

# Programming Languages and Compilers (CS 421)

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<https://courses.engr.illinois.edu/cs421/fa2017/CS421D>

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



# Contact Information - Elsa L Gunter

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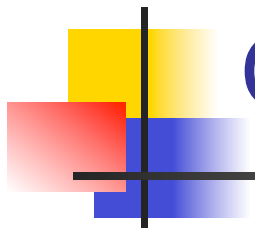
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  - Friday 1:00pm – 1:50pm
  - Also by appointment
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## Overflow Section

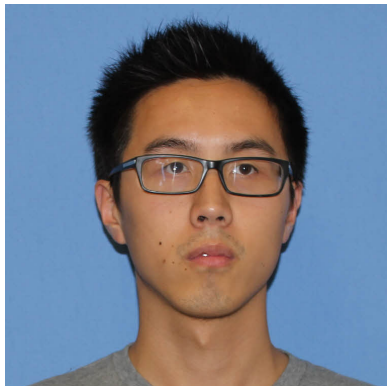
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- If you are not registered and want to be, fill out the form at
- <http://go.cs.illinois.edu/CS421Overflow>

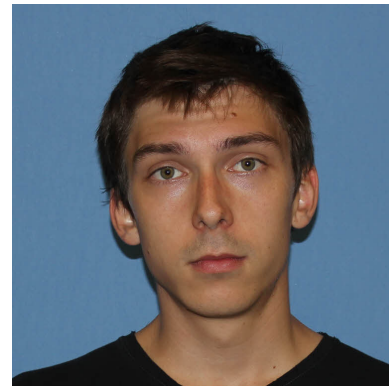


# Course TAs

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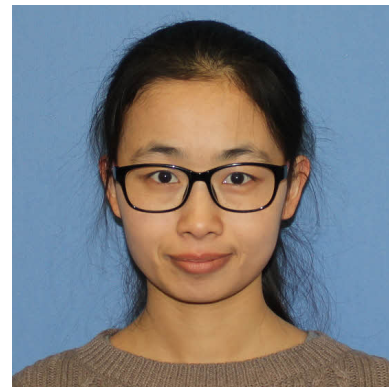
Taiyu Dong



Dan Plyukhin



Jing Huang



Fan Yang



## Contact Information - TAs

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- Teaching Assistants Office: 0207 SC
- Taiyu Dong
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Thu 2:00pm – 2:50pm
- Jing Huang
  - Email: [jhuang81@illinois.edu](mailto:jhuang81@illinois.edu)
  - Hours: Tue 6:00pm – 7:40pm



## Contact Information – TAs cont

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- Dan Plyukhin

- Email: [daniilp2@illinois.edu](mailto:daniilp2@illinois.edu)
- Hours: Mon, Wed 12:30pm – 1:20pm

- Fan Yan

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- Hours: Wed, Fri 9:00am – 9:50am



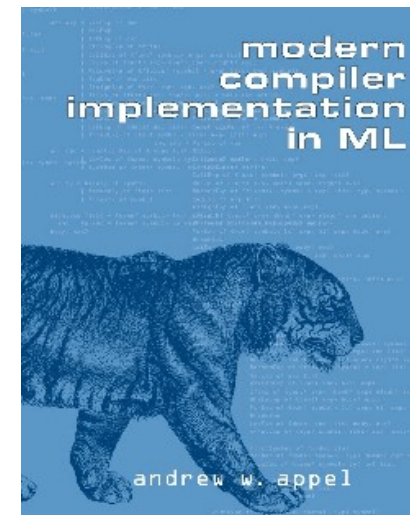
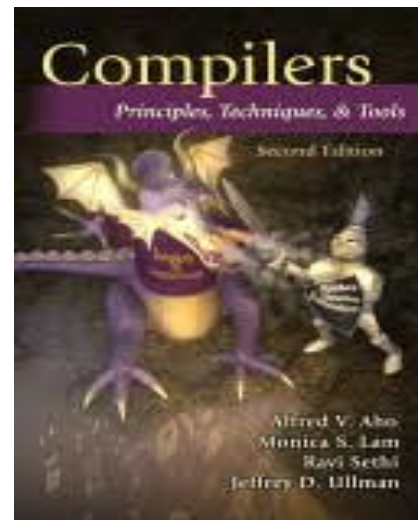
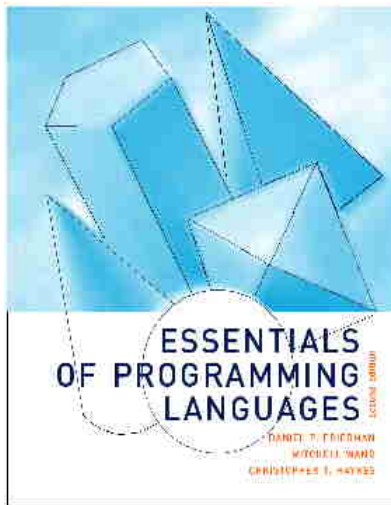
# Course Website

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- <https://courses.engr.illinois.edu/cs421/fa2017/CS421D>
- 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

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- 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

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- Assignments 20%
  - About 12 Web Assignments (WA) ( $\sim 7\%$ )
  - About 6 MPs (in Ocaml) ( $\sim 7\%$ )
  - About 5 Labs ( $\sim 6\%$ )
  - All WAs and MPs Submitted by **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

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- 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
  - Fall back: In class backup dates – **Oct 12, Nov 16**
  - **DO NOT MISS EXAM DATES!**
- Final 40% - Dec 19, 8:00am – 11:00am
- May use of CBTC for Final
- Percentages are approximate



## Course Assignments – WA & MP

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- 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



