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
Mapping 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]
One common form of structural recursion applies a function to each element in the structure.

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

```ocaml
# doubleList [2;3;4];;
- : int list = [4; 6; 8]
```
Mapping Recursion

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

```ocaml
# 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 explicit rec
Your turn now

Try Problem 1 on MP4
Folding Recursion

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

```ocaml
# 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 \((2 \times (4 \times (6 \times 1)))\)
Folding Functions over Lists

How are the following functions similar?

```ml
# 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 multList list = match list with
  [ ] -> 1 | x::xs -> x * multList xs;;
val multList : int list -> int = <fun>
# multList [2;3;4];;
- : int = 24
```
Folding Functions over Lists

How are the following functions similar?

```ocaml
# 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
```

```ocaml
# let rec multList list = match list with
  [ ] -> 1 | x::xs -> x * multList xs;;
val multList : int list -> int = <fun>
# multList [2;3;4];;
- : int = 24
```
Folding Functions over Lists

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- : int = 9
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    [ ] -> 1 | x::xs -> x * multList xs ;;
val multList : int list -> int = <fun>
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Folding Functions over Lists

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```ocaml
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How are the following functions similar?

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val sumList : int list -> int = <fun>
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  [ ] -> 1 | x::xs -> x * multList xs;;
val multList : int list -> int = <fun>
# multList [2;3;4];;
- : int = 24
```

Combing Operation
Folding Functions over Lists

How are the following functions similar?

```ocaml
# 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 multList list = match list with
   [ ] -> 1 | x::xs -> x * multList xs;;
val multList : int list -> int = <fun>
# multList [2;3;4];;
- : int = 24
```

Rec value

Combing Operation
Recursing over lists

```ocaml
# 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 = ()
```

The Primitive Recursion Fairy
Folding Recursion

- multList folds to the right
- Same as:

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

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

# let append list1 list2 =
    fold_right (fun x rv -> x :: rv) 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]
```
Your turn now

Try Problem 2 on MP4
let rec length l =
  match l with [] -> 0
  | (a :: bs) -> 1 + length bs

How do you write length with fold_right, but no explicit recursion?
Question

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

How do you write length with fold_right, but no explicit recursion?

let length list =
    List.fold_right (fun x -> fun n -> n + 1) list 0
Map from Fold

```ocaml
# let map f list =
    fold_right (fun x -> fun y -> f x :: y) list
[ ];;
val map : ('a -> 'b) -> 'a list -> 'b list = <fun>

# map ((+)1) [1;2;3];;
- : int list = [2; 3; 4]
```

Can you write fold_right (or fold_left) with just map? How, or why not?
Iterating over lists

```ocaml
# 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 = ()
```
Encoding Tail Recursion with fold_left

```ocaml
# let prod list = let rec prod_aux l acc =
  match l with [] -> acc
  | (y :: rest) -> prod_aux rest (acc * y)
  in prod_aux list 1;;
val prod : int list -> int = <fun>
Init Acc Value
Recursive Call
Operation

# let prod list =
  List.fold_left (fun acc y -> acc * y) 1 list;;
val prod : int list -> int = <fun>

# prod [4;5;6];;
- : int = 120
```
Your turn now

Try Problem 3 on MP4
Question

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

How do you write length with fold_left, but no explicit recursion?
Question

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

- How do you write length with fold_left, but no explicit recursion?

```ocaml
let length list = List.fold_left (fun n -> fun x -> n + 1) 0 list
```
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 [x₁; x₂;...;xₙ] = f(...f (f a x₁) x₂)...xₙ

