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*

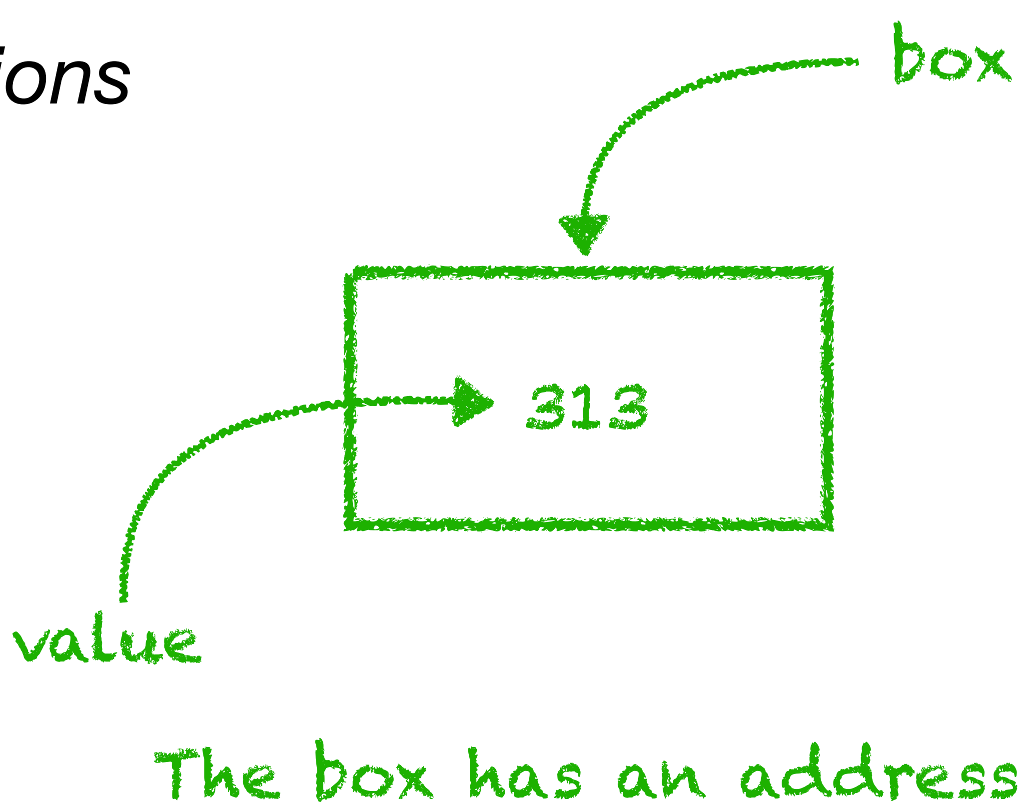
concept: memory cells that are mutable

What are References?

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

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

- 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
$P := E$	*update* the contents of P to the value of E

P for 'pointer'

'dereferencing'

pointer to a 'box'

contents of that 'box'

ML Primitives for References

τ `ref`	*type* of references to type τ
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contents of that 'box'

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.

Example:

```
> 1 + (print_endline "abc"; 3; 101);
```

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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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    done;
    !np (* the final count is returned *)
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```

Example: `length` with Mutability

evaluation steps:

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

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;
```

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
```

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
```

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
```

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>
```

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

Private, Persistent References

```
# exception TooMuch of int
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# let makeAccount initBalance =
    let balance = ref initBalance in
    let withdraw amt =
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       else begin
         balance := !balance - amt;
         !balance
       end
    in
    withdraw
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;
```

Private, Persistent References

```
let my_account = makeAccount 30;
my_account : int -> int = <fun>
```

Private, Persistent References

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

my_account : int -> int = <fun>

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

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
```