# Programming Languages & Compilers

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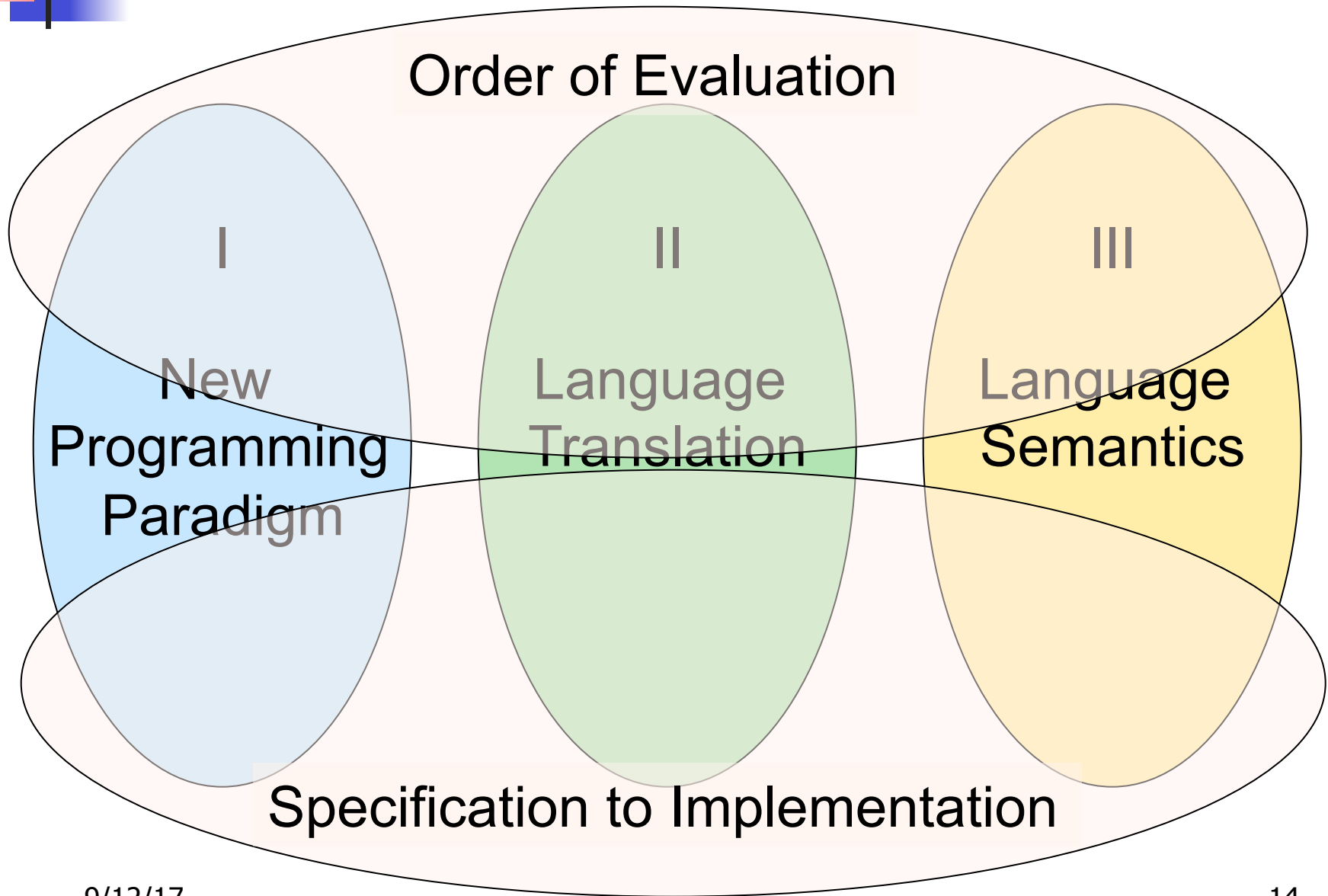
## Three Main Topics of the Course

I  
New  
Programming  
Paradigm

II  
Language  
Translation

III  
Language  
Semantics

# Programming Languages & Compilers





# Programming Languages & Compilers

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## I : New Programming Paradigm

