Foundations of Computer Science
Lecture #11: Procedural Programming

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Intro

```
let rec addLen n = function
  | [] -> n
  | x :: xs -> addLen (n+1) xs
```

Example:

```
addLen 0 [1,2,3]
```

Calling `addLen` with same arguments will *always* produce the same result. We can infer result through function expansion and reduction of expressions. This allows us to:

→ Prove algorithm correctness
→ Understand and predict algorithm outcome

Procedural Programming

a) update variable / array
b) sending / receiving data

Procedural programs can change the *machine state*.

They can interact with its *environment*.

They use control structures like *branching*, *iteration* and *procedures*.

They use data abstractions of the computer's memory:

- *references* to memory cells
- *arrays*: blocks of memory cells
- *linked structures*, especially *linked lists*

concept: memory cells that are mutable

What are References?

In functional programming:
The store is an ***invisible*** device inside the computer

In procedural / imperative programming:
The store is ***visible***

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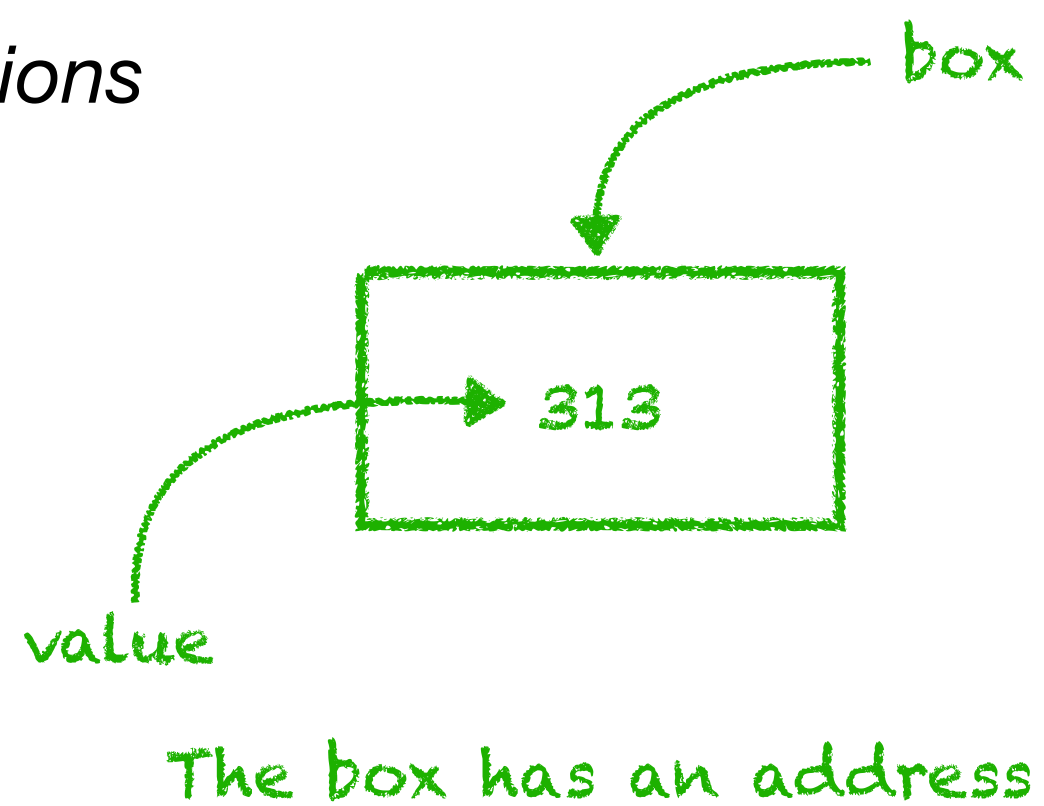
In functional programming:
The store is an ***invisible*** device inside the computer

In procedural / imperative programming:
The store is ***visible***

- References are *storage locations*
- They can be:
  - (a) created
  - (b) inspected
  - (c) updated



ML Primitives for References

τ `ref`	*type* of references to type τ
`ref` E	*create* a reference
	initial contents = the value of E
`!` P	return the *current contents* of reference P 'dereferencing'
P `:=` E	*update* the contents of P to the value of E

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P for 'pointer'

'dereferencing'

pointer to a 'box'

contents of that 'box'

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Three new ML functions / operators:

```
ref : 'a -> 'a ref
!   : 'a ref -> 'a
:=  : 'a ref -> 'a -> unit
```

