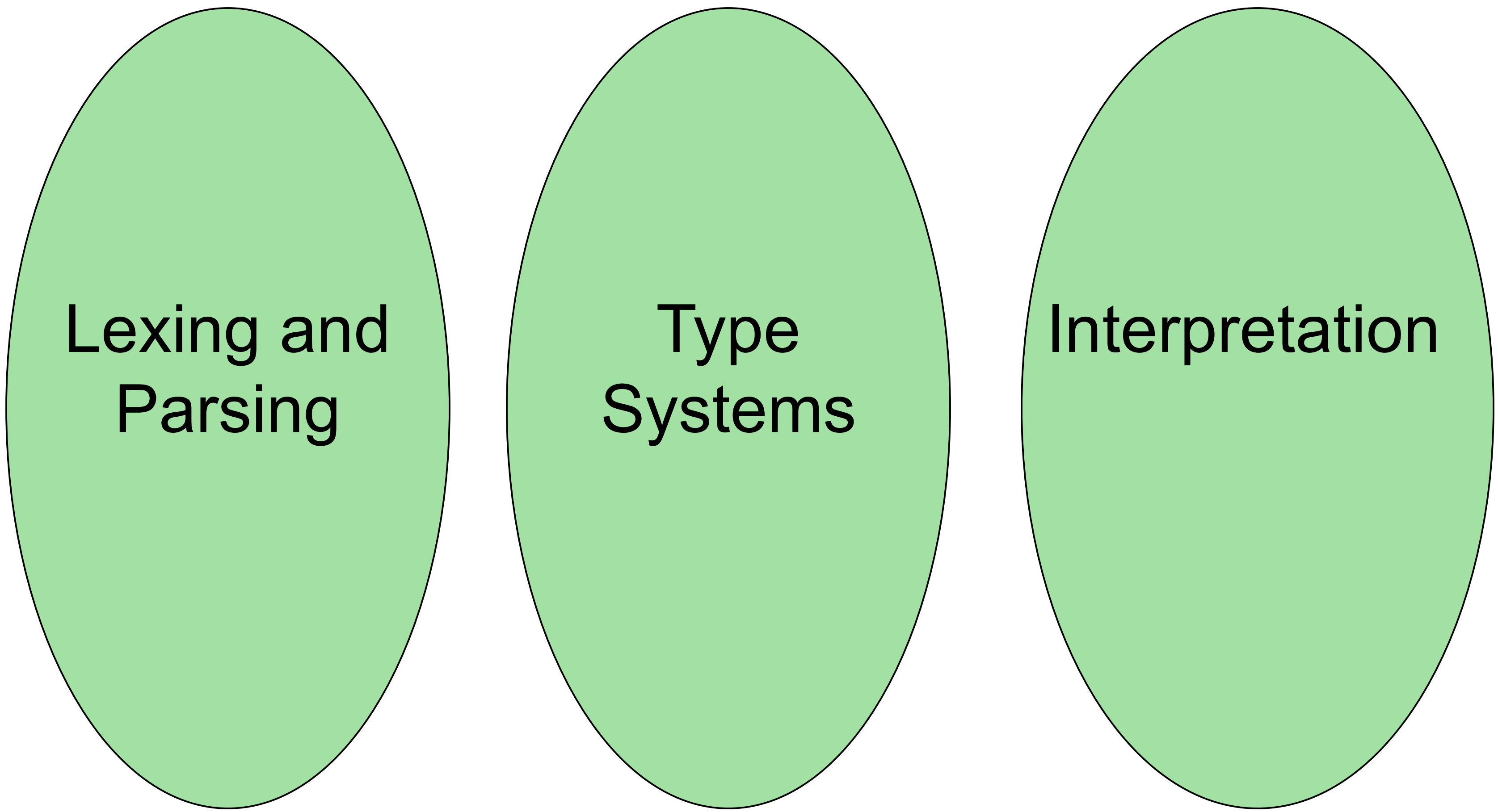
Continuation Passing Style

Programming Languages & Compilers

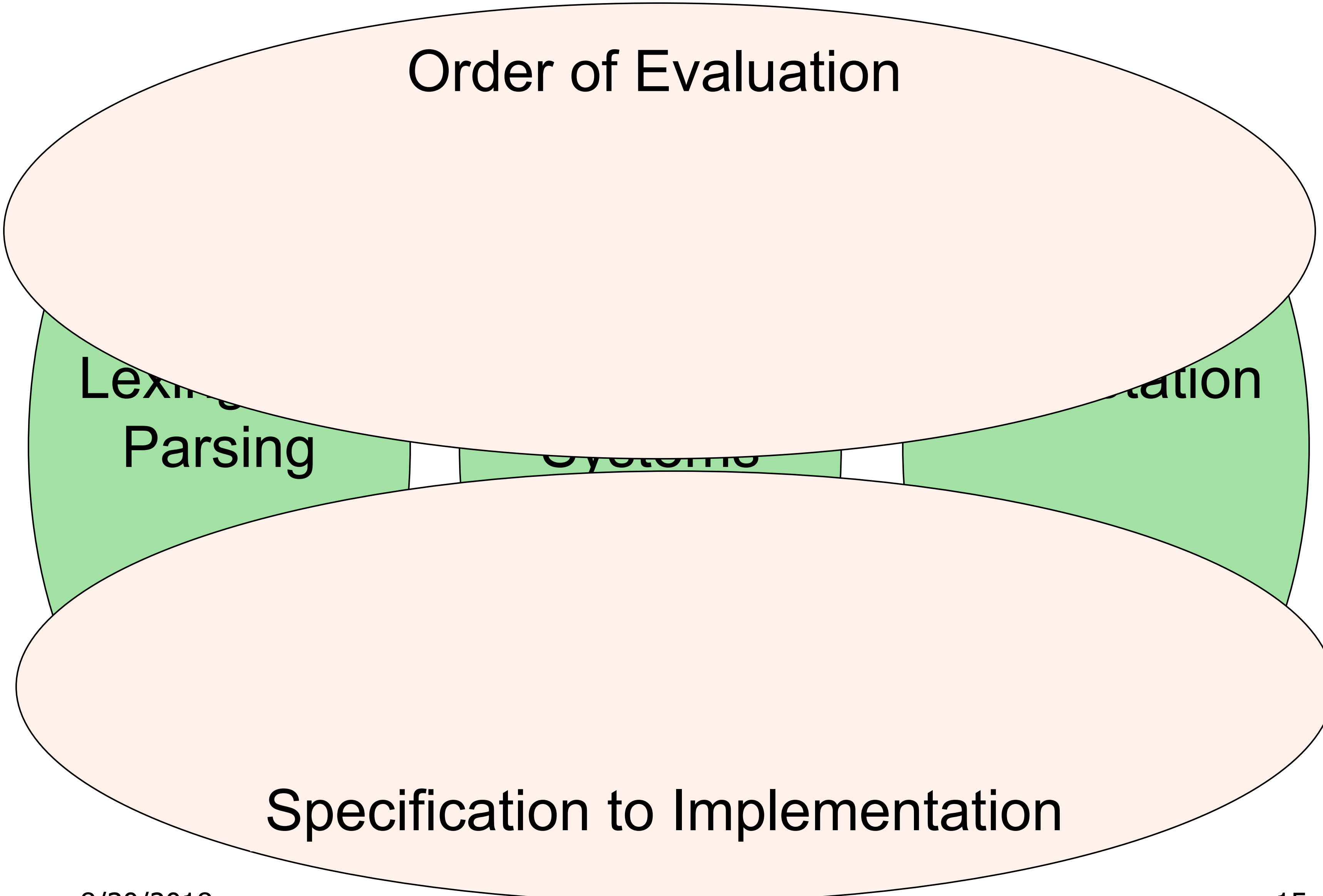


Programming Languages & Compilers

II : Language Translation

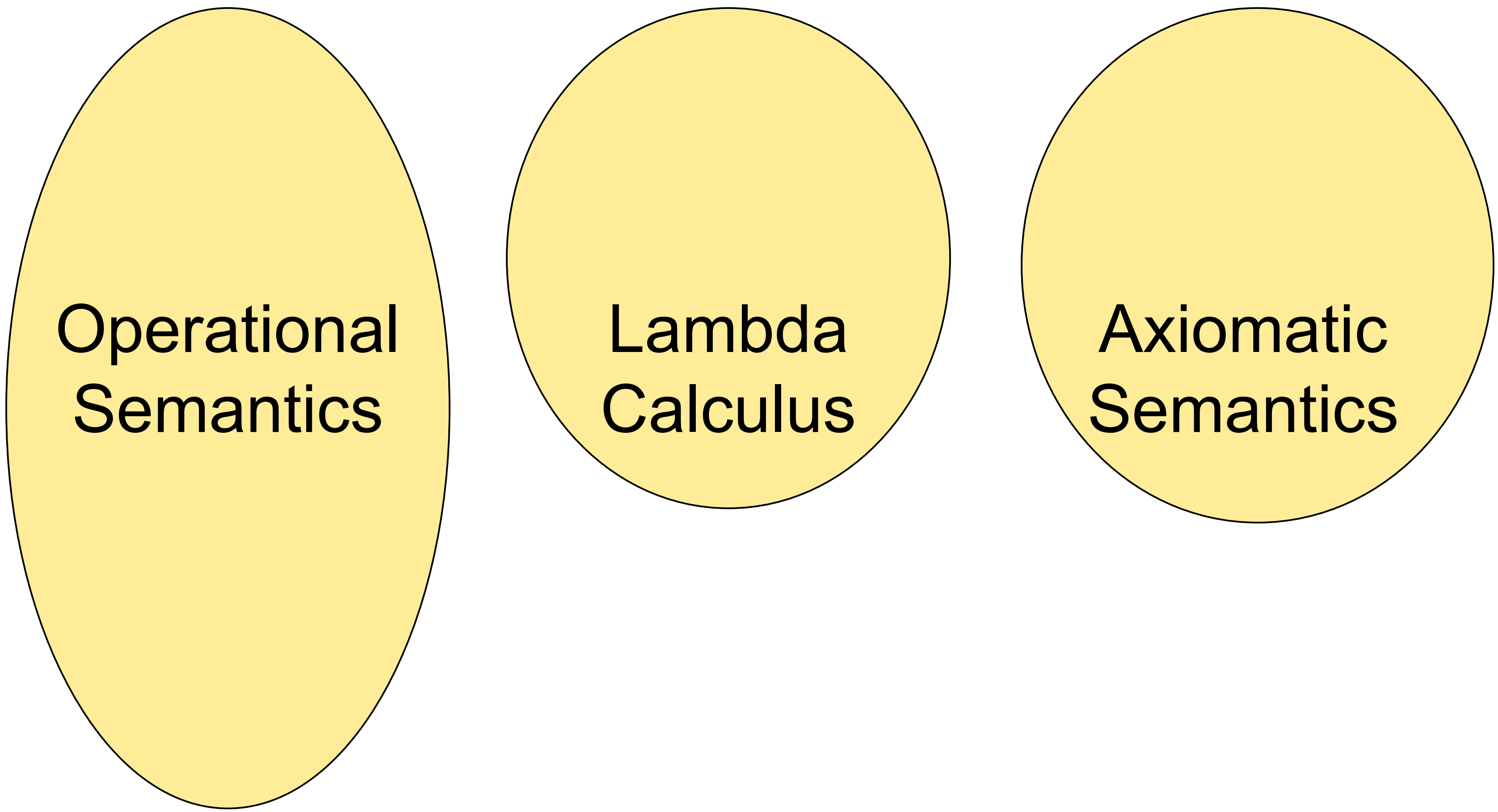


Programming Languages & Compilers

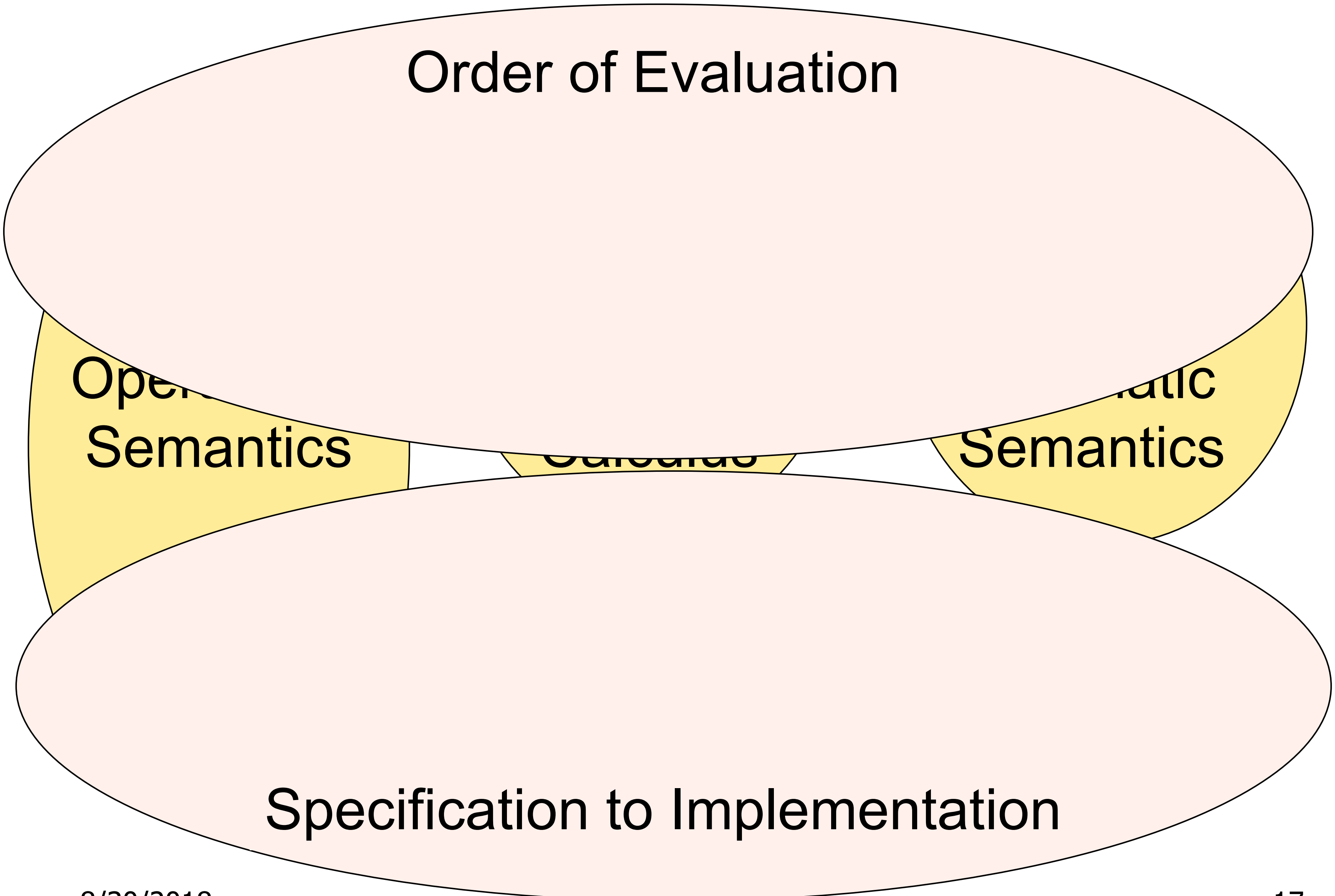


Programming Languages & Compilers

III : Language Semantics



Programming Languages & Compilers



OCAML

- Locally:
  - Compiler is on the EWS-linux systems at /usr/local/bin/ocaml