Functional  
Programming

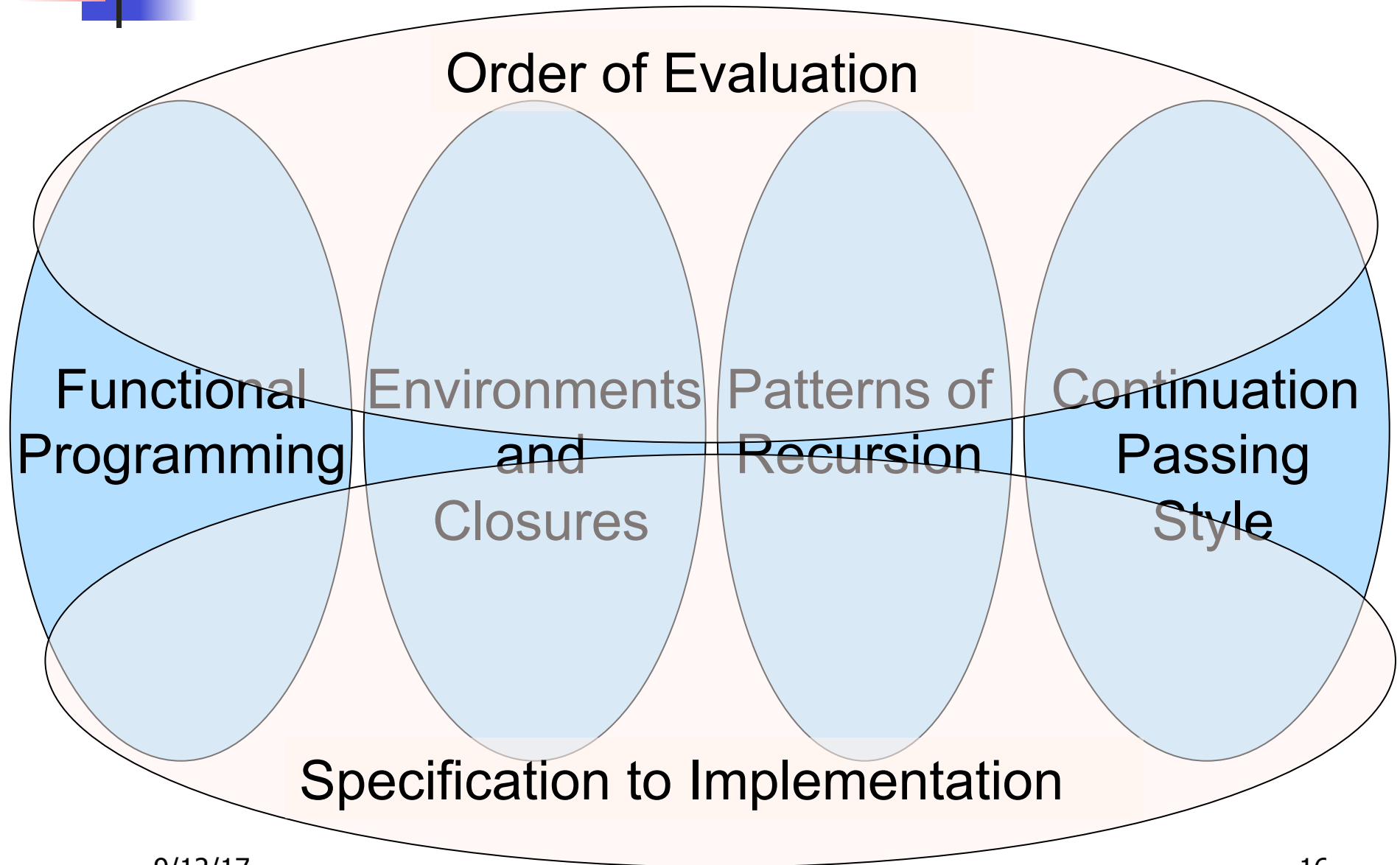
Environments  
and  
Closures

Patterns of  
Recursion

Continuation  
Passing  
Style



# Programming Languages & Compilers



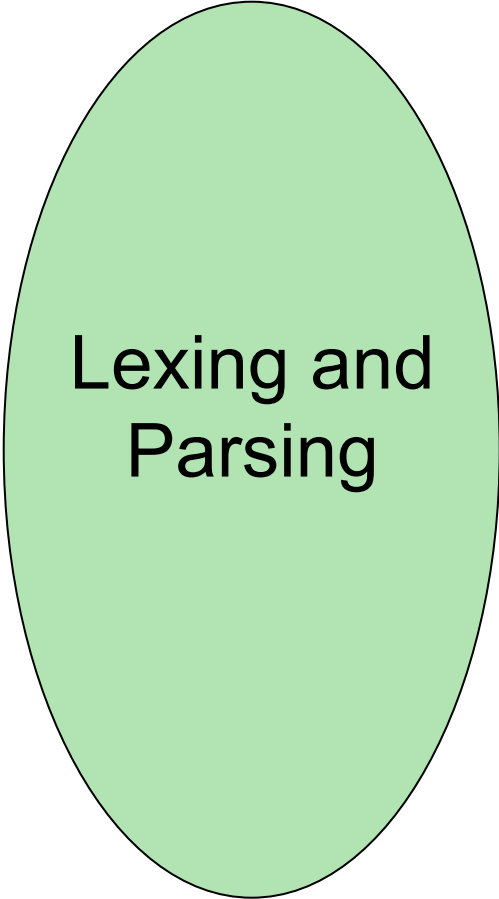




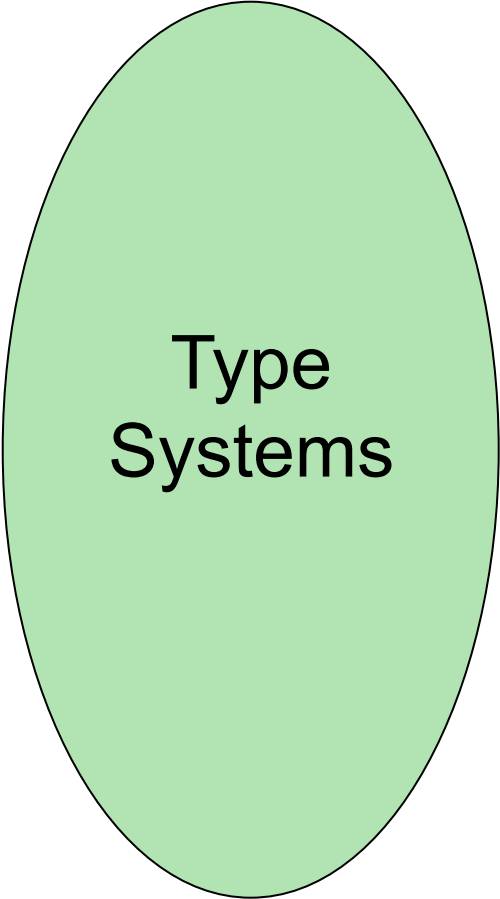
# Programming Languages & Compilers

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## II : Language Translation