(a) create box
(b) inspect box content
(c) update box content

Trying Out References

```
# let p = ref 5 (* create a reference *)
val p : int ref = {contents = 5}

# p := !p + 1   (* p now holds value 6 *)
- : unit = ()

# let ps = [ ref 77; p ]
val ps : int ref list = [{contents = 77}; {contents = 6}]

# List.hd ps := 3
- : unit = ()

# ps
- : int ref list = [{contents = 3}; {contents = 6}]
```

Trying Out References

```
# let p = ref 5 (* create a reference *)
val p : int ref = {contents = 5}

# let z = p
val z : int ref = {contents = 5}

# p := !p + 1    (* p now holds value 6 *)
- : unit = ()

# p
- : int ref = {contents = 6}

# z
- : int ref = {contents = 6}
```

Aliasing: two values refer to the same mutable cell

Commands: Expressions with Effects

- Basic commands update references, write to files, etc.
- C_1;...;C_n causes a series of expressions to be evaluated and returns the value of C_n.
- A typical command returns the empty tuple: ()
- `if` B `then` C_1 `else` C_2 behaves like the traditional control structure if C_1 and C_2 have effects.
- Other ML constructs behave naturally with commands, including `match` expressions and recursive functions.

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- Other ML constructs behave naturally with commands, including `match` expressions and recursive functions.

Example:

```
> 1 + (print_endline "abc"; 3; 101);
abc
- : int = 102
```

Example: `length` without Mutability

```
let rec addLen n = function
  | [] -> n
  | x :: xs -> addLen (n+1) xs
```

```
addLen 0 [1,2,3]
addLen 1 [2,3]
addLen 2 [3]
addLen 3 []
==> returns 3
```

Iteration: the `while` Command

```
# let tlopt = function
  | [] -> None
  | _::xs -> Some xs
val tlopt : 'a list -> 'a list option = <fun>

# let length xs =
    let lp  = ref xs in (* list of uncounted elements *)
    let np  = ref 0  in (* accumulated count *)
    let fin = ref false in
    while not !fin do
      match tlopt !lp with
      | None -> fin := true
      | Some xs ->
          lp := xs;
          np := 1 + !np
    done;
    !np (* the final count is returned *)
val length : 'a list -> int = <fun>
```

Iteration: the while Command

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val length : 'a list -> int = <fun>
```

Example: `length` with Mutability

evaluation steps:

```
length([1;2;3])
==> lp = ref [1,2,3]

tlopt [1;2;3] != None  ==> true
lp := [2,3]; np := 1+0;

tlopt [2;3] != None    ==> true
lp := [3]; np := 1+1

tlopt [3] != None      ==> true
lp := []; np := 1+2

tlopt [] != None       ==> false
fin := true
==> return !np
==> returns 3
```

```
let tlopt = function
  | [] -> None
  | _::xs -> Some xs

let length xs =
    let lp  = ref xs in
    let np  = ref 0  in
    let fin = ref false in
    while not !fin do
      match tlopt !lp with
      | None -> fin := true
      | Some xs ->
          lp := xs;
          np := 1 + !np
    done;
    !np
```
val length : 'a list -> int = <fun>

```
let rec addLen n =
 function
  | [] -> n
  | x :: xs ->
      addLen (n+1) xs
```

Private, Persistent References

```
# exception TooMuch of int
exception TooMuch of int
# let makeAccount initBalance =
    let balance = ref initBalance in
    let withdraw amt =
       if amt > !balance then
         raise (TooMuch (amt - !balance))
       else begin
         balance := !balance - amt;
         !balance
       end
    in
    withdraw
val makeAccount : int -> int -> int = <fun>
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val makeAccount : int -> int -> int = <fun>
```

returns a function that returns contents of 'balance', not the cell itself

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    in
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val makeAccount : int -> int -> int = <fun>
```

balance never escapes the definition of makeAccount

returns a function that returns contents of 'balance', not the cell itself

Private, Persistent References

```
let my_account = makeAccount 30;
```

my_account : int -> int = <fun>

```
let my_new_balance = my_account 10;
```

my_new_balance : int = 20

```
let my_new_balance = my_account ~10;
```

my_new_balance : int = 30

Two Bank Accounts

```
# let student = makeAccount 500
val student : int -> int = <fun>

# let director = makeAccount 4000000
val director : int -> int = <fun>

# student 5          (* coach fare *)
- : int = 495

# director 150000   (* Tesla *)
- : int = 3850000

# student 500        (* oh oh *)
Exception: TooMuch 5.
```