# 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 [x₁; x₂;...;xₙ] b = f x₁(f x₂(...(f xₙ b)...))
Recall

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

What is its running time?
Quadratic Time

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

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

```ocaml
# 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

- \text{rev} [1,2,3] = 
- \text{rev\_aux} [1,2,3] [ ] = 
- \text{rev\_aux} [2,3] [1] = 
- \text{rev\_aux} [3] [2,1] = 
- \text{rev\_aux} [ ] [3,2,1] = [3,2,1]
Folding - Tail Recursion

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

- A programming technique for all forms of “non-local” control flow:
  - non-local jumps
  - exceptions
  - general conversion of non-tail calls to tail calls
- Essentially it’s a higher-order function version of GOTO
Continuations

- Idea: Use functions to represent the control flow of a program

- Method: Each procedure takes a function as an extra argument to which to pass its result; outer procedure “returns” no result

- Function receiving the result called a continuation

- Continuation acts as “accumulator” for work still to be done
Continuation Passing Style

- Writing procedures such that all procedure calls take a continuation to which to give (pass) the result, and return no result, is called continuation passing style (CPS)
Continuation Passing Style

- A compilation technique to implement non-local control flow, especially useful in interpreters.

- A formalization of non-local control flow in denotational semantics

- Possible intermediate state in compiling functional code
Why CPS?

- Makes order of evaluation explicitly clear
- Allocates variables (to become registers) for each step of computation
- Essentially converts functional programs into imperative ones
  - Major step for compiling to assembly or byte code
- Tail recursion easily identified
- Strict forward recursion converted to tail recursion
  - At the expense of building large closures in heap
Example

- Simple reporting continuation:
  ``` OCaml
  # let report x = (print_int x; print_newline( ));
  val report : int -> unit = <fun>
  ```

- Simple function using a continuation:
  ``` OCaml
  # let addk a b k = k (a + b);
  val addk : int -> int -> (int -> 'a) -> 'a = <fun>
  # addk 22 20 report;
  2
  - : unit = ()
  ```
Simple Functions Taking Continuations

- Given a primitive operation, can convert it to pass its result forward to a continuation
- Examples:
  # let subk x y k = k(x + y);;
  val timesk : int -> int -> (int -> 'a) -> 'a = <fun>
  # let eqk x y k = k(x = y);;
  val eqk : 'a -> 'a -> (bool -> 'b) -> 'b = <fun>
  # let timesk x y k = k(x * y);;
  val timesk : int -> int -> (int -> 'a) -> 'a = <fun>
Your turn now

Try Problem 5 on MP4

Try modk
Nesting Continuations

# let add_three x y z = (x + y) + z;;
val add_three : int -> int -> int -> int = <fun>

# let add_three x y z = let p = x + y in p + z;;
val add_three : int -> int -> int -> int = <fun>

# let add_three_k x y z k =
  addk x y (fun p -> addk p z k k);;
val add_three_k : int -> int -> int -> int -> (int -> 'a) -> 'a = <fun>

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add_three: a different order

- # let add_three x y z = x + (y + z);;
- How do we write add_three_k to use a different order?

- let add_three_k x y z k =
Your turn now

Try Problem 6 on MP4
Recall:

```ocaml
# let rec factorial n = 
    if n = 0 then 1 else n * factorial (n - 1);;
val factorial : int -> int = <fun>
# factorial 5;;
- : int = 120
```
Recursive Functions

```ocaml
# let rec factorial n =
    let b = (n = 0) in (* First computation *)
    if b then 1 (* Returned value *)
    else let s = n – 1 in (* Second computation *)
        let r = factorial s in (* Third computation *)
        n * r in (* Returned value *) ;;
val factorial : int -> int = <fun>
#
```

```
# factorial 5;;
- : int = 120
```
Recursive Functions

```ocaml
# let rec factorialk n k =
  eqk n 0
  (fun b -> (* First computation *)
    if b then k 1 (* Passed value *)
    else subk n 1 (* Second computation *)
    (fun s -> factorialk s (* Third computation *)
     (fun r -> timesk n r k))) (* Passed value *)
val factorialk : int -> int = <fun>
# factorialk 5 report;;
120
- : unit = ()
```
Recursive Functions

- To make recursive call, must build intermediate continuation to
  - take recursive value:  $r$
  - build it to final result:  $n * r$
  - And pass it to final continuation:
    - times $n \, r \, k = k \, (n * r)$
Example: CPS for length

```ocaml
def length list = match list with 
    | [] -> 0 
    | (a :: bs) -> 1 + length bs 
```

What is the let-expanded version of this?
Example: CPS for length

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

What is the let-expanded version of this?

let rec length list = match list with [] -> 0
  | (a :: bs) -> let r1 = length bs in 1 + r1
Example: CPS for length

```ocaml
#let rec length list = match list with [] -> 0
     | (a :: bs) -> let r1 = length bs in 1 + r1
```

What is the CSP version of this?
Example: CPS for length

```ocaml
# let rec length list = match list with [] -> 0
  | (a :: bs) -> let r1 = length bs in 1 + r1

What is the CSP version of this?
# let rec lengthk list k = match list with [] -> k 0
  | x :: xs -> lengthk xs (fun r -> addk r 1 k);

val lengthk : 'a list -> (int -> 'b) -> 'b = <fun>
# lengthk [2;4;6;8] report;;
4
- : unit = ()
```

Your turn now

Try Problem 8 on MP4
CPS for Higher Order Functions

- In CPS, every procedure / function takes a continuation to receive its result
- Procedures passed as arguments take continuations
- Procedures returned as results take continuations
- CPS version of higher-order functions must expect input procedures to take continuations
Example: all