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;
```

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 $V = E$

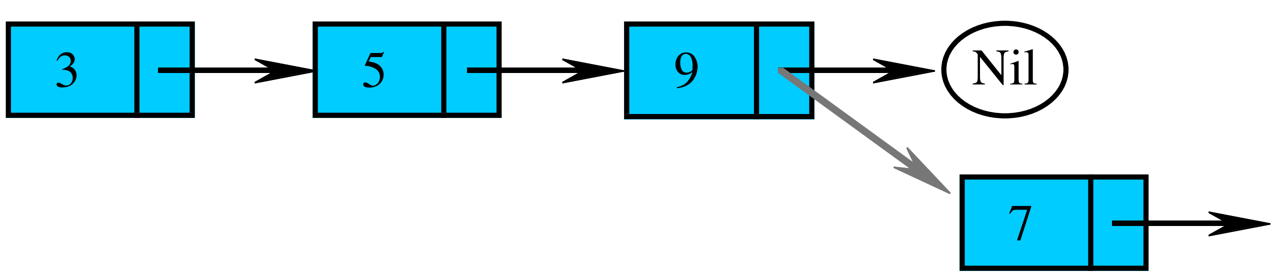
- OCaml has similar control structures: `while/done`, `for/done` and `match/with`

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

What More Is There to ML?

With references, we can now make mutable linked lists

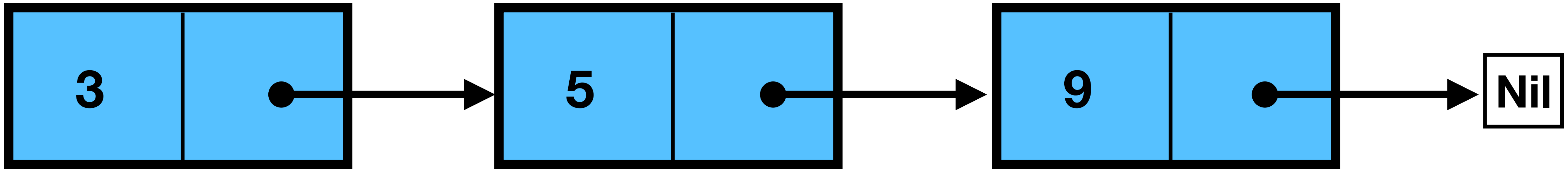
```
# type 'a mlist =
    | Nil
    | Cons of 'a * 'a mlist ref
type 'a mlist = Nil | Cons of 'a * 'a mlist ref
```



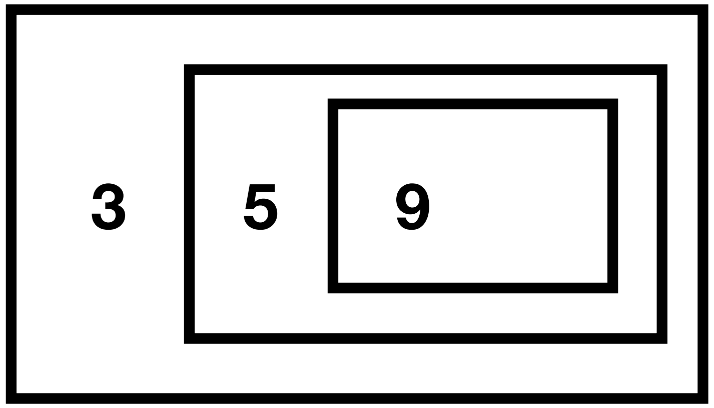
References to References

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!

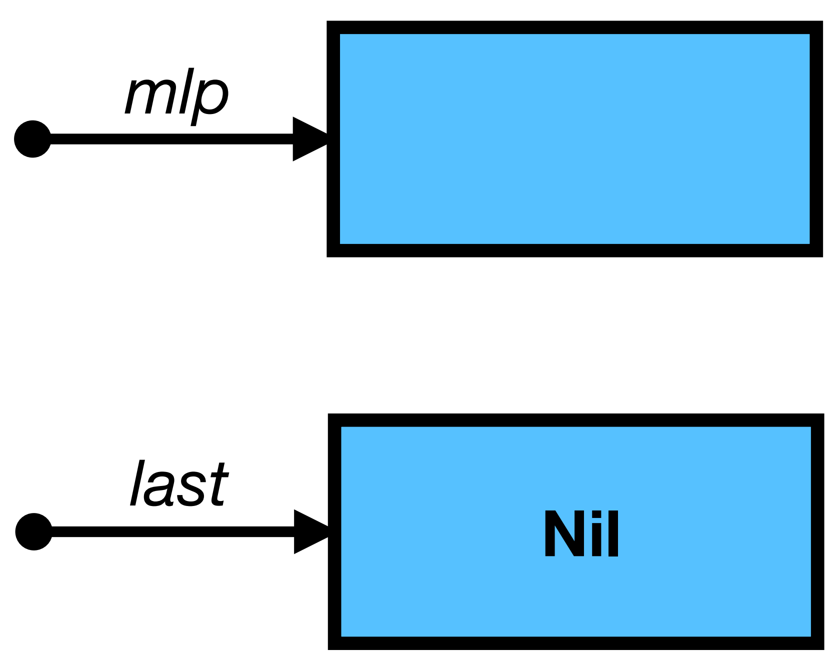
creates a new pointer to rest of mlist

