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

- \( \text{rev} \ [1,2,3] = \)
- \( \text{rev\_aux} \ [1,2,3] \ [ ] = \)
- \( \text{rev\_aux} \ [2,3] \ [1] = \)
- \( \text{rev\_aux} \ [3] \ [2,1] = \)
- \( \text{rev\_aux} \ [ ] \ [3,2,1] = [3,2,1] \)
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
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
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
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:
  
  ``` ocaml
  # let subk (x, y) k = k(x + y);;
  val subk : 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 7 on MP2
Try consk
Nesting Continuations

```ocaml
# let add_triple (x, y, z) = (x + y) + z;;
val add_triple : int * int * int -> int = <fun>
# let add_triple (x,y,z)=let p = x + y in p + z;;
val add_three : int -> int -> int -> int = <fun>
# let add_triple_k (x, y, z) k =
  addk (x, y) (fun p -> addk (p, z) k);;
val add_triple_k: int * int * int -> (int -> 'a) -> 'a = <fun>
```
add_three: a different order

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

- let add_triple_k (x, y, z) k =
Your turn now

Try Problem 8 on MP4
Recall:

```haskell
# 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

# 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: \( n \times r \)
  - And pass it to final continuation:
    - \( \text{times} \ (n, r) \ k = k \ (n \times r) \)
Example: CPS for length

```ocaml
let rec length list = match list with [] -> 0 |
                        | (a :: bs) -> 1 + length bs
```
What is the let-expanded version of this?
Example: CPS for length

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

What is the let-expanded version of this?

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

```haskell
#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

```ml
# 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 = ()
```

9/18/17
Your turn now

Try Problem 12 on MP2
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

```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?
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?
#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

```ml
#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?

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

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
```
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 k else )
```

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
    (fun b -> if b then allk (pk, xs) k else k false)
val allk : ('a -> (bool -> 'b) -> 'b) * 'a list ->
  (bool -> 'b) -> 'b = <fun>
```
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 $e$
  - $\text{if (x>3) then } x + 2 \text{ else } x - 4$
  - $\text{let x = 5 in } x + 4$

- Tail Call: A function call that occurs in tail position
  - $\text{if (h x) then } f x \text{ else } (x + g x)$
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 (fun x -> 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.”
CPS Transformation

- Step 3: Pass the current continuation to every function call in tail position
  - return f arg \Rightarrow f\ arg\ k
  - The function “isn’t going to return,” so we need to tell it where to put the result.
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 $\text{op} (f \text{ arg}) \Rightarrow f \text{ arg} (\text{fun } r \rightarrow k(\text{op } r))$
- $\text{op}$ represents a primitive operation

- return $f(g \text{ arg}) \Rightarrow g \text{ arg} (\text{fun } r \rightarrow f \ r \ k)$
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
    (* rule 3 *)
  | 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

```ocaml
# 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>
# 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

# 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;
val () = (); product result: 24

# list_multk [7;4;0] report;;
val () = (); product result: 0
```

Implementing Exceptions