Programming Languages and Compilers (CS 421)

Elsa L Gunter

2112 SC, UIUC

http://courses.engr.illinois.edu/cs421

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

Dennis Griffith, guest lecturer

Contact Information - Elsa L Gunter

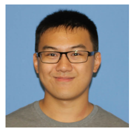
- Office: 2112 SC
- Office hours:
  - Tuesday 12:00pm – 1:30pm
  - Thursday 3:30pm - 4:20pm
  - Also by appointment
- Email: egunter@illinois.edu

Overflow Section

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

Course TAs

Susannah Johnson



Terence Nip

John Lee

Michael Bay

Contact Information - TAs

- Teaching Assistants Office: 0207 SC
- Susannah Johnson
  - Email: sjohnsn2@illinois.edu
  - Hours: Wed 10:00am – 11:45am
- John Lee
  - Email: lee170@illinois.edu
  - Hours: Mon 12:00pm – 12:50pm
    Fri 10:00am – 10:50am

Contact Information – TAs cont

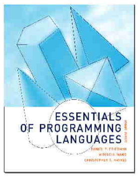
- Terence Nip
  - Email: nip2@illinois.edu
  - Hours: Tues 4:00pm – 4:50pm
    Thurs 11:15am – 12:05am
- Michael Bay
  - Email: bay2@illinois.edu
  - Hours: Fri 4:00pm – 5:45pm

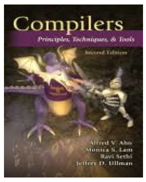
Course Website

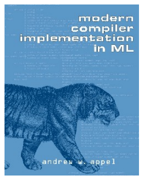
- http://courses.engr.illinois.edu/cs421
- Main page - summary of news items
- Policy - rules governing course
- Lectures - syllabus and slides
- MPs - information about assignments
- Exams
- Unit Projects - for 4 credit students
- Resources - tools and helpful info
- FAQ

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 20%
  - About 12 Hand Written (HW) assignments (~7%)
  - About 8 MPs (in Ocaml) (~7%)
  - About 4 Labs (~6%)
  - All HW and MPs Submitted by **svn**
    - MPs – plain text code that compiles; HWs – pdf
  - Late submission penalty: 20% of assignments total value

  - Labs in Computer-Based Testing Center (DCL)
  - 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 (DCL)
  - Self-scheduled over a three day period
  - No extensions beyond the three day period

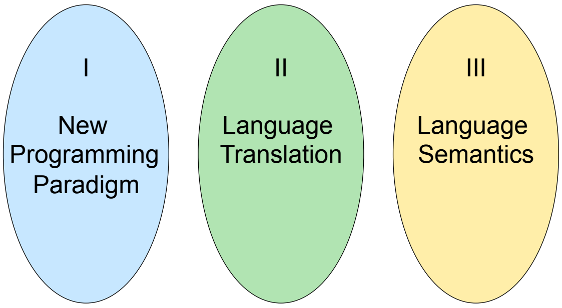
  - Fall back: In class backup dates – **Oct 8, Nov 11**
  - **DO NOT MISS EXAM DATES!**
- Final 40% - Dec 16, 8:00am – 11:00am
- Will investigate use of CBTC for Final
- Percentages are approximate

Course Assingments – Handwritten & MP

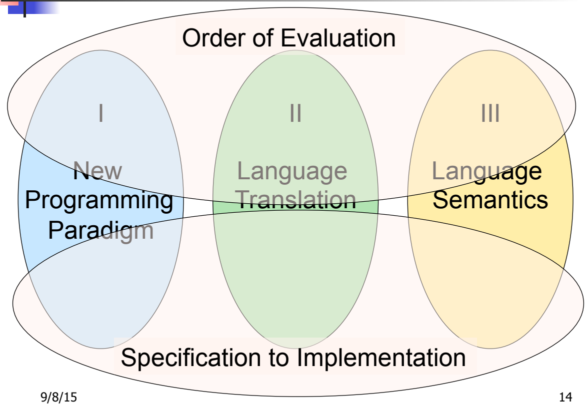
- You may discuss assignments and their solutions with others
- You may work in groups, but you must **list members with whom you worked** if you share solutions or solution outlines
- **Each student must write up and turn in their own solution separately**
- You may look at examples from class and other 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