```
# 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
```



Extending a List to the Rear

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> val extend = fn : 'a mlist ref * 'a -> 'a mlist ref
```
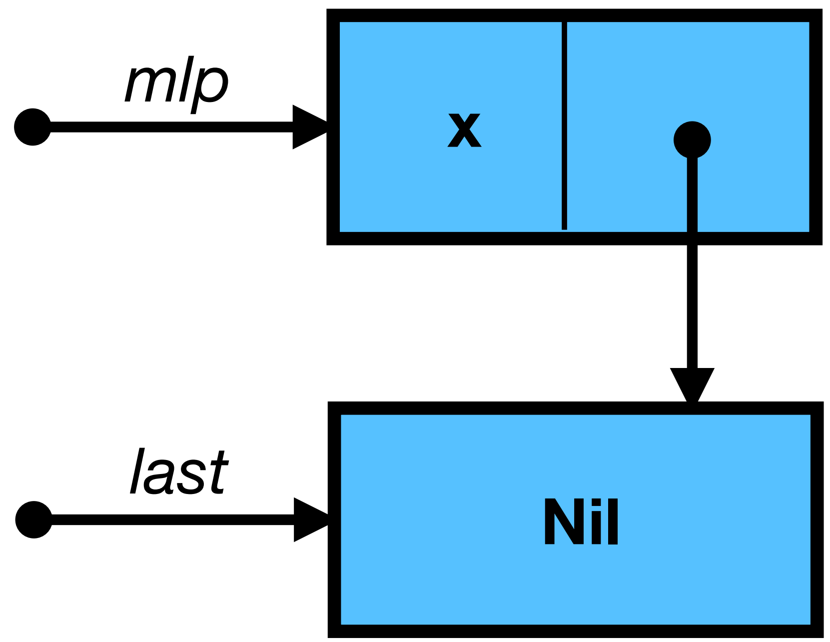
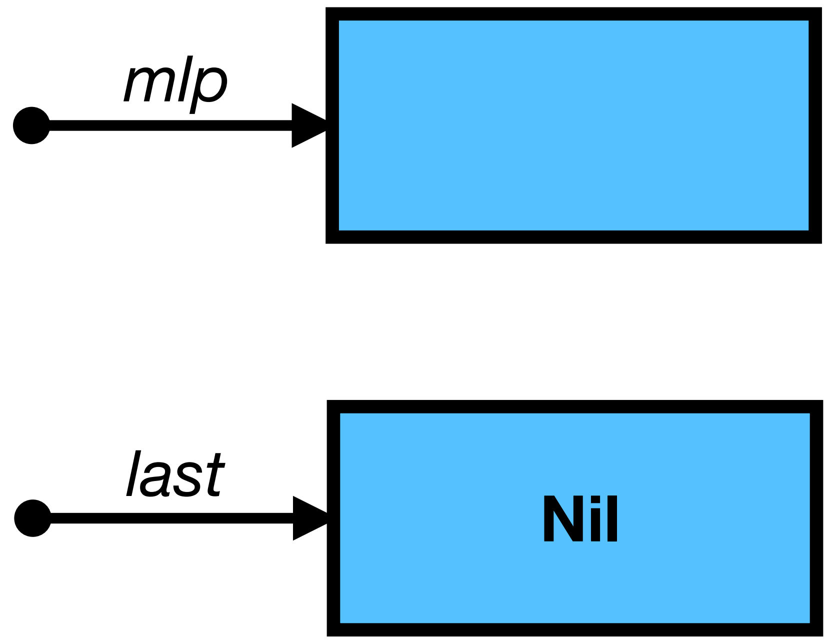
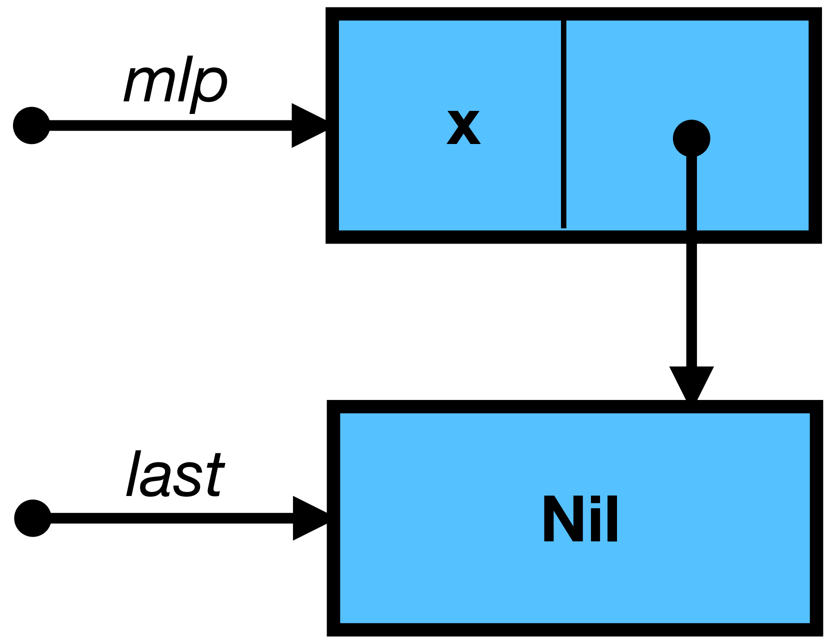
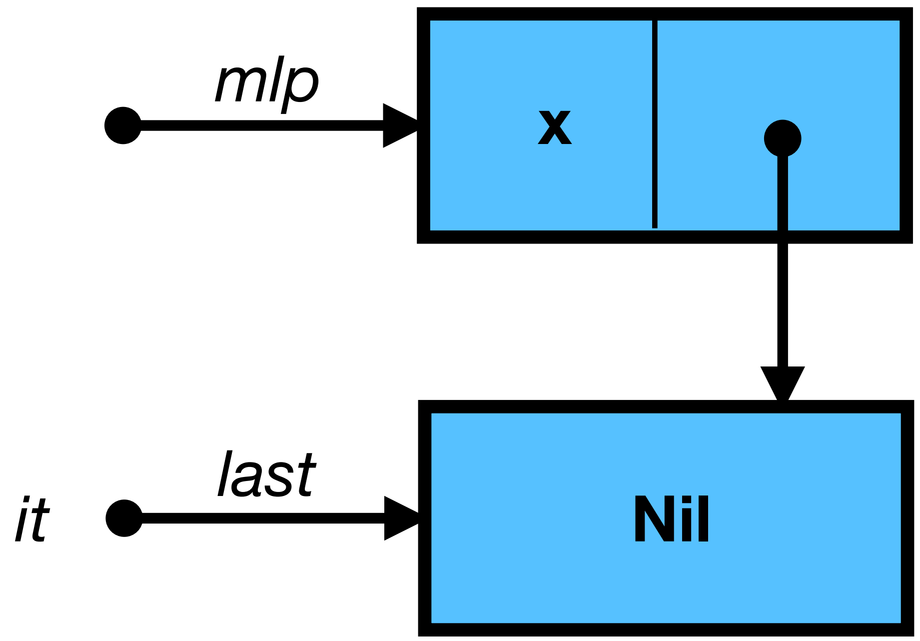