ML Primitives for Arrays

```
# [|"a"; "b"; "c"|]
  (* allocate a fresh string array *)
- : string array = [|"a"; "b"; "c"|]

# Array.make 3 'a'
  (* array of size 3 with cell containing 'a' *)
- : char array = [|'a'; 'a'; 'a'|]

# let aa = Array.init 5 (fun i -> i * 10)
  (* array of size 5 initialised to (fun i) *)
val aa : int array = [|0; 10; 20; 30; 40|]

# Array.get aa 3
(* retrieve the 4th cell in the array *)
- : int = 30

# Array.set aa 3 42
(* set the 4th cell's value to 42 *)
- : unit = ()
```

Array Examples

```
# Array.make
- : int -> 'a -> 'a array = <fun>

# Array.init
- : int -> (int -> 'a) -> 'a array = <fun>

# Array.get
- : 'a array -> int -> 'a = <fun>

# Array.set
- : 'a array -> int -> 'a -> unit = <fun>
```

References: ML Versus Conventional Languages

- We must write `!p` to get the *contents* of `p`
- We write just `p` for the address of `p`

- We can store *private* reference cells in functions; simulating object oriented programming

- OCaml's assignment syntax is $V := E$ instead of $V = E$

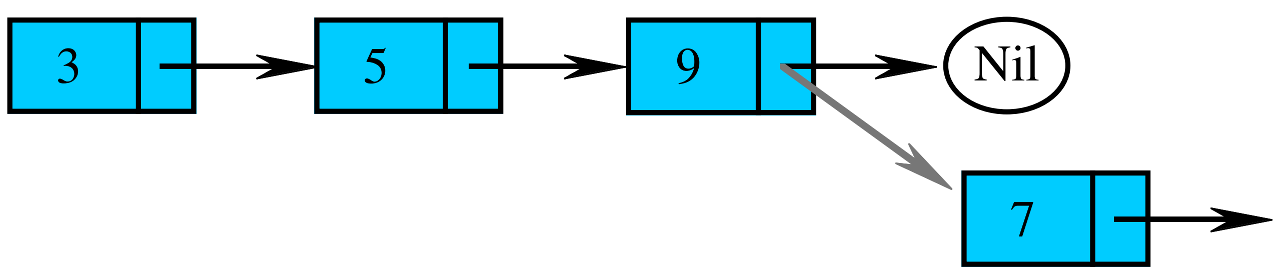
- OCaml has similar control structures: `while/done`, `for/done` and `match/with`

- OCaml has short syntax for updating arrays x.(1) and the access is safe against buffer overflows

What More Is There to ML?

With references, we can now make mutable linked lists

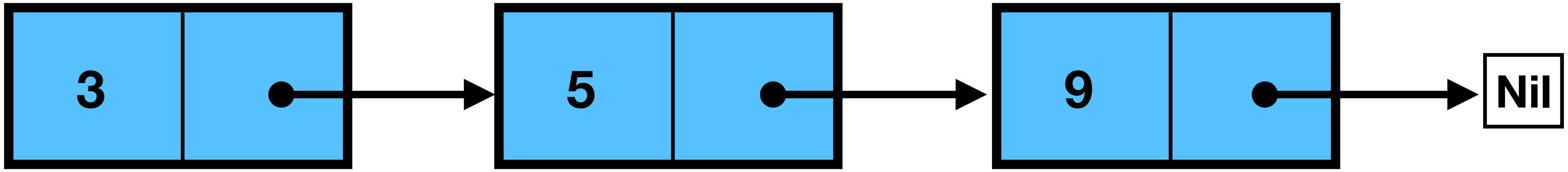
```
# type 'a mlist =
   | Nil
   | Cons of 'a * 'a mlist ref
type 'a mlist = Nil | Cons of 'a * 'a mlist ref
```