Lexing and  
Parsing

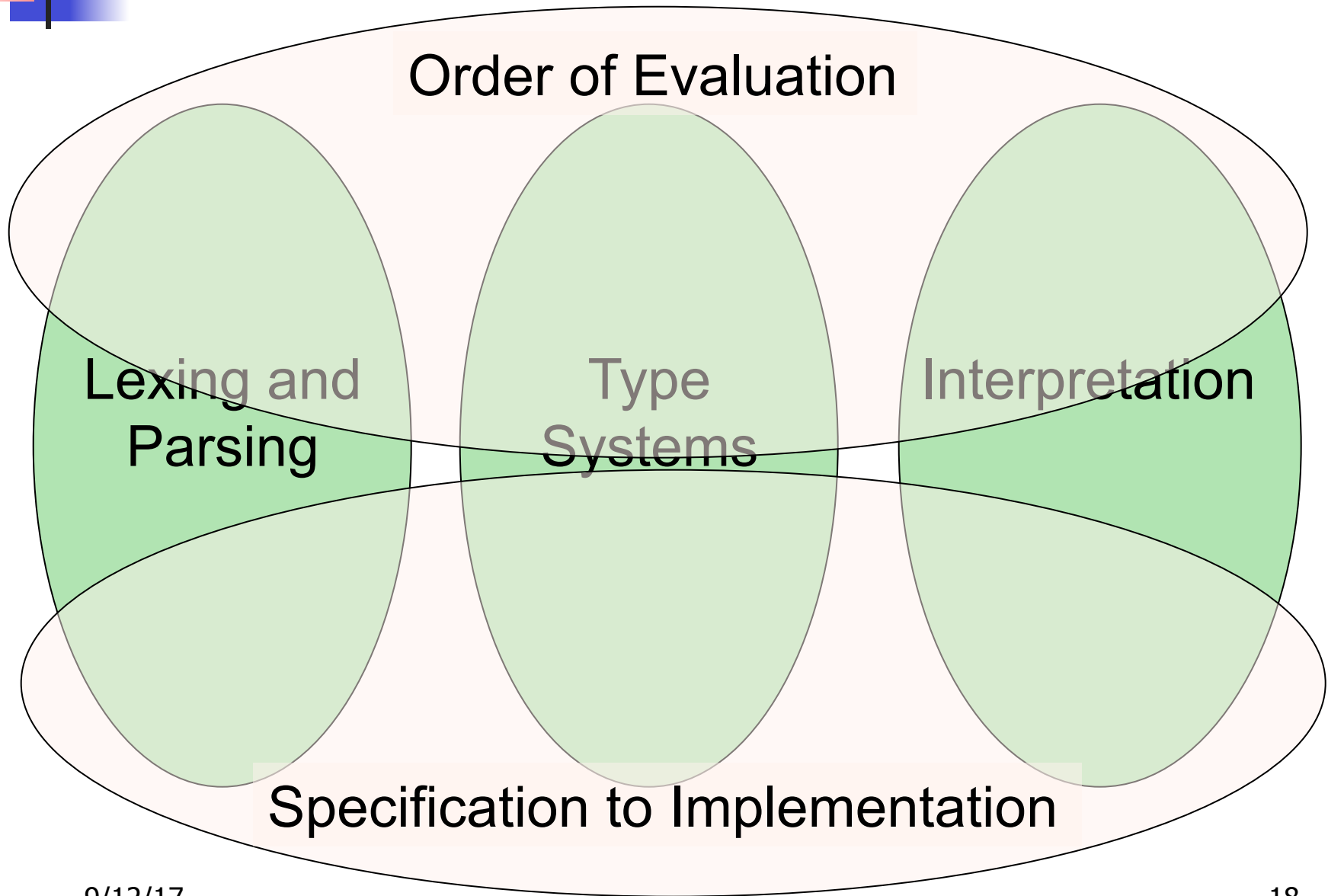


Type  
Systems



Interpretation

# Programming Languages & Compilers





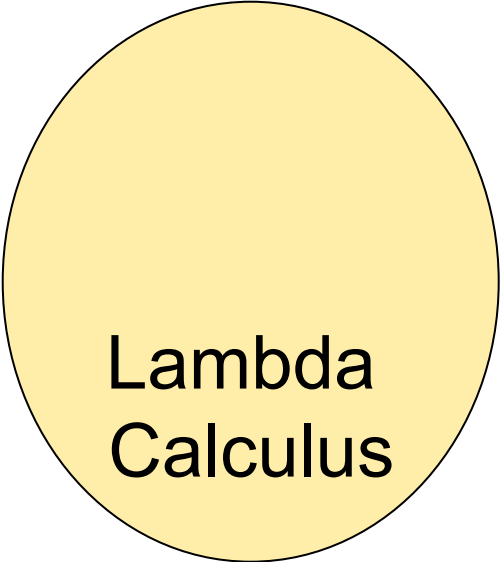
# Programming Languages & Compilers

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## III : Language Semantics



Operational  
Semantics

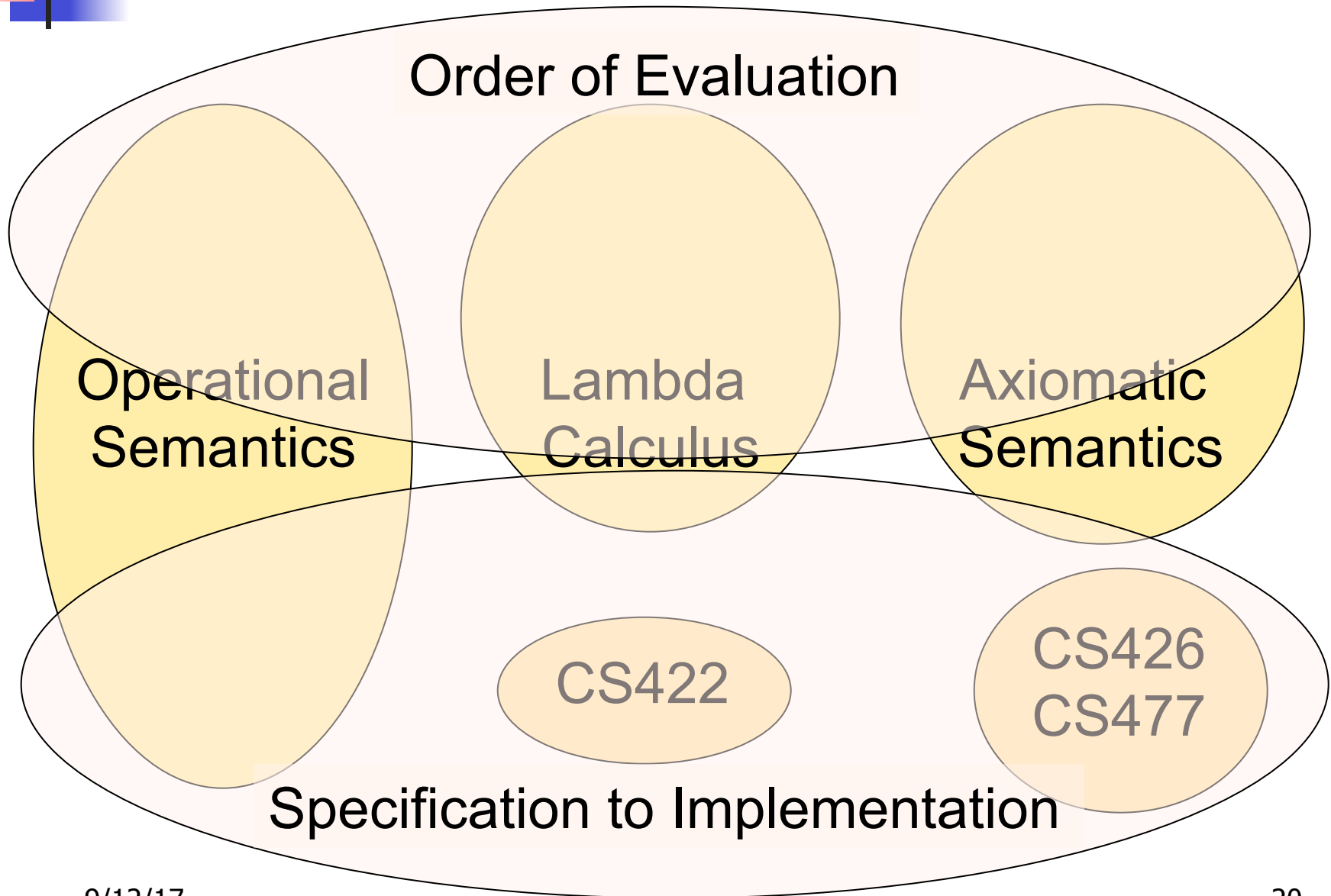


Lambda  
Calculus



Axiomatic  
Semantics

# Programming Languages & Compilers





# Course Objectives

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- **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



- Locally:
  - Compiler is on the EWS-linux systems at  
`/usr/local/bin/ocaml`
- Globally:
  - Main CAML home: <http://ocaml.org>
  - To install OCAML on your computer see:  
<http://ocaml.org/docs/install.html>