Programming Languages & Compilers

Three Main Topics of the Course

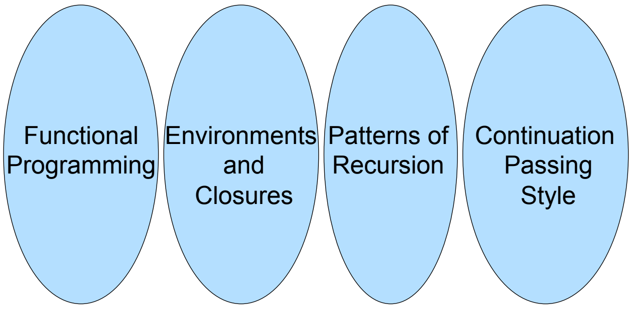


Programming Languages & Compilers

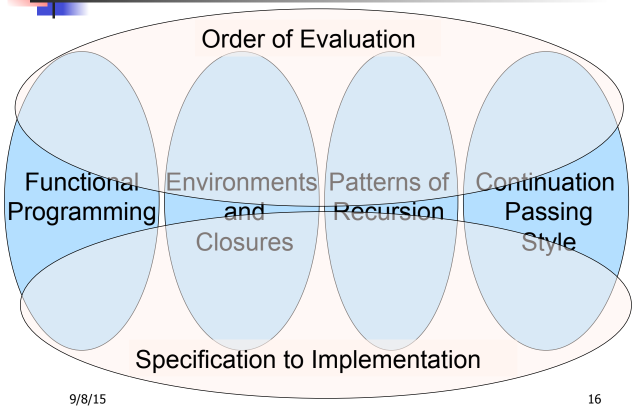


Programming Languages & Compilers

I : New Programming Paradigm

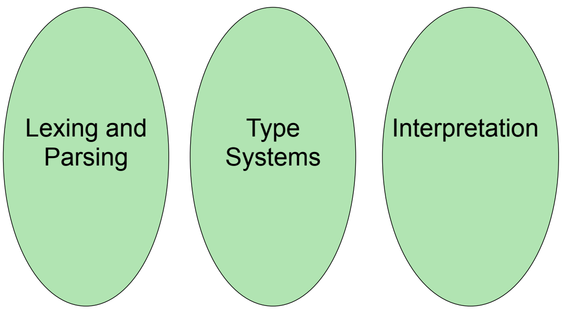


Programming Languages & Compilers

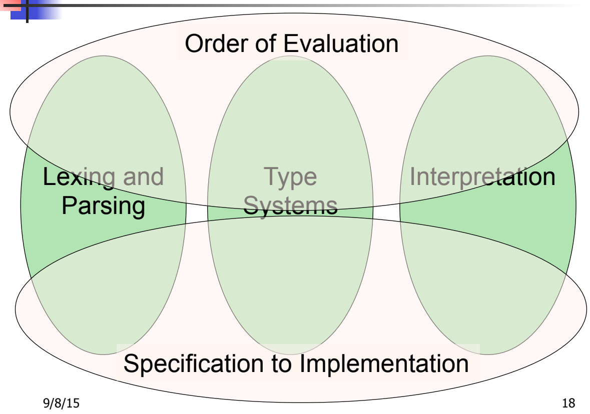


Programming Languages & Compilers

II : Language Translation

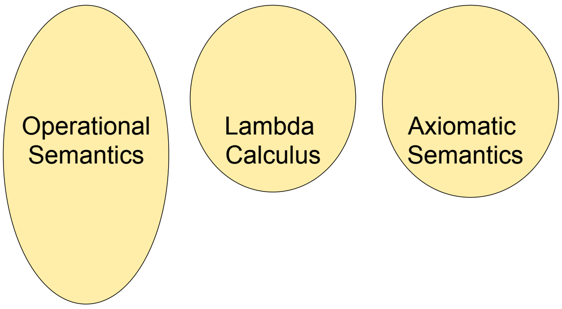


Programming Languages & Compilers

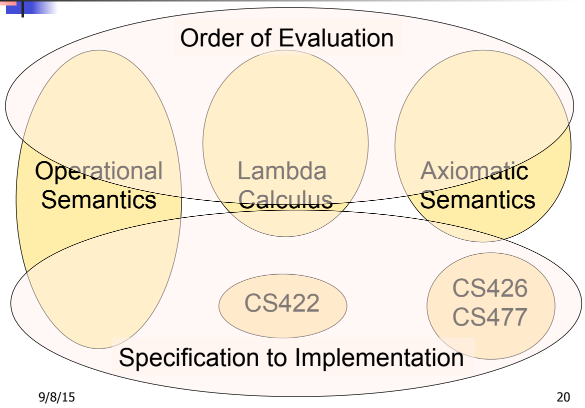


Programming Languages & Compilers

III : Language Semantics



Programming Languages & Compilers



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

OCAML

- 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

- Supplemental texts (not required):
- The Objective Caml system release 4.02, 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

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
  - 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

- 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?