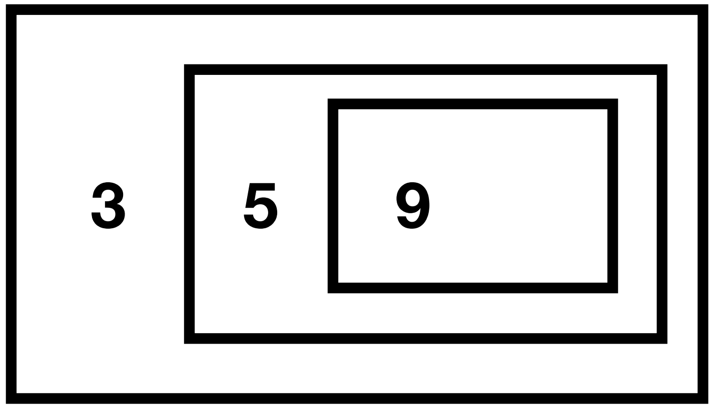
References to References

Two ways to visualize references to references:

(1) Using pointers:



(2) Using nested boxes:



Linked (Mutable) Lists

```
# type 'a mlist =
   | Nil
   | Cons of 'a * 'a mlist ref
type 'a mlist = Nil | Cons of 'a * 'a mlist ref
```

→ The tail can be redirected!

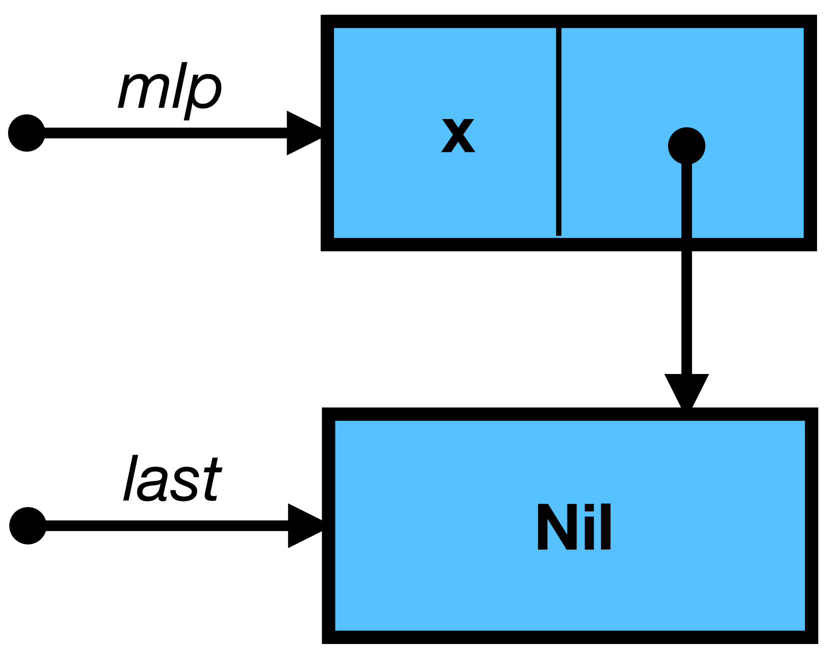
creates a new pointer to rest of mlist

```
# let rec mlistOf = function
   | [] -> Nil
   | x :: l -> Cons (x, ref (mlistOf l))
mlist : 'a list -> 'a mlist = <fun>
```

Extending a List to the Rear

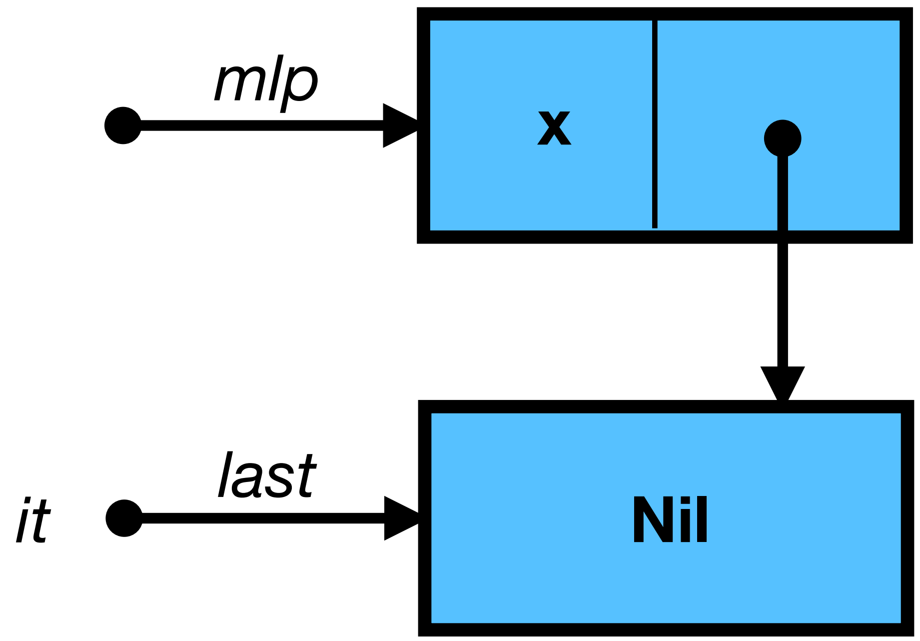
pointing to a 'box'