## References for OCaml

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- 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 Chailoux, Pascal Manoury, and Bruno Pagano, on O' Reilly
    - Available online from course resources



# OCAML Background

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- 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
  - 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





# Features of OCAML

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- Higher order applicative language
- Call-by-value parameter passing
- Modern syntax
- Parametric polymorphism
  - Aka structural polymorphism
- Automatic garbage collection
- User-defined algebraic data types
  
- It's fast - winners of the 1999 and 2000 ICFP Programming Contests used OCAML



# Why learn OCAML?

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- 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
- Similar languages: Microsoft F#, SML, Haskell, Scala



# Session in OCAML

---

```
% ocaml
```

```
Objective Caml version 4.01
```

```
# (* 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
```



# Environments

---

- *Environments* record what value is associated with a given identifier
- Central to the semantics and implementation of a language
- Notation
$$\rho = \{\text{name}_1 \rightarrow \text{value}_1, \text{name}_2 \rightarrow \text{value}_2, \dots\}$$
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

---

$x \rightarrow 3$

name  $\rightarrow$  "Steve"

...

$y \rightarrow 17$

region  $\rightarrow$  (5.4, 3.7)

$b \rightarrow \text{true}$

id  $\rightarrow$  {Name = "Paul",  
Age = 23,  
SSN = 999888777}



# Global Variable Creation

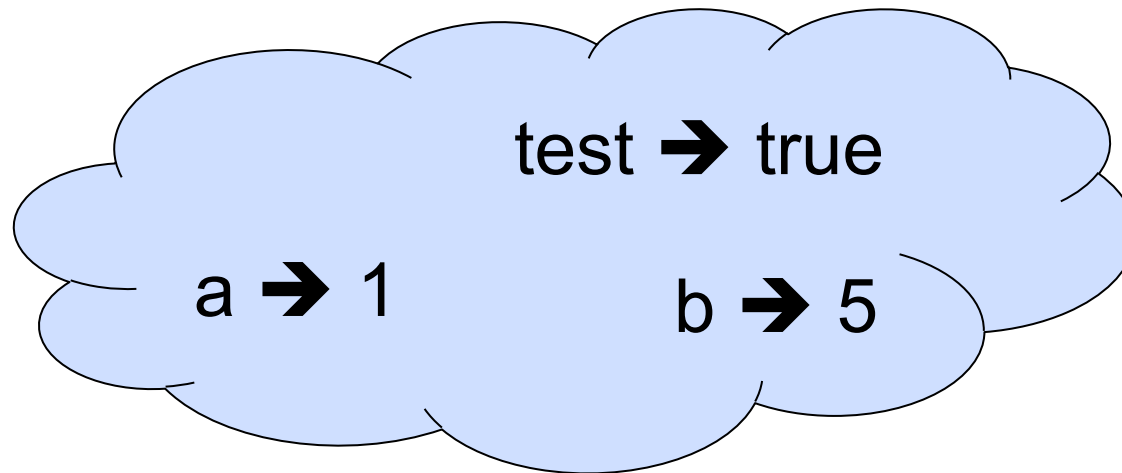
---

```
# 2 + 3;;    (* Expression *)  
// doesn't affect the environment  
# let test = 3 < 2;;    (* Declaration *)  
val test : bool = false  
//  $\rho_1 = \{\text{test} \rightarrow \text{false}\}$   
# let a = 1 let b = a + 4;; (* Seq of dec *)  
//  $\rho_2 = \{b \rightarrow 5, a \rightarrow 1, \text{test} \rightarrow \text{false}\}$ 
```



# 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

---

```
//  $\rho_2 = \{b \rightarrow 5, a \rightarrow 1, test \rightarrow false\}$   
let test = 3.7;;
```

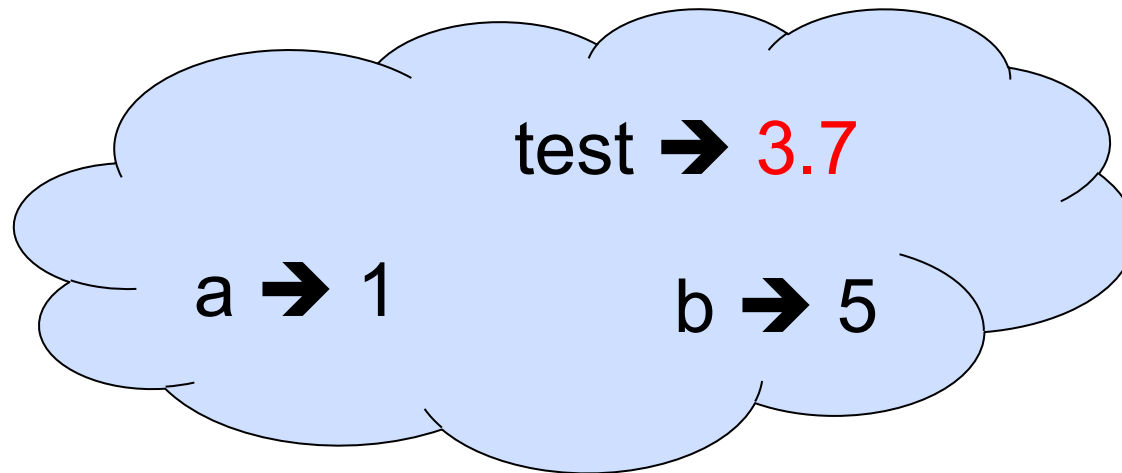
- What is the environment after this declaration?

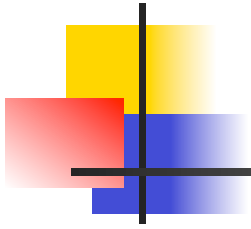
```
//  $\rho_3 = \{test \rightarrow 3.7, a \rightarrow 1, b \rightarrow 5\}$ 
```



# Environments

---





# Now it's your turn

You should be able to do WA1  
Problem 1 , parts (\* 1 \*) and (\* 2 \*)

# Local Variable Creation

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

```
# let b = 5 * 4
```

```
//  $\rho_4 = \{b \rightarrow 20, \text{test} \rightarrow 3.7, a \rightarrow 1\}$ 
```

