Programming Languages and Compilers (CS 421)

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

Your turn now

Try steps 1 - 3 from WA0-practice

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

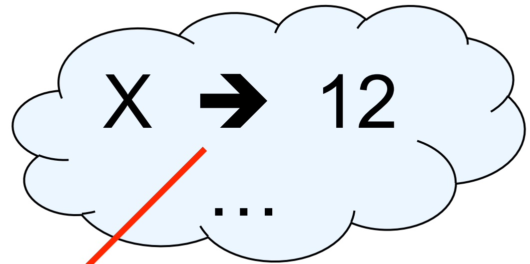
- # (fun x -> x * 3) 5;;   (* An application *)
- - : int = 15
- # ((fun y -> y +. 2.0), (fun z -> z * 3));;
  (* As data *)
- - : (float -> float) * (int -> int) = (<fun>, <fun>)

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
```

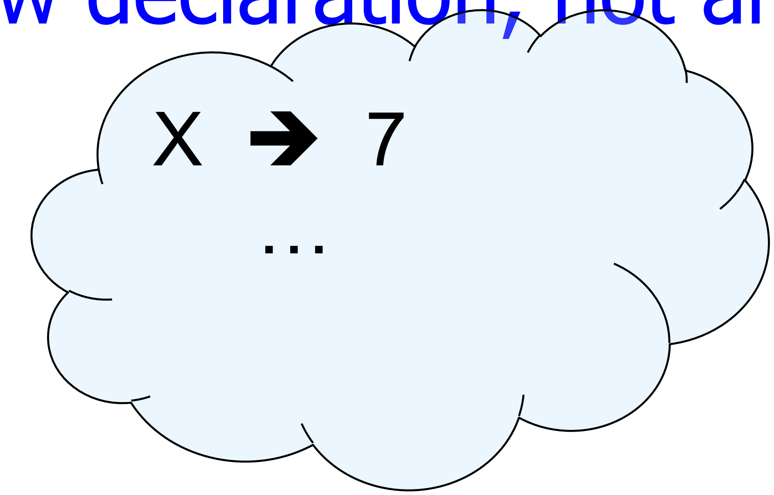
Values fixed at declaration time

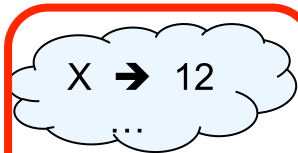
```
# let x = 7;;   (* New declaration, not an update *)
val x : int = 7

# 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:

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

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

Closure for plus_x

- When plus_x was defined, had environment:

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

- 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 remainder of WA0-practice

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

Recursive Functions

```
# let rec factorial n =
    if n = 0 then 1 else n * factorial (n - 1);;
  val factorial : int -> int = <fun>
# factorial 5;;
- : int = 120
# (* rec  is needed for recursive function
   declarations *)
```

Recursion Example

Compute n^2 recursively using:

$$n^2 = (2 * n - 1) + (n - 1)^2$$

```
# let rec nthsq n =           (* rec for recursion *)
   match n                    (* pattern matching for cases *)
   with 0 -> 0                (* base case *)
   | n -> (2 * n -1)          (* recursive case *)
        + nthsq (n -1);;      (* recursive call *)
val nthsq : int -> int = <fun>
# nthsq 3;;
- : int = 9
```

Structure of recursion similar to inductive proof

Recursion and Induction

```
# let rec nthsq n = match n with 0 -> 0
      | n -> (2 * n - 1) + nthsq (n - 1) ;;
```

- Base case is the last case; it stops the computation
- Recursive call must be to arguments that are somehow smaller - must progress to base case
- **if** or **match** must contain base case
- Failure of these may cause failure of termination

Lists

- First example of a recursive datatype (aka algebraic datatype)

- Unlike tuples, lists are homogeneous in type (all elements same type)

Lists

- List can take one of two forms:
  - Empty list, written [ ]
  - Non-empty list, written x :: xs
    - x is head element, xs is tail list, :: called "cons"
  - Syntactic sugar: [x] == x :: [ ]
  - [x1; x2; …; xn] == x1 :: x2 :: … :: xn :: [ ]