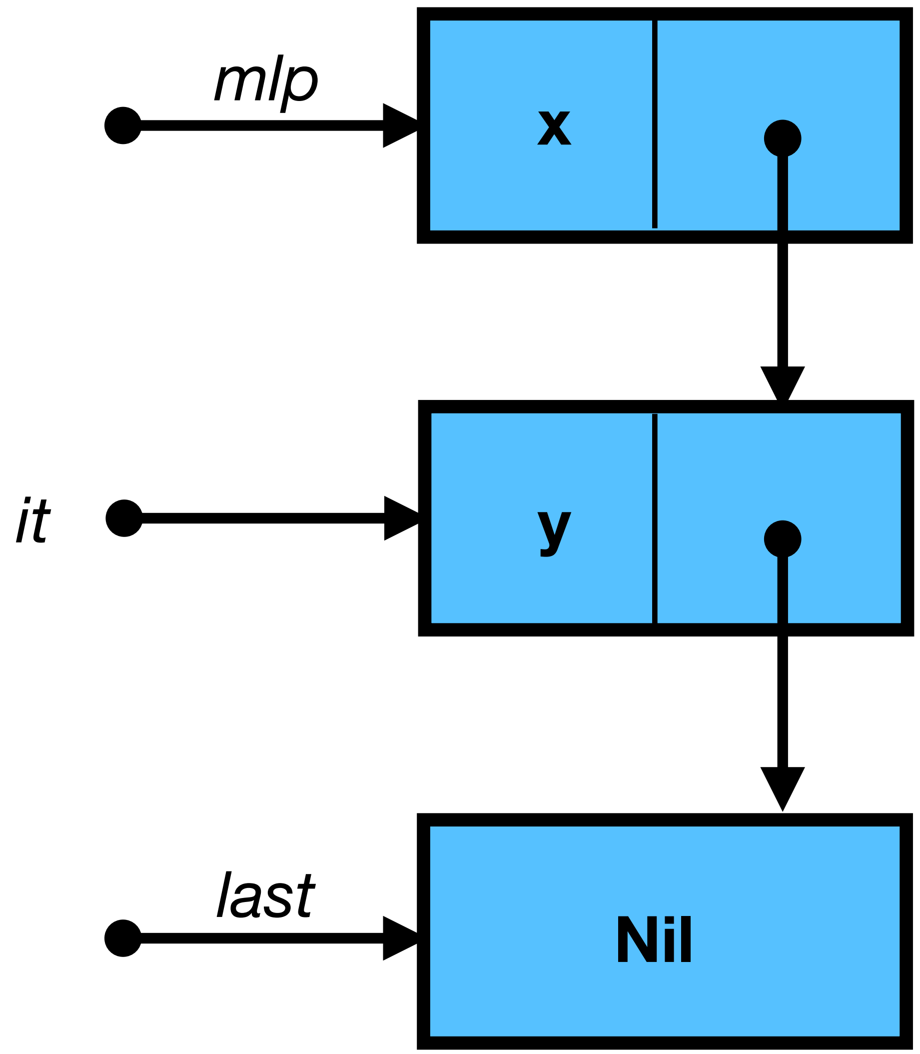
```
# let extend mlp x =
  let last = ref Nil in
  mlp := Cons (x, last);
  last
> val extend = fn : 'a mlist ref * 'a -> 'a mlist ref
```