```plaintext
#let rec all p l = match l with [] -> true
| (x :: xs) -> let b = p x in
  if b then all p xs else false
val all : ('a -> bool) -> 'a list -> bool = <fun>
```

- What is the CPS version of this?
Example: all

```ocaml
#let rec all p l = match l with [] -> true
  | (x :: xs) -> let b = p x in
    if b then all p xs else false

val all : ('a -> bool) -> 'a list -> bool = <fun>
```

What is the CPS version of this?

```ocaml
#let rec allk pk l k =
```
Example: all

```ocaml
#let rec all p l = match l with [] -> true
  | (x :: xs) -> let b = p x in
    if b then all p xs else false
val all : ('a -> bool) -> 'a list -> bool = <fun>
```

What is the CPS version of this?

```ocaml
#let rec allk pk l k = match l with [] -> true
```
Example: all

```ocaml
# let rec all p l = match l with [] -> true
  | (x :: xs) -> let b = p x in
    if b then all p xs else false

val all : ('a -> bool) -> 'a list -> bool = <fun>
```

What is the CPS version of this?

```ocaml
# let rec allk pk l k = match l with [] -> k true
```
Example: all

```ocaml
# let rec all p l = match l with [] -> true
  | (x :: xs) -> let b = p x in
    if b then all p xs else false
val all : ('a -> bool) -> 'a list -> bool = <fun>
```

What is the CPS version of this?

```ocaml
# let rec allk pk l k = match l l with [] -> k true
  | (x :: xs) ->
```

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Example: all

```ocaml
#let rec all p l = match l with [] -> true
    | (x :: xs) -> let b = p x in
      if b then all p xs else false
val all : ('a -> bool) -> 'a list -> bool = <fun>

- What is the CPS version of this?
#let rec allk pk l k = match l with [] -> k true
    | (x :: xs) -> pk x
```

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Example: all

```ocaml
# let rec all p l = match l with [] -> true
  | (x :: xs) -> let b = p x in
    if b then all p xs else false
val all : ('a -> bool) -> 'a list -> bool = <fun>
```

What is the CPS version of this?

```ocaml
# let rec allk pk l k = match l with [] -> k true
  | (x :: xs) -> pk x
    (fun b -> if b then 
      else )
```

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Example: all

```ocaml
#let rec all p l = match l with [] -> true
  | (x :: xs) -> let b = p x in
    if b then all p xs else false

val all : ('a -> bool) -> 'a list -> bool = <fun>
```

What is the CPS version of this?

```ocaml
#let rec allk pk l k = match l with [] -> k true
  | (x :: xs) -> pk x
    (fun b -> if b then allk pk xs k else k false)