Lists

```
# let fib5 = [8;5;3;2;1;1];;
val fib5 : int list = [8; 5; 3; 2; 1; 1]
# let fib6 = 13 :: fib5;;
val fib6 : int list = [13; 8; 5; 3; 2; 1; 1]
# (8::5::3::2::1::1::[ ]) = fib5;;
- : bool = true
# fib5 @ fib6;;
- : int list = [8; 5; 3; 2; 1; 1; 13; 8; 5; 3; 2; 1;
  1]
```

Lists are Homogeneous

```
# let bad_list = [1; 3.2; 7];;
Characters 19-22:
  let bad_list = [1; 3.2; 7];;
                     ^^^
This expression has type float but is here
  used with type int
```

Question

- Which one of these lists is invalid?

1. [2; 3; 4; 6]
2. [2,3; 4,5; 6,7]
3. [(2.3,4); (3.2,5); (6,7.2)]
4. [[“hi”; “there”]; [“wahcha”]; [ ]; [“doin”]]

Answer

- Which one of these lists is invalid?

1. [2; 3; 4; 6]
2. [2,3; 4,5; 6,7]
3. [(2.3,4); (3.2,5); (6,7.2)]
4. [[“hi”; “there”]; [“wahcha”]; [ ]; [“doin”]]

- 3 is invalid because of last pair

Functions Over Lists

```
# let rec double_up list =
    match list
    with [ ] -> [ ]  (* pattern before ->,
                        expression after *)
        | (x :: xs) -> (x :: x :: double_up xs);;
val double_up : 'a list -> 'a list = <fun>
# let fib5_2 = double_up fib5;;
val fib5_2 : int list = [8; 8; 5; 5; 3; 3; 2; 2; 1;
  1; 1; 1]
```

Functions Over Lists

```
# let silly = double_up ["hi"; "there"];;
val silly : string list = ["hi"; "hi"; "there"; "there"]
# let rec poor_rev list =
  match list
  with [] -> []
     | (x::xs) -> poor_rev xs @ [x];;
val poor_rev : 'a list -> 'a list = <fun>
# poor_rev silly;;
- : string list = ["there"; "there"; "hi"; "hi"]
```

Question: Length of list

- Problem: write code for the length of the list
  - How to start?

```
let length l =
```

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let rec length l =
   match l with
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  - What patterns should we match against?

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Question: Length of list

- Problem: write code for the length of the list
  - What patterns should we match against?

```
let rec length l =
   match l with [] ->
    | (a :: bs) ->
```

Question: Length of list

- Problem: write code for the length of the list
  - What result do we give when l is empty?

```
let rec length l =
    match l with [] -> 0
     | (a :: bs) ->
```

Question: Length of list

- Problem: write code for the length of the list
  - What result do we give when l is not empty?

```
let rec length l =
    match l with [] -> 0
     | (a :: bs) ->
```

Question: Length of list

- Problem: write code for the length of the list
  - What result do we give when l is not empty?

```
let rec length l =
    match l with [] -> 0
     | (a :: bs) -> 1 + length bs
```

Same Length

- How can we efficiently answer if two lists have the same length?

Same Length

- How can we efficiently answer if two lists have the same length?

```
let rec same_length list1 list2 =
   match list1 with [] ->
     (match list2 with [] -> true
       | (y::ys) -> false)
   | (x::xs) ->
     (match list2 with [] -> false
       | (y::ys) -> same_length xs ys)
```