  - Be sure to **module load ocaml/2.07.0** in EWS!
- Globally:
  - Main CAML home: http://ocaml.org
  - To install OCAML on your computer see: http://ocaml.org/docs/install.html
  - Or use one of the online OCAML compilers…

References for OCaml

- Supplemental texts (not required):
- The Objective Caml system release 4.07, 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)

Why Learn OCAML?

- Industrially Relevant: Jane Street trades billions of dollars per day using OCaml programs
- Similar languages: Microsoft F#, SML, Haskell, Scala, Scheme
- Who uses functional programming?
  - Google – MapReduce
  - Microsoft – LinQ
  - Twitter – Scala
  - Bonus: who likes set comprehensions in Python?

```
>>> squares = [x**2 for x in range(10)]
```

OCAML Background

- CAML is European descendant of original ML
  - American/British version is SML
  - **O** is for object-oriented extension
- ML stands for **Meta-Language**
- ML family designed for implementing theorem provers (back in 1970s)
  - It was the meta-language for programming the "object" language of the theorem prover
  - Despite obscure original application area, OCAML is a full general-purpose programming language

Session in OCAML

```
% ocaml
Objective Caml version 4.07
# _
# (* 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;;
  ^^^
Error: This expression has type float but an expression
    was expected of type int
```

```
# 1.0 *. 2;; (* No Implicit Coercion *)
Characters 7-8:
  1.0 *. 2;;
         ^^
Error: This expression has type int but an expression was
    expected of type float
```