- 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

OCaml Intro Code

- A (possibly better, non-PowerPoint) text version of this lecture can be found at http://course.engr.illinois.edu/class/cs421/lectures/ocaml-intro-shell.txt
- For the OCAML code for today' s lecture see http://course.engr.illinois.edu/class/cs421/lectures/ocaml-intro.ml

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
```

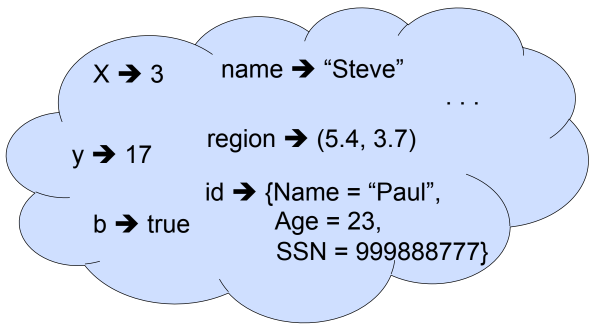

Environments

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

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

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

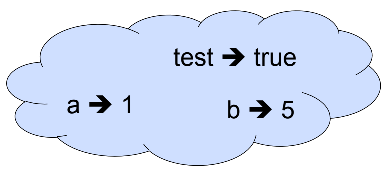
Environments



Global Variable Creation

```
# 2 + 3;;     (* Expression *)
// doesn't affect the environment
# let test = 3 < 2;;      (* Declaration *)
val test : bool = false
//  ρ1 = {test → false}
# let a = 1 let b = a + 4;; (* Seq of dec *)
//  ρ2 = {b → 5, a → 1, test → false}
```


Environments



New Bindings Hide Old

// ρ_2 = {b → 5, a → 1, test → false}
let test = 3.7;;

- What is the environment after this declaration?

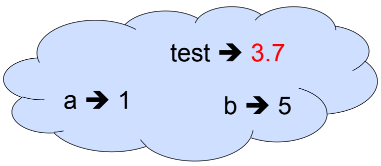
New Bindings Hide Old

// ρ_2 = {b → 5, a → 1, test → false}
let test = 3.7;;

- What is the environment after this declaration?

// ρ_3 = {test → 3.7, a → 1, b → 5}

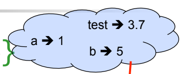
Environments



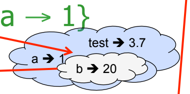
Now it's your turn

You should be able to do HW1 Problem 1 , parts (* 1 *) and (* 2 *)

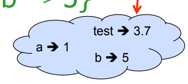
Local Variable Creation



// 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;;

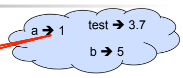


- : int = 40
// ρ_5 = ρ_3= {test → 3.7, a → 1, b → 5}
b;;



- : int = 5

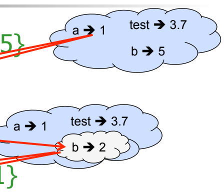
Local let binding



// ρ_5 = {test → 3.7, a → 1, b → 5}
let c =
let b = a + a
// ρ_6 = {b → 2} + ρ_3
// ={b → 2, test → 3.7, a → 1}
in b * b;;
val c : int = 4
// ρ_7 = {c → 4, test → 3.7, a → 1, b → 5}
b;;
- : int = 5

Local let binding

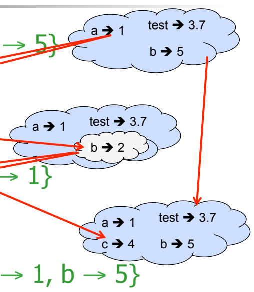
// ρ_5 = {test → 3.7, a → 1, b → 5}




```
# let c =
    let b = a + a
//  ρ6 = {b → 2} + ρ3
//       ={b → 2, test → 3.7, a → 1}
    in b * b;;
val c : int = 4
//  ρ7 = {c → 4, test → 3.7, a → 1, b → 5}
# b;;
- : int = 5
```


Local let binding

// ρ_5 = {test → 3.7, a → 1, b → 5}