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")
```

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:

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

Warm-up 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

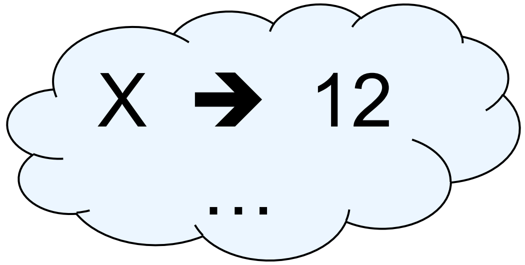
10

12

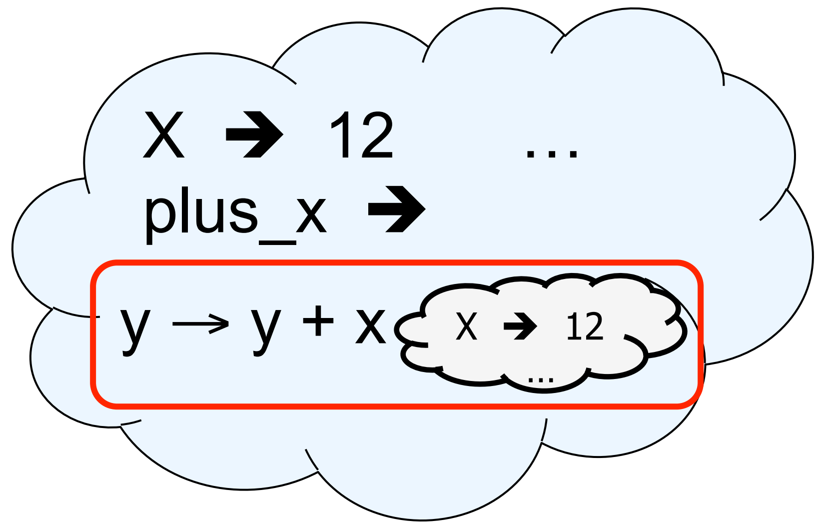
27

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

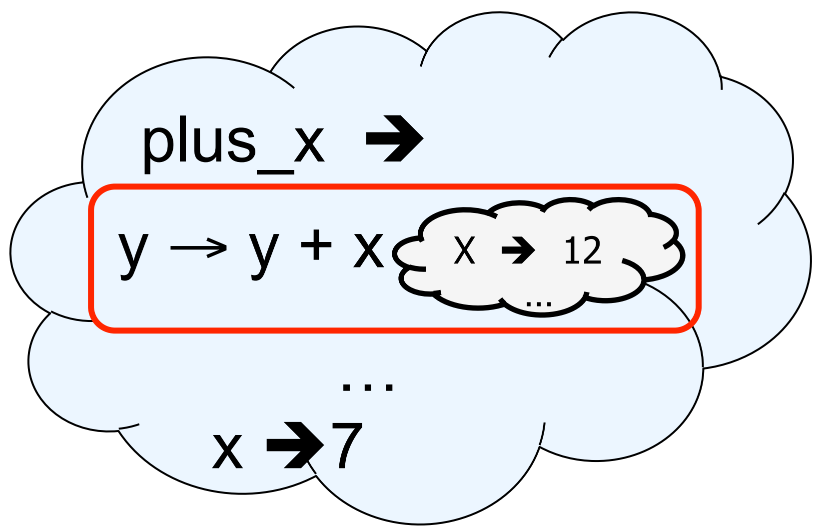
let x = 12



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:

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

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")
```

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)

Closure for plus_pair

- Assume ρ_{plus_pair} was the environment just before plus_pair defined
- Closure for fun (n,m) -> n + m:

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

- Environment just after plus_pair defined:

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

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

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>
```

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
```

Your turn now

Try later parts from WA1

Caution!