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
```

Environments

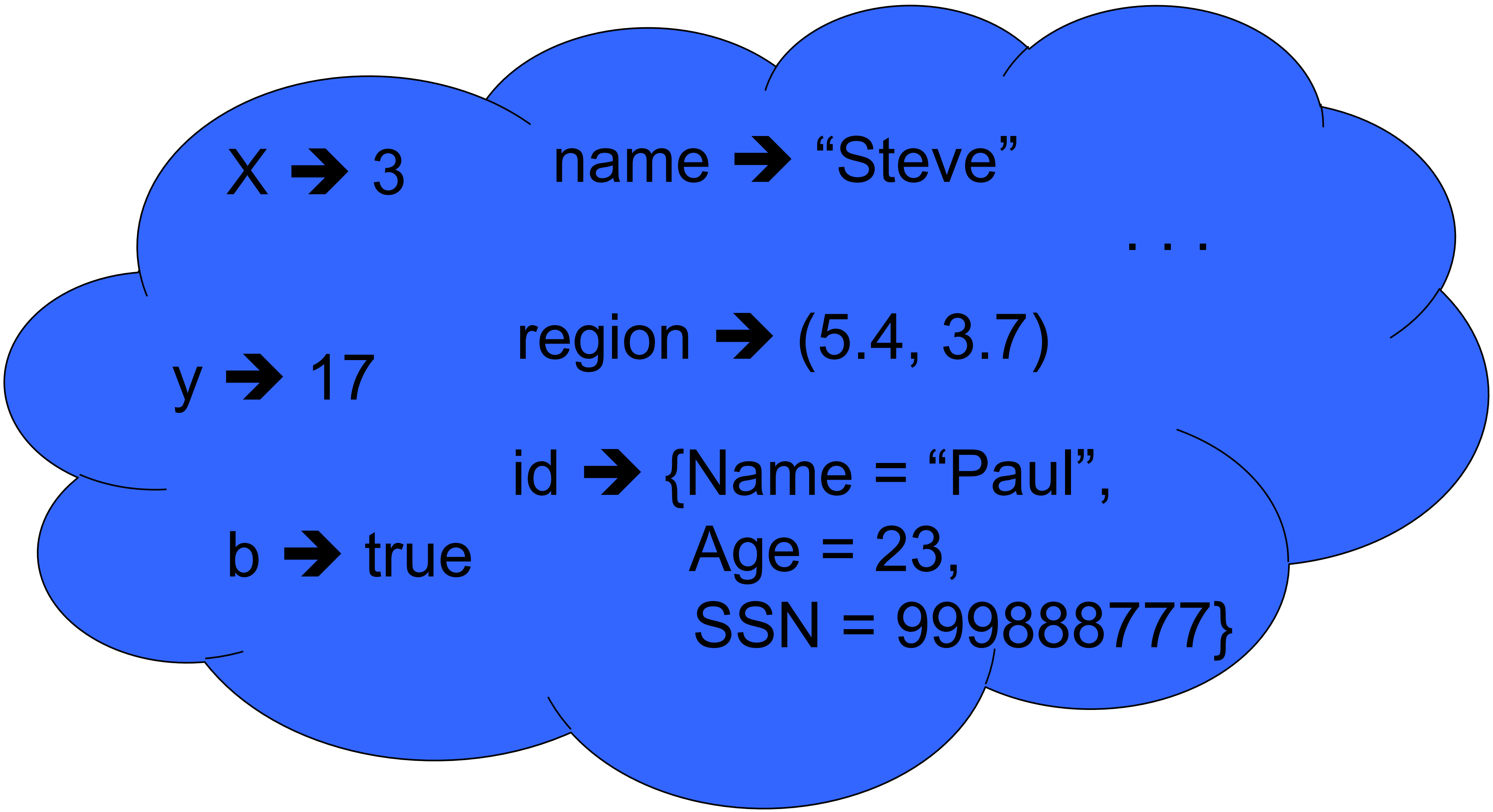
- *Environments* record what value is associated with a given identifier
- Central to the semantics and implementation of a language
- Notation

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

Using set notation, but describes a partial function

- Implementation: Often stored as list, or stack
  - To find value start from left and take first match

Environments



Global Variable Creation

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

// $\rho_1 = \{test \rightarrow false\}$

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

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

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