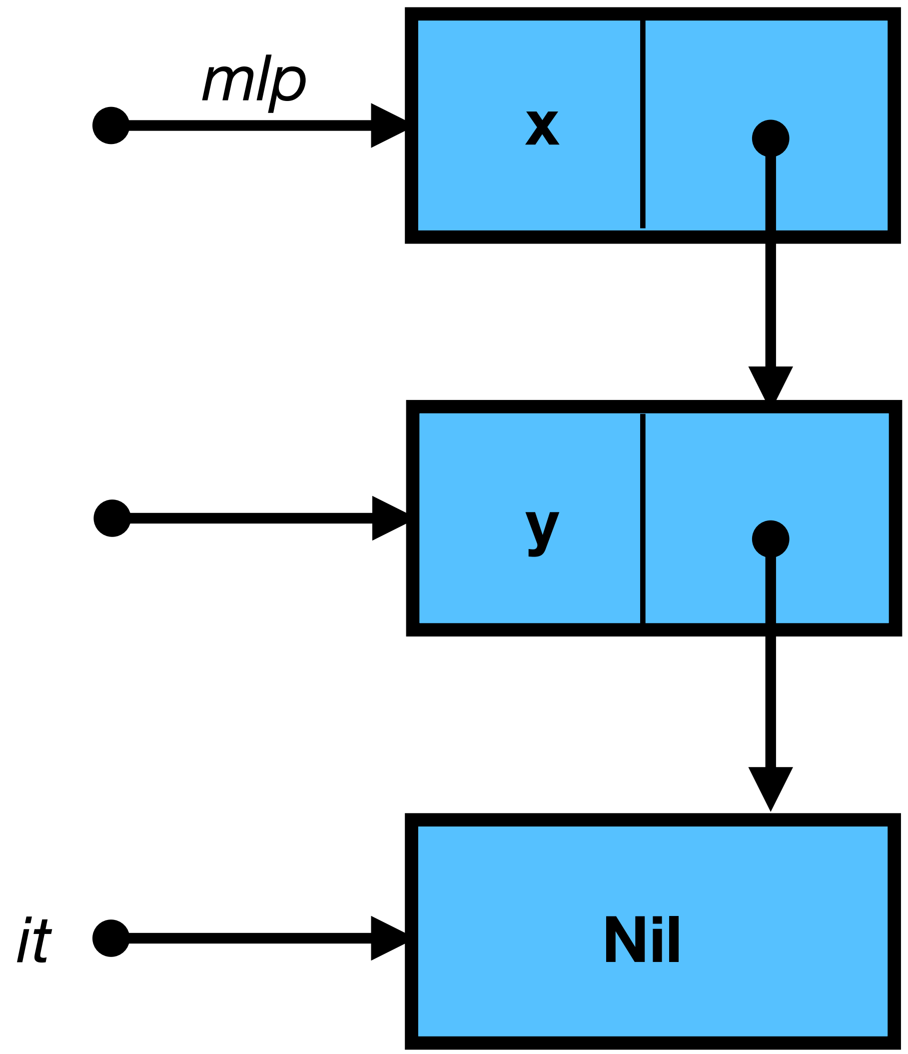


Example of Extending a List

```
# let mlp = ref (Nil: string mlist);;
val mlp : string mlist ref = {contents = Nil}

# extend mlp "a";;
- : string mlist ref = {contents = Nil}

# let mlp = ref (Nil : string mlist);;
val mlp : string mlist ref = {contents = Nil}

# let it = extend mlp "a" ;;
val it : string mlist ref = {contents = Nil}

# extend it "b" ;;
- : string mlist ref = {contents = Nil}

# mlp ;;
- : string mlist ref =
{contents = Cons ("a",
  {contents = Cons ("b", {contents = Nil})})}
```


mlp
x
it
last
Nil


mlp
x
it
y
last
Nil



ref (Cons (x, ref (Cons (y, ref Nil))))

Destructive Concatenation

pointing to a 'box' contents of a 'box'

```
# let rec joining mlp ml2 =
  match !mlp with
  | Nil -> mlp := ml2
  | Cons (_, mlp1) -> joining mlp1 ml2
val joining : 'a mlist ref * 'a mlist -> unit = <fun>

# let join ml1 ml2 =
  let mlp = ref ml1 in
  joining mlp ml2;
  !mlp
val join : 'a mlist -> 'a mlist -> 'a mlist = <fun>
```

Side-Effects

```
# let ml1 = mlistOf ["a"];;
val ml1 : string mlist = Cons ("a", {contents = Nil})
# let ml2 = mlistOf ["b";"c"];;
val ml2 : string mlist =
  Cons ("b", {contents = Cons ("c", {contents = Nil})})
# join ml1 ml2 ;;
```

What does this return?

```
- : string mlist =
Cons ("a",
 {contents = Cons ("b",
   {contents = Cons ("c", {contents = Nil})})})
```