Know what the argument is and what the body is

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!"
```

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 → 2, y → 3, a → "hi"} + {y → 100, b → 6}

= {x → 2, y → 3, a → "hi", b → 6}

Evaluating expressions

- Evaluation uses an environment ρ
- A constant evaluates to itself
- To evaluate an variable, look it up in ρ ($\rho(v)$)
- 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, eval e2 using $\{x \to v\} + \rho$

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 value $(v_1,\ldots,v_n)$
- 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_x;;

- Have environment:

  $\rho = \{plus\_x \rightarrow$ <$y \rightarrow y + x, \rho_{plus\_x}$ >$, \ldots ,$
  $y \rightarrow 3, \ldots\}$

  where $\rho_{plus\_x} = \{x \rightarrow 12, \ldots\}$
- Eval (plus_x y, ρ) rewrites to
- App (<$y \rightarrow y + x, \rho_{plus\_x}$ >, 3) rewrites to
- Eval ($y + x, \{y \rightarrow 3\} + \rho_{plus\_x}$) rewrites to
- Eval ($3 + 12 , \rho_{plus\_x}$) = 15

Evaluation of Application of plus_pair

- Assume environment

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

- Eval (plus_pair (4,x), ρ)=
- App (<(n,m) $\rightarrow$n + m, ρ_{plus_pair}>, (4,3)) =
- 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 -> n + 5;;
(* 0 *)
let pair_map g (n,m) = (g n, g m);;
let f = pair_map f;;
let a = f (4,6);;
```

What is the environment at (* 0 *)?

Answer

let f = fun n -> n + 5;;

ρ_0 = {f $\rightarrow$ <n $\rightarrow$ 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;;
let a = f (4,6);;
```

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 *)
let a = f (4,6);;
```

What is the environment at (* 2 *)?

Evaluate pair_map f

ρ_0 = {f → <n → n + 5, { }>}

ρ_1 = {pair_map →<g→fun (n,m) -> (g n, g m), ρ_0>,
f→<n → n + 5, { }>}

let f = pair_map f;;

Evaluate pair_map f

ρ_0 = {f → <n → n + 5, { }>}

ρ_1 = {pair_map →<g→fun (n,m) -> (g n, g m), ρ_0>,

f→<n → n + 5, { }>}

Eval(pair_map f, ρ_1) =

Evaluate pair_map f

ρ_0 = {f → <n → n + 5, { }>}

ρ_1 = {pair_map →<g→fun (n,m) -> (g n, g m), ρ_0>,

f→<n → n + 5, { }>}

Eval(pair_map f, ρ_1) =

App (<g→fun (n,m) -> (g n, g m), ρ_0>,

<n → n + 5, { }>) =

Evaluate pair_map f

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

$\rho_1 = \{pair\_map \rightarrow <g \rightarrow fun\ (n,m) \text{ -> } (g\ n, g\ m), \rho_0>,$
$\quad f \rightarrow <n \rightarrow n + 5, \{\ \}>\}$

$Eval(pair\_map\ f, \rho_1) =$

$App\ (<g \rightarrow fun\ (n,m) \text{ -> } (g\ n, g\ m), \rho_0>,$
$\quad <n \rightarrow n + 5, \{\ \}>) =$

$Eval(fun\ (n,m)\text{->}(g\ n, g\ m), \{g \rightarrow <n \rightarrow n + 5, \{\ \}>\} + \rho_0)$

$= <(n,m) \rightarrow (g\ n, g\ m), \{g \rightarrow <n \rightarrow n + 5, \{\ \}>\} + \rho_0>$

$= <(n,m) \rightarrow (g\ n, g\ m), \{g \rightarrow <n \rightarrow n + 5, \{\ \}>$
$\quad f \rightarrow <n \rightarrow n + 5, \{\ \}>\}$

Answer

ρ_1 = {pair_map →
<g → fun (n,m) -> (g n, g m),{f → <n → n + 5, { }>}>,
f → <n → n + 5, { }>}

let f = pair_map f;;

ρ_2 = {f → <(n,m) →(g n, g m),
{g → <n → n + 5, { }>,
f → <n → n + 5, { }>}>,
pair_map → <g → fun (n,m) -> (g n, g m),
{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;;
let a = f (4,6);;
```

(* 3 *)

What is the environment at (* 3 *)?

Final Evalution?