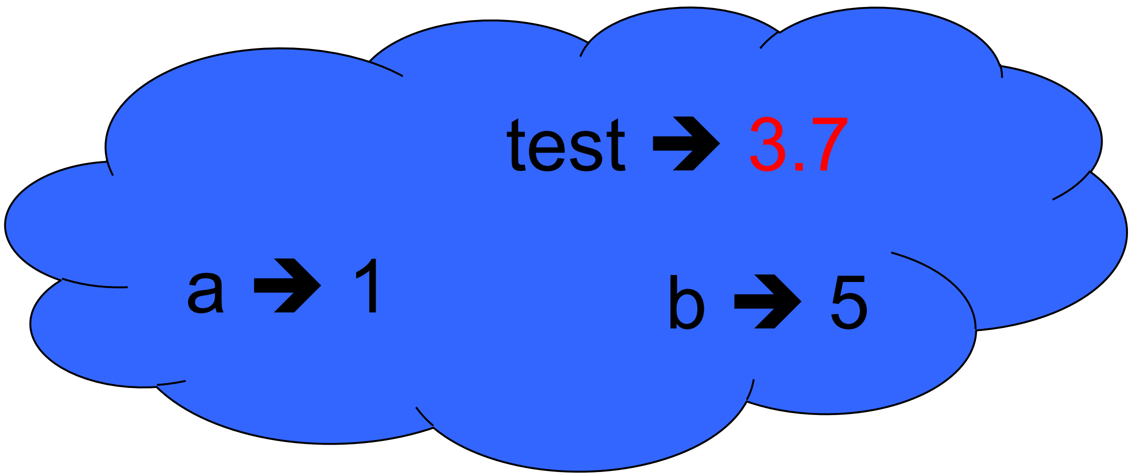
// $\rho_2 = \{b \rightarrow 5, a \rightarrow 1, \textbf{test} \rightarrow \textbf{false}\}$

let test = 3.7;;

- What is the environment after this declaration?

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

Environments



Local Variable Creation

// ρ_3 = {test → 3.7, a → 1, b → 5}

let b = 5 * 4

// ρ_4 = {b → 20, test → 3.7, a → 1}

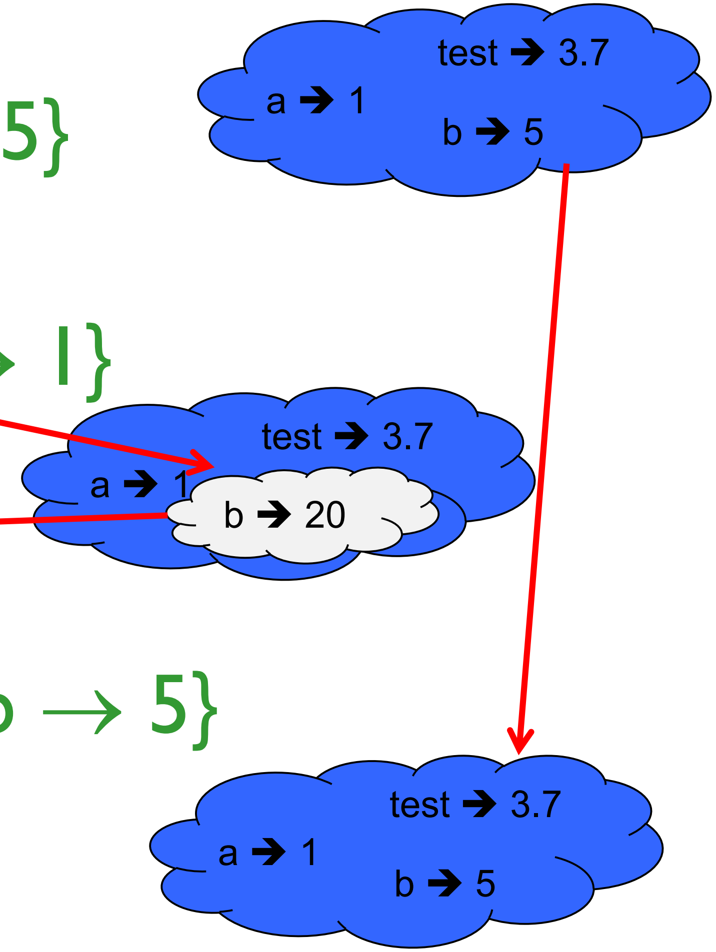
in 2 * b;;

- : int = 40

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

b;;

- : int = 5

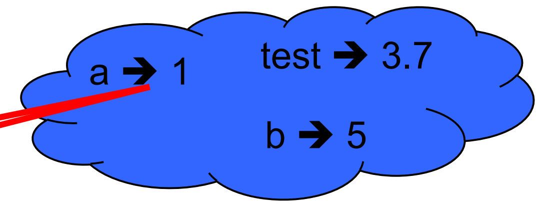


Local let binding

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

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



    in b * b;;



# b;;
```