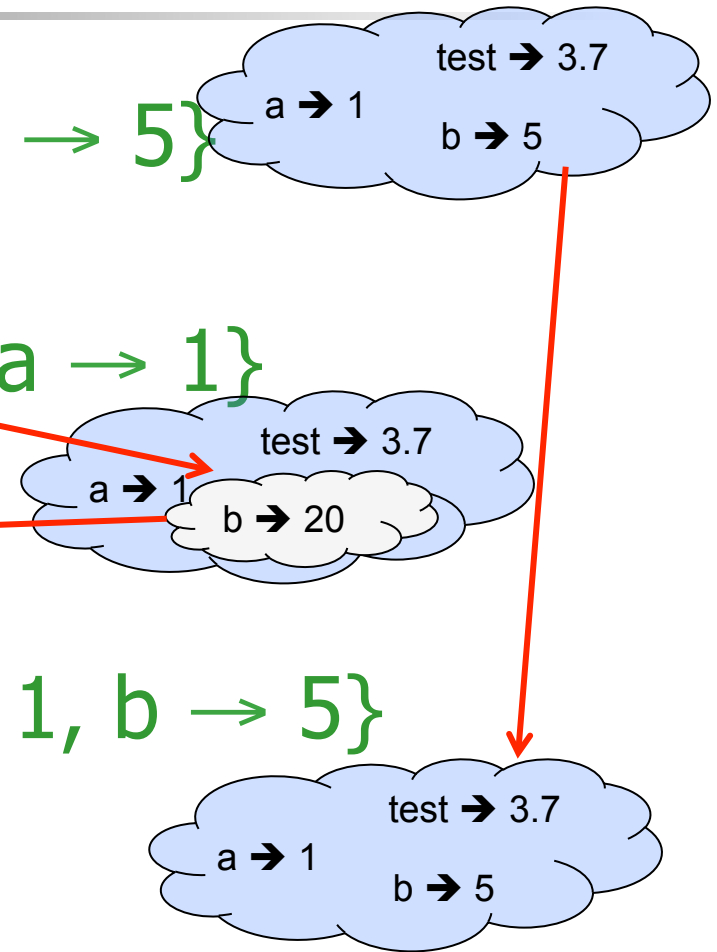
```
in 2 * b;;
```

```
- : int = 40
```

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

```
# 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
```

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

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

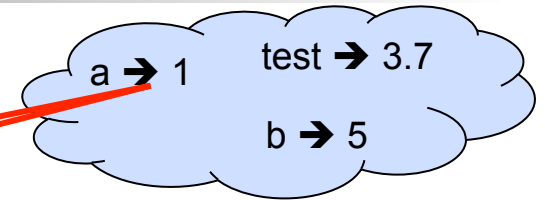
```
  in b * b;;
```

```
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

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

```
# let c =
```

```
  let b = a + a
```

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

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

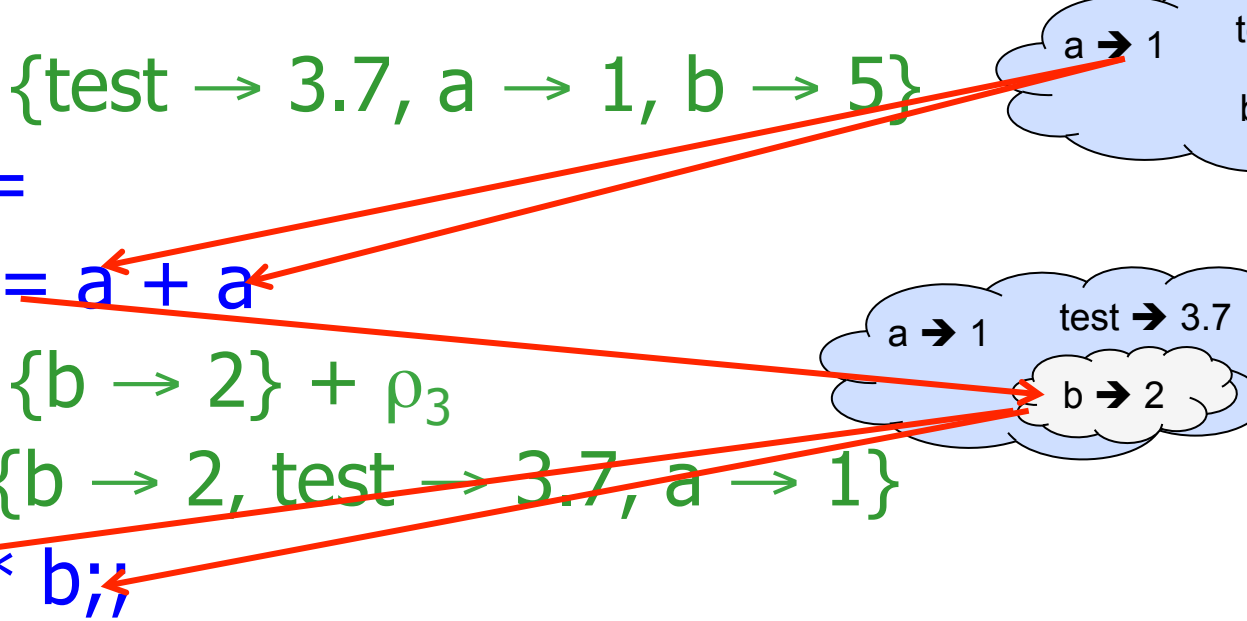
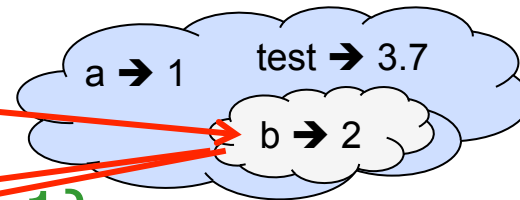
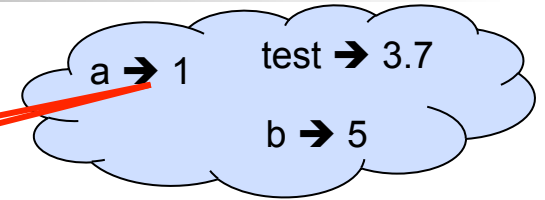
```
  in b * b;;
```

```
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

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

```
# let c =
```

```
  let b = a + a
```