```
ρ2 = {f → <(n,m) →(g n, g m),
              {g → <n → n + 5, { }>,
               f → <n → n + 5, { }>}>,
      pair_map → <g →  fun (n,m) -> (g n, g m),
                      {f → <n → n + 5, { }>}>}
let a = f (4,6);;
```

Evaluate f (4,6);;

ρ_2 = {f → <(n,m) →(g n, g m),

{g → <n → n + 5, { }>,

f → <n → n + 5, { }>}>,

pair_map → <g → fun (n,m) -> (g n, g m),

{f → <n → n + 5, { }>}>}

Eval(f (4,6), ρ_2) =

Evaluate f (4,6);;

ρ_2 = {f → <(n,m) →(g n, g m),
{g → <n → n + 5, { }>,
f → <n → n + 5, { }>}>,
pair_map → <g → fun (n,m) -> (g n, g m),
{f → <n → n + 5, { }>}>}

Eval(f (4,6), ρ_2) =

App(<(n,m) →(g n, g m), {g → <n → n + 5, { }>,
f → <n → n + 5, { }>}>,
(4,6)) =

Evaluate f (4,6);;

App(<(n,m) →(g n, g m), {g → <n → n + 5, { }>,
f → <n → n + 5, { }>}>,
(4,6)) =

Eval((g n, g m), {n → 4, m → 6} +
{g → <n → n + 5, { }>,
f → <n → n + 5, { }>}) =

Eval((App(<n → n + 5, { }>, 4),
App (<n → n + 5, { }>, 6)),
{n → 4, m → 6, g → <n → n + 5, { }>,
f → <n → n + 5, { }>}) =

Evaluate f (4,6);;

$\rho_3 = \{n \to 4, m \to 6, g \to <n \to n + 5, \{\ \}>, f \to <n \to n + 5, \{\ \}>\})$

$\text{Eval}((\text{App}(<n \to n + 5, \{\ \}>, 4), \text{App}(<n \to n + 5, \{\ \}>, 6)), \rho_3) =$

$\text{Eval}((\text{Eval}(n + 5, \{n \to 4\} + \{\ \}), (\text{Eval}(n + 5, \{n \to 6\} + \{\ \})), \rho_3) =$

$\text{Eval}((\text{Eval}(4 + 5, \{n \to 4\} + \{\ \}), (\text{Eval}(6 + 5, \{n \to 6\} + \{\ \})), \rho_3) =$

$\text{Eval}((9, 11), \rho_3) = (9, 11)$

Higher Order Functions

- A function is *higher-order* if it takes a function as an argument or returns one as a result
- Example:

```
# let compose f g = fun x -> f (g x);;
val compose : ('a -> 'b) -> ('c -> 'a) -> 'c ->
  'b = <fun>
```

- The type ('a -> 'b) -> ('c -> 'a) -> 'c -> 'b is a higher order type because of ('a -> 'b) and ('c -> 'a) and -> 'c -> 'b

Thrice

- Recall:

```
# let thrice f x = f (f (f x));;
val thrice : ('a -> 'a) -> 'a -> 'a = <fun>
```

- How do you write thrice with compose?

Thrice

- Recall:

```
# let thrice f x = f (f (f x));;
val thrice : ('a -> 'a) -> 'a -> 'a = <fun>
```

- How do you write thrice with compose?

```
# let thrice f = compose f (compose f f);;
val thrice : ('a -> 'a) -> 'a -> 'a = <fun>
```

- Is this the only way?

Partial Application

```
# (+);;
- : int -> int -> int = <fun>
# (+) 2 3;;
- : int = 5
# let plus_two = (+) 2;;
val plus_two : int -> int = <fun>
# plus_two 7;;
- : int = 9
```

- Patial application also called *sectioning*

Lambda Lifting

- You must remember the rules for evaluation when you use partial application

```
# let add_two = (+) (print_string "test\n"; 2);;
test
val add_two : int -> int = <fun>
# let add2 =      (* lambda lifted *)
   fun x -> (+) (print_string "test\n"; 2) x;;
val add2 : int -> int = <fun>
```

Lambda Lifting

