Programming Languages and Compilers (CS 421)

Elsa L Gunter

2112 SC, UIUC

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

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

Booleans (aka Truth Values)

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

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

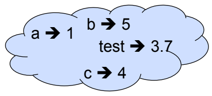
```
# if b > a then 25 else 0;;
- : int = 25
```


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
```

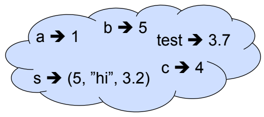

Tuples as Values

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



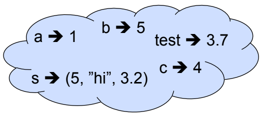

```
# let s = (5,"hi",3.2);;
val s : int * string * float = (5, "hi", 3.2)
```

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

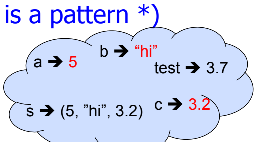


Pattern Matching with Tuples

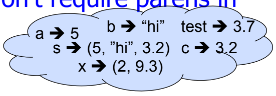
/ $\rho_8 = \{s \rightarrow (5, \text{"hi"}, 3.2), c \rightarrow 4, test \rightarrow 3.7, a \rightarrow 1, b \rightarrow 5\}$




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




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



Nested Tuples

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

Functions on tuples

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


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>

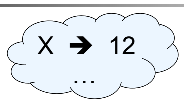
Partial application of functions

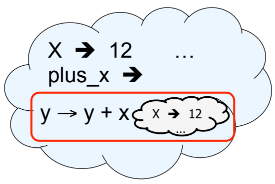
let add_three x y z = x + y + z;;

let h = add_three 5 4;;
val h : int -> int = <fun>
h 3;;
- : int = 12
h 7;;
- : int = 16
- Partial application also called *sectioning*

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

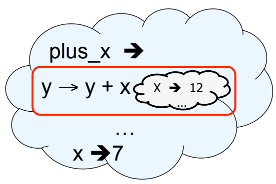
let x = 12





let plus_x = fun y => y + x

let x = 7



Closure for plus_x

- When plus_x was defined, had environment:

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

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

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: $\{x \rightarrow v\} + \rho$
- 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 $\{x \rightarrow v\} + \rho$

Evaluation of Application with Closures

- Given application expression $f(e_1,\ldots,e_n)$
- In environment ρ, evaluate left term to closure, $c = <(x_1,\ldots,x_n) \rightarrow b, \rho>$
- $(x_1,\ldots,x_n)$ variables in (first) argument
- Evaluate $(e_1,\ldots,e_n)$ to value $(v_1,\ldots,v_n)$
- Update the environment ρ to

  $\rho' = \{x_1 \rightarrow v_1,\ldots, x_n \rightarrow v_n\} + \rho$
- 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 $\rho_{plus\_x} = \{x \rightarrow 12, \ldots , y \rightarrow 24, \ldots\}$
- Eval (plus_x y, ρ) rewrites to
- App (Eval(plus_x, ρ) , Eval(y, ρ)) rewrites to
- App (<y $\rightarrow$ y + x, ρ_{plus_x} >, 3) rewrites to
- Eval (y + x, {y $\rightarrow$ 3} +ρ_{plus_x}) rewrites to
- Eval (3 + 12 , ρ_{plus_x}) = 15

Evaluation of Application of plus_pair

- Assume environment

$\rho = \{x \rightarrow 3\ldots,$
plus_pair $\rightarrow$<(n,m) $\rightarrow$n + m, ρ_{plus_pair}>} +
ρ_{plus_pair}

- Eval (plus_pair (4,x), ρ)=
- App (Eval (plus_pair, ρ), Eval ((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;;

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

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

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, { }>) =

Eval(fun (n,m)->(g n, g m), {g→<n→n + 5, { }>}+ρ_0)

=<(n,m) →(g n, g m), {g→<n→n + 5, { }>}+ρ_0>

=<(n,m) →(g n, g m), {g→<n→n + 5, { }>
f→<n→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?

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, { }>}>}

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, { }>}) =

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

Evaluate f (4,6);;

(App(<n → n + 5, { }>, 4),
App (<n → n + 5, { }>, 6)) =
(Eval(n + 5, {n → 4} + { }),
Eval(n + 5, {n → 6} + { })) =
(Eval(4 + 5, {n → 4} + { }),
Eval(6 + 5, {n → 6} + { })) = (9, 11)

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!"
```


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?

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>
```


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 =

Question: Length of list

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

```
let rec length l =
   match l with
```

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
```


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 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

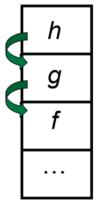
- Hideous running times on input of any size
- Each step of recursion takes constant time
- Each recursion makes two recursive calls
- Easy to write naïve code that is exponential for functions that can be linear

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

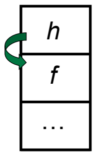
Normal call



- 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

Tail call



- 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>
```

$\boxed{\text{fold\_left f a } [x_1; x_2;\ldots;x_n] = \text{f}(\ldots(\text{f } (\text{f a } x_1)\ x_2)\ldots)x_n}$

```
# 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>
```

$\boxed{\text{fold\_right f } [x_1; x_2;\ldots;x_n] \text{ b} = \text{f } x_1(\text{f } x_2 (\ldots(\text{f } x_n \text{ b})\ldots))}$

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