Local let binding



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

let c =

let b = a + a

// $\rho_6 = \{b \to 2\} + \rho_5$

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

in b * b;;

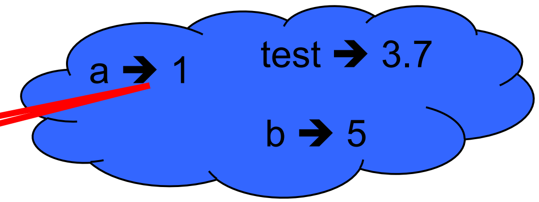
val c : int = 4

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

b;;

- : int = 5

Local let binding

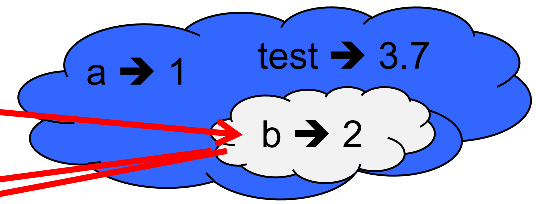


// $\rho_5 = \{\text{test} \rightarrow 3.7, a \rightarrow 1, b \rightarrow 5\}$

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

// $\rho_6 = \{b \rightarrow 2\} + \rho_5$

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




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

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

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

Local let binding

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

\# let c =

let b = a + a

// $\rho_6 = \{b \rightarrow 2\} + \rho_5$

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

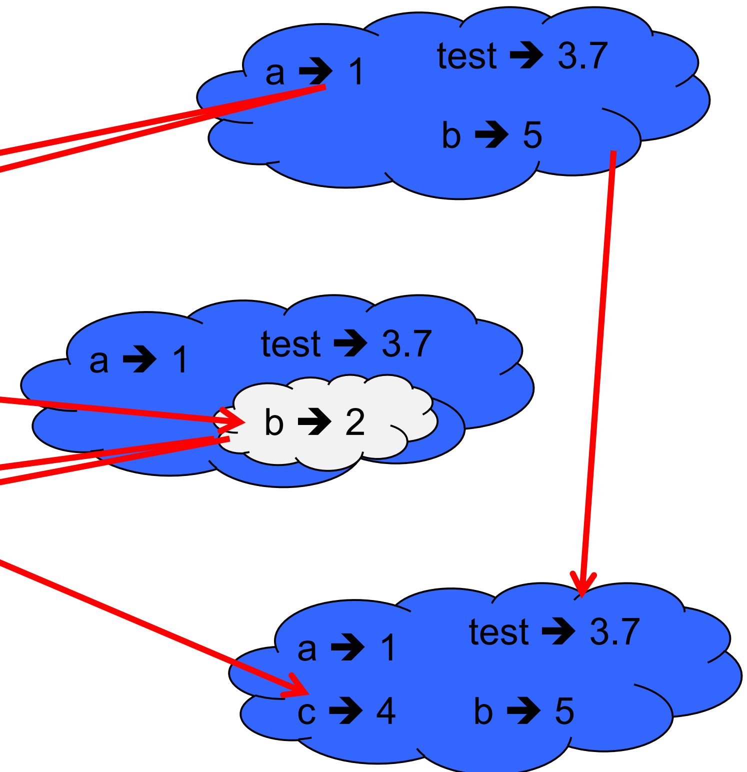
in b * b;;

val c : int = 4

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

\# b;;

\- : int = 5



Booleans (aka Truth Values)

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

# false;;
- : bool = false

//  ρ7 = {c → 4, test → 3.7, a → 1, b → 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

# not (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
```

Tuples as Values

```
//  ρ0 = {c → 4, a → 1, b → 5}
# let s = (5,"hi",3.2);;
val s : int * string * float = (5, "hi", 3.2)

//  ρ = {s → (5, "hi", 3.2), c → 4, a → 1, b → 5}
```

Pattern Matching with Tuples

```
//  ρ = {s → (5, "hi", 3.2), a → 1, b → 5, c → 4}

# 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 (a, _, _) = s;;
val a : int = 5

# 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"
```

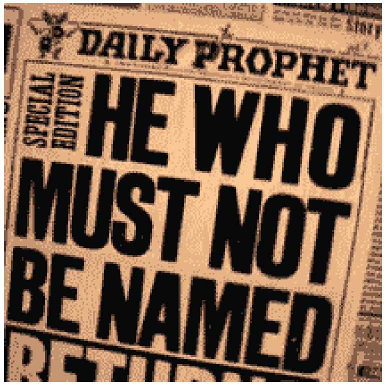
Functions

```
# 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

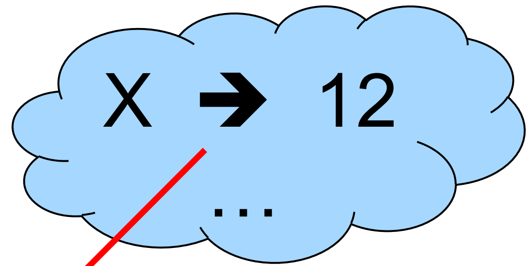
Using a nameless function

```
(* An application *)
# (fun x -> x * 3) 5;;
 : int = 15

(* As data *)
# ((fun y -> y +. 2.0), (fun z -> z * 3));;
- : (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
```

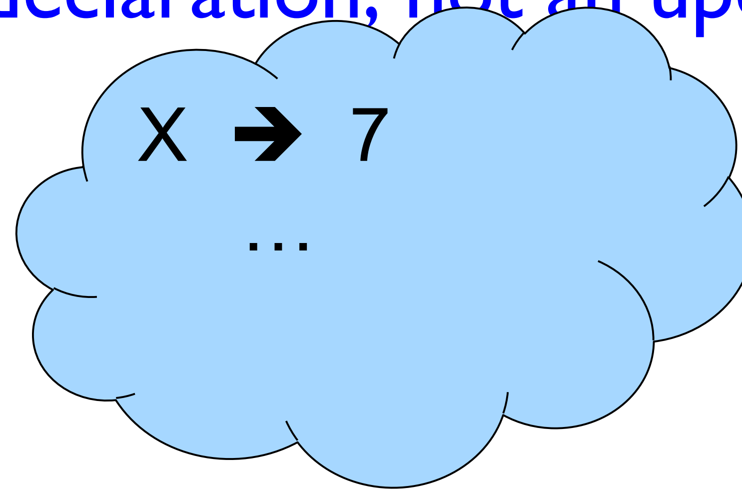
```
# plus_x 3;;
```

What is the result this time?

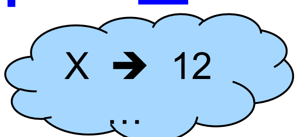
Values fixed at declaration time

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!