```
# thrice add_two 5;;
- : int = 11
# thrice add2 5;;
test
test
test
- : int = 11
```

- Lambda lifting delayed the evaluation of the argument to (+) until the second argument was supplied

Partial Application and “Unknown Types”

- Recall compose plus_two:

```
# let f1 = compose plus_two;;
val f1 : ('_a -> int) -> '_a -> int = <fun>
```

- Compare to lambda lifted version:

```
# let f2 = fun g -> compose plus_two g;;
val f2 : ('a -> int) -> 'a -> int = <fun>
```

- What is the difference?

Partial Application and "Unknown Types"

- '_a can only be instantiated once for an expression

```
# f1 plus_two;;
- : int -> int = <fun>
# f1 List.length;;
Characters 3-14:
  f1 List.length;;
     ^^^^^^^^^^^
This expression has type 'a list -> int but is here used
   with type int -> int
```

Partial Application and "Unknown Types"

- 'a can be repeatedly instantiated

```
# f2 plus_two;;
- : int -> int = <fun>
# f2 List.length;;
- : '_a list -> int = <fun>
```

Functions Over Lists

```
# let rec map f list =
  match list
  with [] -> []
  | (h::t) -> (f h) :: (map f t);;
val map : ('a -> 'b) -> 'a list -> 'b list = <fun>
# map plus_two fib5;;
- : int list = [10; 7; 5; 4; 3; 3]
# map (fun x -> x - 1) fib6;;
: int list = [12; 7; 4; 2; 1; 0; 0]
```

Iterating over lists

```
# let rec fold_left f a list =
  match list
  with [] -> a
  | (x :: xs) -> fold_left f (f a x) xs;;
val fold_left : ('a -> 'b -> 'a) -> 'a -> 'b list -> 'a =
   <fun>
# fold_left
   (fun () -> print_string)
   ()
   ["hi"; "there"];;
hithere- : unit = ()
```

Iterating over lists

```
# let rec fold_right f list b =
  match list
  with [] -> b
  | (x :: xs) -> f x (fold_right f xs b);;
val fold_right : ('a -> 'b -> 'b) -> 'a list -> 'b -> 'b =
   <fun>
# fold_right
    (fun s -> fun () -> print_string s)
    ["hi"; "there"]
    ();;
therehi- : unit = ()
```

Structural Recursion

- Functions on recursive datatypes (eg lists) tend to be recursive
- Recursion over recursive datatypes generally by structural recursion
  - Recursive calls made to components of structure of the same recursive type
  - Base cases of recursive types stop the recursion of the function

Structural Recursion : List Example

```
# let rec length list = match list
  with [ ] -> 0   (* Nil case *)
  | x :: xs -> 1 + length xs;;  (* Cons case *)
val length : 'a list -> int = <fun>
# length [5; 4; 3; 2];;
- : int = 4
```

- Nil case [ ] is base case
- Cons case recurses on component list xs

Forward Recursion

- In Structural Recursion, split input into components and (eventually) recurse
- Forward Recursion form of Structural Recursion
- In forward recursion, first call the function recursively on all recursive components, and then build final result from partial results
- Wait until whole structure has been traversed to start building answer

Forward Recursion: Examples

```
# let rec double_up list =
    match list
    with [ ] -> [ ]
       | (x :: xs) -> (x :: x :: double_up xs);;
val double_up : 'a list -> 'a list = <fun>

# let rec poor_rev list =
  match list
  with [] -> []
     | (x::xs) -> poor_rev xs @ [x];;
val poor_rev : 'a list -> 'a list = <fun>
```

Encoding Recursion with Fold

```
# let rec append list1 list2 = match list1 with
  [ ] -> list2 | x::xs -> x :: append xs list2;;
val append : 'a list -> 'a list -> 'a list = <fun>
```

Base Case | Operation | Recursive Call