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

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

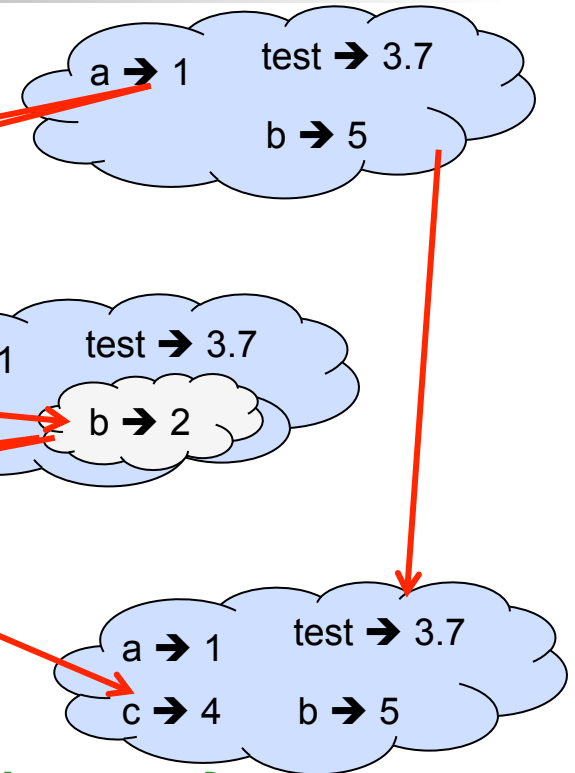
```
  in b * b;;
```

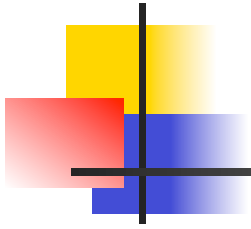
```
val c : int = 4
```

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

```
# b;;
```

```
- : int = 5
```





# Now it's your turn

You should be able to do WA1  
Problem 1 , parts (\* 3 \*) and (\* 4 \*)



# Booleans (aka Truth Values)

---

```
# true;;
```

```
- : bool = true
```

```
# false;;
```

```
- : bool = false
```

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

```
# 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
```

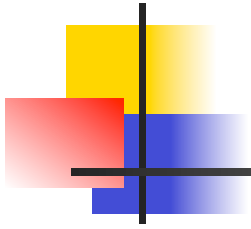
```
- : bool = true
```

```
# 3 > 1 || (print_string "Bye\n"; 4 > 6);;
```

```
- : bool = true
```

```
# not (4 > 6);;
```

```
- : bool = true
```



Now it's your turn

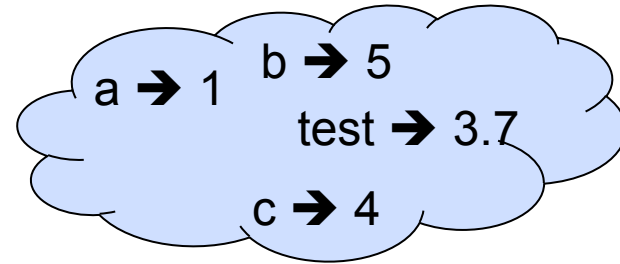
You should be able to do WA1  
Problem 1 , part (\* 5 \*)

# Tuples as Values

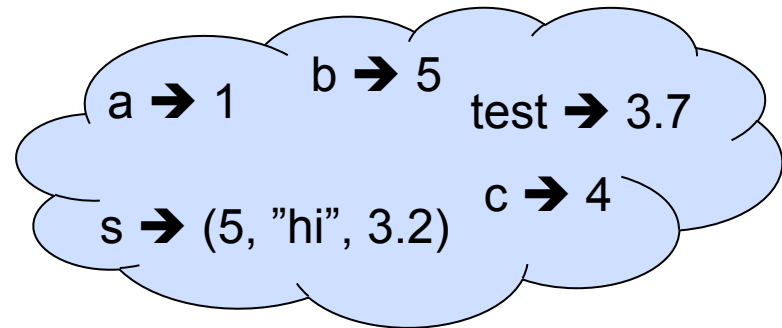
```
//  $\rho_7 = \{c \rightarrow 4, \text{test} \rightarrow 3.7,$   
           $a \rightarrow 1, b \rightarrow 5\}$ 
```

```
# let s = (5, "hi", 3.2);;
```

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



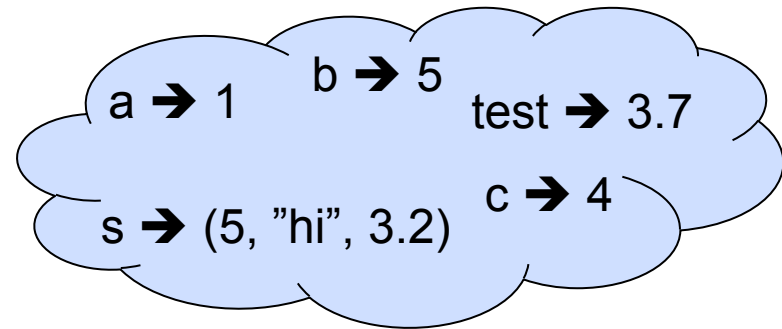
```
//  $\rho_8 = \{s \rightarrow (5, \text{"hi"}, 3.2),$   
           $c \rightarrow 4, \text{test} \rightarrow 3.7,$   
           $a \rightarrow 1, b \rightarrow 5\}$ 
```





# Pattern Matching with Tuples

```
/ ρ8 = {s → (5, "hi", 3.2),  
         c → 4, test → 3.7,  
         a → 1, b → 5}
```



```
# let (a,b,c) = s;; (* (a,b,c) is a pattern *)
```

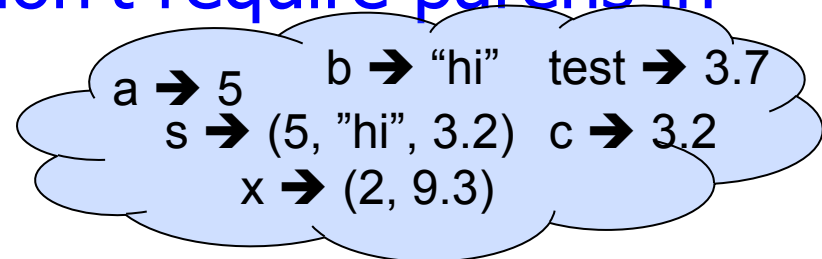
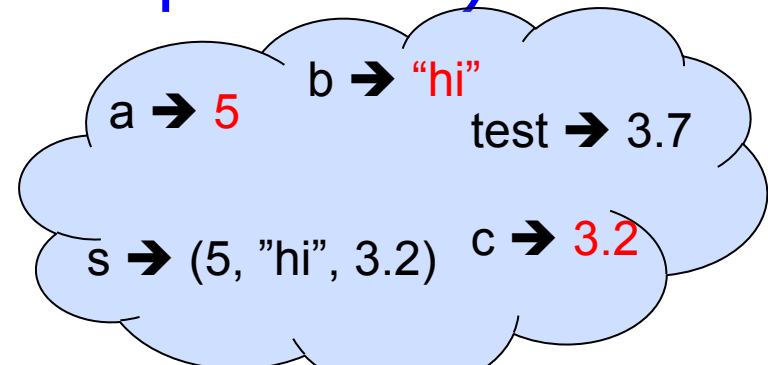
```
val a : int = 5
```

```
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);;
```