```
# let c =
    let b = a + a
//  ρ6 = {b → 2} + ρ3
//       ={b → 2, test → 3.7, a → 1}
    in b * b;;
val c : int = 4
//  ρ7 = {c → 4, test → 3.7, a → 1, b → 5}
# b;;
- : int = 5
```


Now it's your turn

You should be able to do HW1 Problem 1 , parts (* 3 *) and (* 4 *)

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

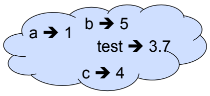
```
# 3 > 1 && 4 > 6;;
- : bool = false
# 3 > 1 || 4 > 6;;
- : bool = true
# (print_string "Hi\n"; 3 > 1) || 4 > 6;;
Hi
- : bool = true
# 3 > 1 || (print_string "Bye\n"; 4 > 6);;
- : bool = true
# not (4 > 6);;
- : bool = true
```


Now it's your turn

You should be able to do HW1 Problem 1 , part (* 5 *)

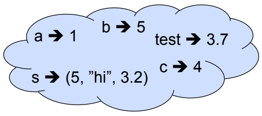
Tuples as Values

// ρ_7 = {c → 4, test → 3.7,
a → 1, b → 5}



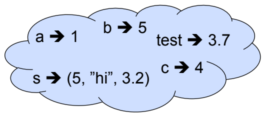
let s = (5,"hi",3.2);;
val s : int * string * float = (5, "hi", 3.2)

// ρ_8 = {s → (5, "hi", 3.2),
c → 4, test → 3.7,
a → 1, b → 5}

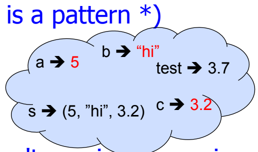


Pattern Matching with Tuples

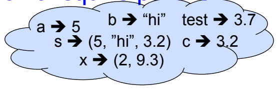
/ ρ_8 = {s → (5, "hi", 3.2),
c → 4, test → 3.7,
a → 1, b → 5}



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 HW1 Problem 1 , part (* 6 *)

Functions

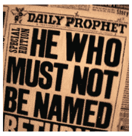
let plus_two n = n + 2;;
val plus_two : int -> int = <fun>
plus_two 17;;
- : int = 19

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;; → 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
```

x → 12 …

```
# plus_x 3;;
```

x → 7 …

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:

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

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

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 to do HW1 Problem 1 , parts (* 7 *) and (* 8 *)

Evaluation of Application of plus_x;;

- Have environment:

  ρ = {plus_x → <y → y + x, ρ_{plus_x} >, … ,
  y → 3, …}

  where ρ_{plus_x} = {x → 12, … , y → 24, …}
- Eval (plus_x y, ρ) rewrites to
- Eval (App <y → y + x, ρ_{plus_x} > 3, ρ) rewrites to
- Eval (y + x, {y → 3} +ρ_{plus_x}) rewrites to
- Eval (3 + 12 , ρ_{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);;
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:

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

- Environment just after plus_pair defined:

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

Evaluation of Application with Closures

- 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
- Evaluate the right term to values, $(v_1,\ldots,v_n)$
- Update the environment ρ to

  $\rho' = \{x_1 \to v_1,\ldots, x_n \to v_n\} + \rho$

- Evaluate body b in environment ρ'

Evaluation of Application of plus_pair

- Assume environment

$\rho = \{x \to 3\ldots,$
$plus\_pair \to <(n,m) \to n + m, \rho_{plus\_pair}>\} + \rho_{plus\_pair}$

- Eval (plus_pair (4,x), ρ)=
- Eval (App $<(n,m) \to n + m, \rho_{plus\_pair}>$ (4,x), ρ)) =
- Eval (App $<(n,m) \to n + m, \rho_{plus\_pair}>$ (4,3), ρ)) =
- Eval (n + m, {n -> 4, m -> 3} + ρ_{plus_pair}) =
- Eval (4 + 3, {n -> 4, m -> 3} + ρ_{plus_pair}) = 7

Closure question

- If we start in an empty environment, and we execute:

```
let f = fun => n + 5;;
(* 0 *)
let pair_map g (n,m) = (g n, g m);;
let f = pair_map f;;
```

What is the environment at (* 0 *)?

Answer

$\rho_0 = \{f \to <n \to n + 5, \{ \}>\}$

Closure question

- If we start in an empty environment, and we execute:

```
let f = fun => n + 5;;
let pair_map g (n,m) = (g n, g m);;
(* 1 *)
let f = pair_map f;;
```

What is the environment at (* 1 *)?

Answer

ρ_0 = {f → <n → n + 5, { }>}

let pair_map g (n,m) = (g n, g m);;

ρ_1 = {pair_map →

<g → fun (n,m) -> (g n, g m),

{f → <n → n + 5, { }>}>,

f → <n → n + 5, { }>}

Closure question

- If we start in an empty environment, and we execute:

```
let f = fun => n + 5;;
let pair_map g (n,m) = (g n, g m);;
let f = pair_map f;;
(* 2*)
```

What is the environment at (* 2 *)?

Answer

Curried vs Uncurried

- Recall

```
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_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>
```


Scoping Question

Consider this code:

```
let x = 27;;
let f x =
    let x = 5 in
        (fun x -> print_int x) 10;;
f 12;;
```

What value is printed?

5

10

12

27