```
# let append list1 list2 =
   fold_right (fun x y -> x :: y) list1 list2;;
val append : 'a list -> 'a list -> 'a list = <fun>
# append [1;2;3] [4;5;6];;
 - : int list = [1; 2; 3; 4; 5; 6]
```

Mapping Recursion

- One common form of structural recursion applies a function to each element in the structure

```
# let rec doubleList list = match list
   with [ ] -> [ ]
   | x::xs -> 2 * x :: doubleList xs;;
val doubleList : int list -> int list = <fun>
# doubleList [2;3;4];;
- : int list = [4; 6; 8]
```

Mapping Recursion

- Can use the higher-order recursive map function instead of direct recursion

```
# let doubleList list =
    List.map (fun x -> 2 * x) list;;
val doubleList : int list -> int list = <fun>
# doubleList [2;3;4];;
- : int list = [4; 6; 8]
```

- Same function, but no rec

Folding Recursion

- Another common form “folds” an operation over the elements of the structure

```
# let rec multList list = match list
  with [ ] -> 1
  | x::xs -> x * multList xs;;
val multList : int list -> int = <fun>
# multList [2;4;6];;
- : int = 48
```

- Computes (2 * (4 * (6 * 1)))

Folding Recursion

- multList folds to the right
- Same as:

```
# let multList list =
    List.fold_right
    (fun x -> fun p -> x * p)
    list 1;;
val multList : int list -> int = <fun>
# multList [2;4;6];;
- : int = 48
```

How long will it take?

- Remember the big-O notation from CS 225 and CS 273
- Question: given input of size *n*, how long to generate output?
- Express output time in terms of input size, omit constants and take biggest power

How long will it take?

Common big-O times:

- Constant time $O(1)$
  - input size doesn't matter
- Linear time $O(n)$
  - double input $\Rightarrow$ double time
- Quadratic time $O(n^2)$
  - double input $\Rightarrow$ quadruple time
- Exponential time $O(2^n)$
  - increment input $\Rightarrow$ double time

Linear Time

- Expect most list operations to take linear time $O(n)$
- Each step of the recursion can be done in constant time
- Each step makes only one recursive call
- List example: multList, append
- Integer example: factorial

Quadratic Time

- Each step of the recursion takes time proportional to input
- Each step of the recursion makes only one recursive call.
- List example:

```
# let rec poor_rev list = match list
  with [] -> []
     | (x::xs) -> poor_rev xs @ [x];;
val poor_rev : 'a list -> 'a list = <fun>
```

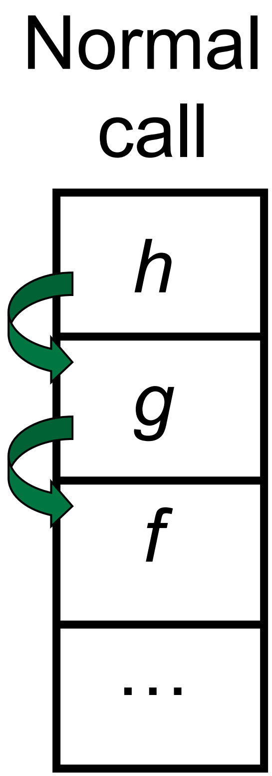
Exponential running time

- Hideous running times on input of any size
- Each step of recursion takes constant time
- Each recursion makes two recursive calls
- Easy to write naïve code that is exponential for functions that can be linear

Exponential running time

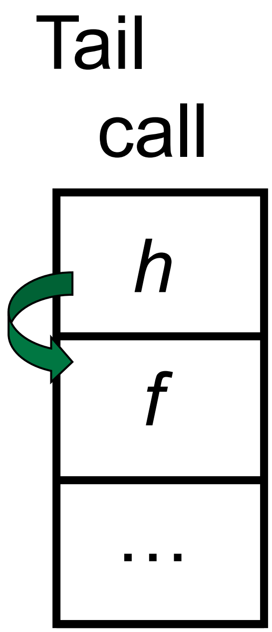
```
# let rec naiveFib n = match n
  with 0 -> 0
  | 1 -> 1
  | _ -> naiveFib (n-1) + naiveFib (n-2);;
val naiveFib : int -> int = <fun>
```

An Important Optimization



- When a function call is made, the return address needs to be saved to the stack so we know to where to return when the call is finished
- What if *f* calls *g* and *g* calls *h*, but calling *h* is the last thing *g* does (a *tail call*)?

An Important Optimization



- When a function call is made, the return address needs to be saved to the stack so we know to where to return when the call is finished
- What if *f* calls *g* and *g* calls *h*, but calling *h* is the last thing *g* does (a *tail call*)?
- Then *h* can return directly to *f* instead of *g*

Tail Recursion

- A recursive program is tail recursive if all recursive calls are tail calls
- Tail recursive programs may be optimized to be implemented as loops, thus removing the function call overhead for the recursive calls
- Tail recursion generally requires extra “accumulator” arguments to pass partial results
  - May require an auxiliary function

Tail Recursion - Example