val allk : ('a -> (bool -> 'b) -> 'b) -> 'a list ->
    (bool -> 'b) -> 'b = <fun>
```
Terms

- A function is in **Direct Style** when it returns its result back to the caller.
- A **Tail Call** occurs when a function returns the result of another function call without any more computations (e.g., tail recursion).
- A function is in **Continuation Passing Style** when it, and every function call in it, passes its result to another function.
- Instead of returning the result to the caller, we pass it forward to another function.
Terminology

- Tail Position: A subexpression $s$ of expressions $e$, such that if evaluated, will be taken as the value of $e$
  - if $(x>3)$ then $x + 2$ else $x - 4$
  - let $x = 5$ in $x + 4$

- Tail Call: A function call that occurs in tail position
  - if $(h \, x)$ then $f \, x$ else $(x + g \, x)$
**Terminology**

- **Available**: A function call that can be executed by the current expression.
- The fastest way to be unavailable is to be guarded by an abstraction (anonymous function, lambda lifted).

  - if \((h \ x)\) then \(f \ x\) else \((x + g \ x)\)
  - if \((h \ x)\) then \((\text{fun} \ x \rightarrow f \ x)\) else \((g \ (x + x))\)

Not available
CPS Transformation

- Step 1: Add continuation argument to any function definition:
  - let f arg = e  ⇒  let f arg k = e
  - Idea: Every function takes an extra parameter saying where the result goes
- Step 2: A simple expression in tail position should be passed to a continuation instead of returned:
  - return a  ⇒  k a
  - Assuming a is a constant or variable.
  - “Simple” = “No available function calls.”
Step 3: Pass the current continuation to every function call in tail position

- return f arg ⇒ f arg k
- The function “isn’t going to return,” so we need to tell it where to put the result.
CPS Transformation

- Step 4: Each function call not in tail position needs to be converted to take a new continuation (containing the old continuation as appropriate)
  - return op (f arg) ⇒ f arg (fun r -> k(op r))
  - op represents a primitive operation

- return  f(g arg) ⇒ g arg (fun r-> f r k)
Example

**Before:**
let rec add_list lst =
  match lst with
  | [] -> 0
  | 0 :: xs -> add_list xs
  | x :: xs -> (+) x
     (add_list xs);

**After:**
let rec add_listk lst k =
  (* rule 1 *)
  match lst with
  | [] -> k 0  (* rule 2 *)
  | 0 :: xs -> add_listk xs k
  | x :: xs -> add_listk xs
             (fun r -> k ((+) x r));
  (* rule 4 *)
CPS for sum

# let rec sum list = match list with [ ] -> 0
  | x :: xs -> x + sum xs ;;
val sum : int list -> int = <fun>
CPS for sum

# let rec sum list = match list with [ ] -> 0
| x :: xs -> x + sum xs ;;
val sum : int list -> int = <fun>

# let rec sum list = match list with [ ] -> 0
| x :: xs -> let r1 = sum xs in x + r1;;
CPS for sum

# let rec sum list = match list with [ ] -> 0
  | x :: xs -> x + sum xs ;;
val sum : int list -> int = <fun>

# let rec sum list = match list with [ ] -> 0
  | x :: xs -> let r1 = sum xs in x + r1;;
val sum : int list -> int = <fun>

# let rec sumk list k = match list with [ ] -> k 0
  | x :: xs -> sumk xs (fun r1 -> addk x r1 k);;
CPS for sum

# let rec sum list = match list with [ ] -> 0
      | x :: xs -> x + sum xs ;;
val sum : int list -> int = <fun>

# let rec sum list = match list with [ ] -> 0
      | x :: xs -> let r1 = sum xs in x + r1;;
val sum : int list -> int = <fun>

# let rec sumk list k = match list with [ ] -> k 0
      | x :: xs -> sumk xs (fun r1 -> addk x r1 k);;
val sumk : int list -> (int -> 'a) -> 'a = <fun>

# sumk [2;4;6;8] report;;
20
- : unit = ()
Other Uses for Continuations

- CPS designed to preserve order of evaluation
- Continuations used to express order of evaluation
- Can be used to change order of evaluation
- Implements:
  - Exceptions and exception handling
  - Co-routines
  - (pseudo, aka green) threads
Exceptions - Example

# exception Zero;;
exception Zero

# let rec list_mult_aux list =
  match list with [ ] -> 1
  | x :: xs ->
    if x = 0 then raise Zero
    else x * list_mult_aux xs;;

val list_mult_aux : int list -> int = <fun>
Exceptions - Example

```ocaml
# let list_mult list =
    try list_mult_aux list with Zero -> 0;;
val list_mult : int list -> int = <fun>
# list_mult [3;4;2];;
- : int = 24
# list_mult [7;4;0];;
- : int = 0
# list_mult_aux [7;4;0];;
Exception: Zero.
```
Exceptions

- When an exception is raised
  - The current computation is aborted
  - Control is “thrown” back up the call stack until a matching handler is found
  - All the intermediate calls waiting for a return values are thrown away
Implementing Exceptions

```ocaml
# let multkp m n k =
    let r = m * n in
    (print_string "product result: ");
    print_int r; print_string "\n";
    k r);

val multkp : int -> int -> (int -> 'a) -> 'a
```

= <fun>
Implementing Exceptions

# let rec list_multk_aux list k kexcp =
    match list with [ ] -> k 1
    | x :: xs -> if x = 0 then  kexcp 0
              else list_multk_aux xs
               (fun r -> multkp x r k) kexcp;;
val list_multk_aux : int list -> (int -> 'a) -> (int -> 'a) -> 'a = <fun>

# let rec list_multk list k = list_multk_aux list k k;;
val list_multk : int list -> (int -> 'a) -> 'a = <fun>
Implementing Exceptions

```ocaml
# list_multk [3;4;2] report;;
product result: 2
product result: 8
product result: 24
24
- : unit = ()

# list_multk [7;4;0] report;;
0
- : unit = ()
```