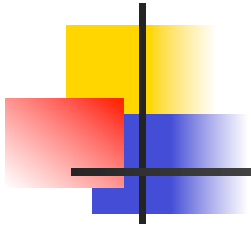
```
val d : (int * int * int) * (string * int) * float =  
  ((1, 4, 62), ("bye", 15), 73.95)
```

```
# (*Patterns can be nested *)
```

```
let (p,(st,_),_) = d;; (* _ matches all, binds nothing  
*)
```

```
val p : int * int * int = (1, 4, 62)
```

```
val st : string = "bye"
```



---

Now it's your turn

You should be able to do WA1  
Problem 1 , part (\* 6 \*)



# Functions

---

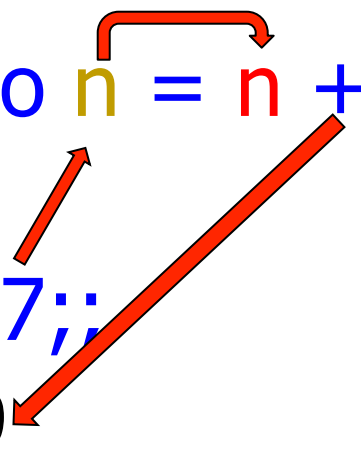
```
# let plus_two n = n + 2;;  
val plus_two : int -> int = <fun>  
# plus_two 17;;  
- : int = 19
```



# 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

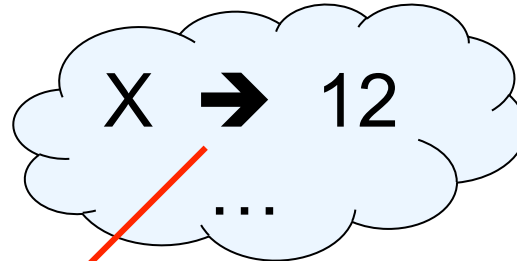
```
# let x = 12;;
```

```
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
```

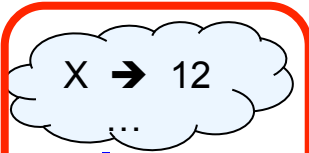
```
# plus_x 3;;
```

What is the result this time?

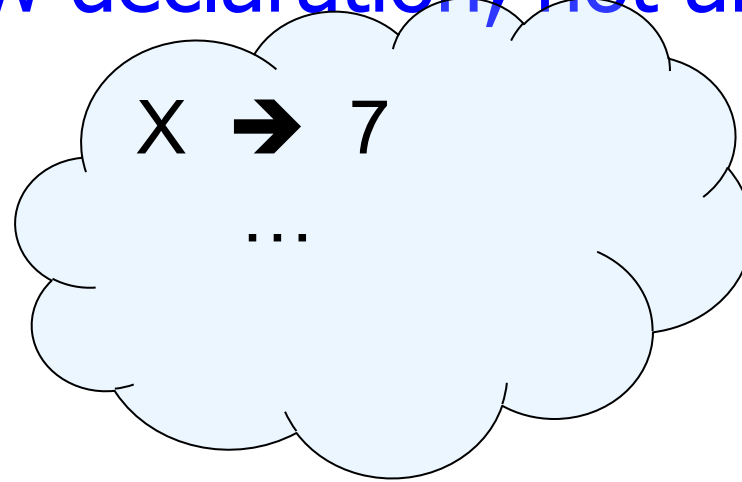
# Values fixed at declaration time

```
# 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 sequence of variables (the input variables) with an expression (the function body), written:

$$f \rightarrow \langle (v_1, \dots, v_n) \rightarrow \text{exp}, \rho_f \rangle$$

- Where  $\rho_f$  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:

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

- Recall: `let plus_x y = y + x`

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

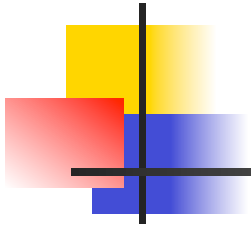
- Closure for `fun y -> y + x`:

$$\langle y \rightarrow y + x, \rho_{\text{plus\_x}} \rangle$$

- Environment just after plus\_x defined:

$$\{\text{plus\_x} \rightarrow \langle y \rightarrow y + x, \rho_{\text{plus\_x}} \rangle\} + \rho_{\text{plus\_x}}$$





# Now it's your turn

You should be able to do WA1  
Problem 1 , parts (\* 7 \*) and (\* 8 \*)



## Evaluation of Application of plus\_x;;

---

- Have environment:

$$\rho = \{ \text{plus\_x} \rightarrow \langle y \rightarrow y + x, \rho_{\text{plus\_x}} \rangle, \dots, \\ y \rightarrow 3, \dots \}$$

where  $\rho_{\text{plus\_x}} = \{ x \rightarrow 12, \dots, y \rightarrow 24, \dots \}$

- $\text{Eval}(\text{plus\_x } y, \rho)$  rewrites to
- $\text{App}(\text{Eval}(\text{plus\_x}, \rho), \text{Eval}(y, \rho))$  rewrites to
- $\text{App}(\langle y \rightarrow y + x, \rho_{\text{plus\_x}} \rangle, 3)$  rewrites to
- $\text{Eval}(y + x, \{y \rightarrow 3\} + \rho_{\text{plus\_x}})$  rewrites to
- $\text{Eval}(3 + 12, \rho_{\text{plus\_x}}) = 15$



## 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



# 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
```



## 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!"
```



# 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);;
```

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

```
val triple_to_pair : int * int * int -> int * int =  
  <fun>
```



## Closure for plus\_pair

---

- Assume  $\rho_{\text{plus\_pair}}$  was the environment just before `plus_pair` defined

- Closure for `plus_pair`:

$$\langle (n,m) \rightarrow n + m, \rho_{\text{plus\_pair}} \rangle$$

- Environment just after `plus_pair` defined:

$$\{\text{plus\_pair} \rightarrow \langle (n,m) \rightarrow n + m, \rho_{\text{plus\_pair}} \rangle\} \\ + \rho_{\text{plus\_pair}}$$