```
# let rec rev_aux list revlist =
  match list with [ ] -> revlist
  | x :: xs -> rev_aux xs (x::revlist);;
val rev_aux : 'a list -> 'a list -> 'a list = <fun>

# let rev list = rev_aux list [ ];;
val rev : 'a list -> 'a list = <fun>
```

- What is its running time?

Comparison

- poor_rev [1,2,3] =
- (poor_rev [2,3]) @ [1] =
- ((poor_rev [3]) @ [2]) @ [1] =
- (((poor_rev [ ]) @ [3]) @ [2]) @ [1] =
- (([ ] @ [3]) @ [2]) @ [1]) =
- ([3] @ [2]) @ [1] =
- (3:: ([ ] @ [2])) @ [1] =
- [3,2] @ [1] =
- 3 :: ([2] @ [1]) =
- 3 :: (2:: ([ ] @ [1])) = [3, 2, 1]

Comparison

- rev [1,2,3] =
- rev_aux [1,2,3] [ ] =
- rev_aux [2,3] [1] =
- rev_aux [3] [2,1] =
- rev_aux [ ] [3,2,1] = [3,2,1]

Folding Functions over Lists

How are the following functions similar?

```
# let rec sumlist list = match list with
  [ ] -> 0 | x::xs -> x + sumlist xs;;
val sumlist : int list -> int = <fun>
# sumlist [2;3;4];;
- : int = 9
# let rec prodlist list = match list with
  [ ] -> 1 | x::xs -> x * prodlist xs;;
val prodlist : int list -> int = <fun>
# prodlist [2;3;4];;
- : int = 24
```

Folding

```
# let rec fold_left f a list = match list
  with [] -> a | (x :: xs) -> fold_left f (f a x) xs;;
val fold_left : ('a -> 'b -> 'a) -> 'a -> 'b list -> 'a =
  <fun>
```

fold_left f a [x_1; x_2;…;x_n] = f(…(f (f a x_1) x_2)…)x_n

```
# let rec fold_right f list b = match list
  with [ ] -> b | (x :: xs) -> f x (fold_right f xs b);;
val fold_right : ('a -> 'b -> 'b) -> 'a list -> 'b -> 'b =
  <fun>
```

fold_right f [x_1; x_2;…;x_n] b = f x_1(f x_2 (…(f x_n b)…))

Folding - Forward Recursion

```
# let sumlist list = fold_right (+) list 0;;
val sumlist : int list -> int = <fun>
# sumlist [2;3;4];;
- : int = 9
# let prodlist list = fold_right ( * ) list 1;;
val prodlist : int list -> int = <fun>
# prodlist [2;3;4];;
- : int = 24
```

Folding - Tail Recursion

```
# let rev list =
        fold_left
          (fun l -> fun x -> x :: l)     //comb op
         []                 //accumulator cell
         list
```

Folding

- Can replace recursion by fold_right in any forward primitive recursive definition
  - Primitive recursive means it only recurses on immediate subcomponents of recursive data structure
- Can replace recursion by fold_left in any tail primitive recursive definition