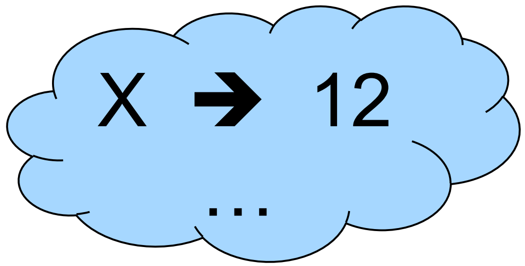
- A **closure** is a pair of an environment and an association of a sequence of variables (the input variables) with an expression (the function body), written:

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

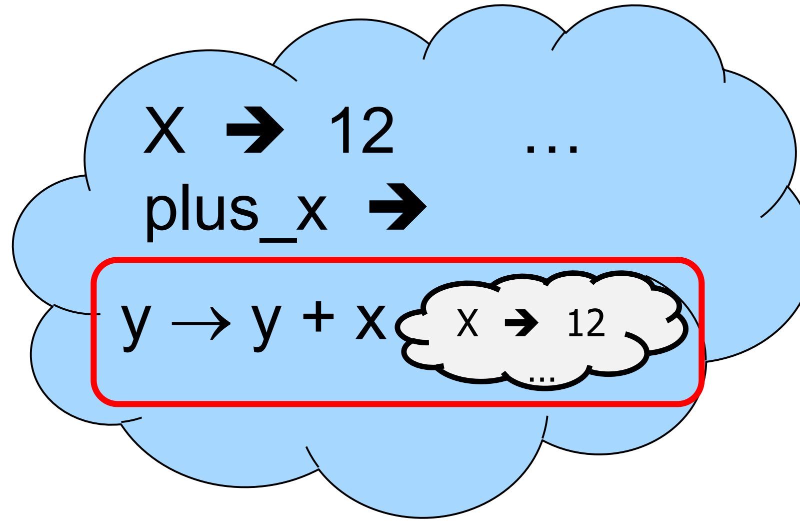
- Where ρ is the environment in effect when the function is defined (for a simple function)

Recall: let plus_x = fun x => y + x

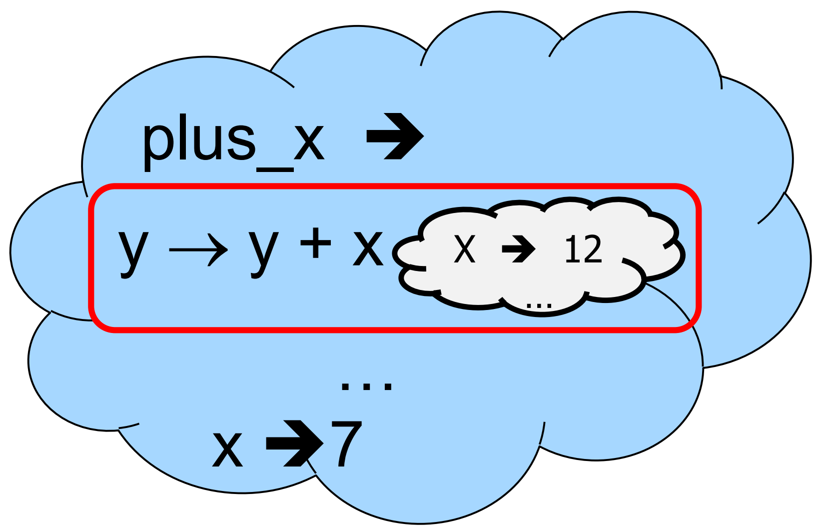
let x = 12



let plus_x = fun y -> y + x



let x = 7



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:

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

Like set union! (but subtle differences; new decl. replaces old)

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 on tuples

```
# let plus_pair (n,m) = n + m;;
val plus_pair : int * int -> int = <fun>

# plus_pair (3,4);;
- : int = 7

# let twice x = (x,x);;
val twice : 'a -> 'a * 'a = <fun>

# twice 3;;
- : int * int = (3, 3)

# twice "hi";;
- : string * string = ("hi", "hi")
```

Curried vs Uncurried

- Recall

```
# let add_three u v w = u + v + w;;
val add_three : int -> int -> int -> int = <fun>
```

- How does it differ from

```
# let add_triple (u,v,w) = u + v + w;;
val add_triple : int * int * int -> int = <fun>
```

- add_three is **curried**;
- add_triple is **uncurried**

Curried vs Uncurried

```
# add_three 6 3 2;;
- : int = 11

# add_triple (6,3,2);;
- : int = 11

# add_triple 5 4;;
Characters 0-10:  add_triple 5 4;;
                  ^^^^^^^^^^
This function is applied to too many arguments,
maybe you forgot a `;'

# fun x -> add_triple (5,4,x);;
: int -> int = <fun>
```

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*

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