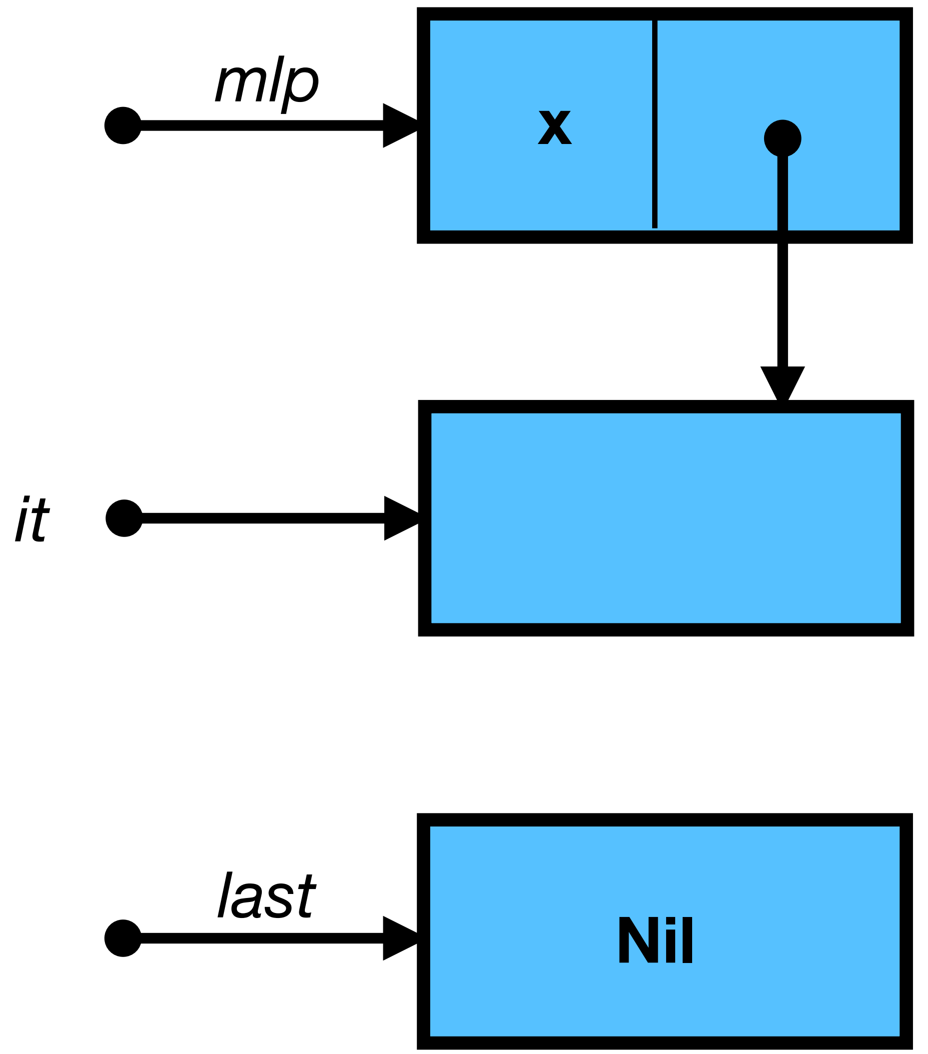
Example of Extending a List

```
# 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
last
Nil


mlp
x
last
Nil


mlp
x
it
last
Nil


mlp
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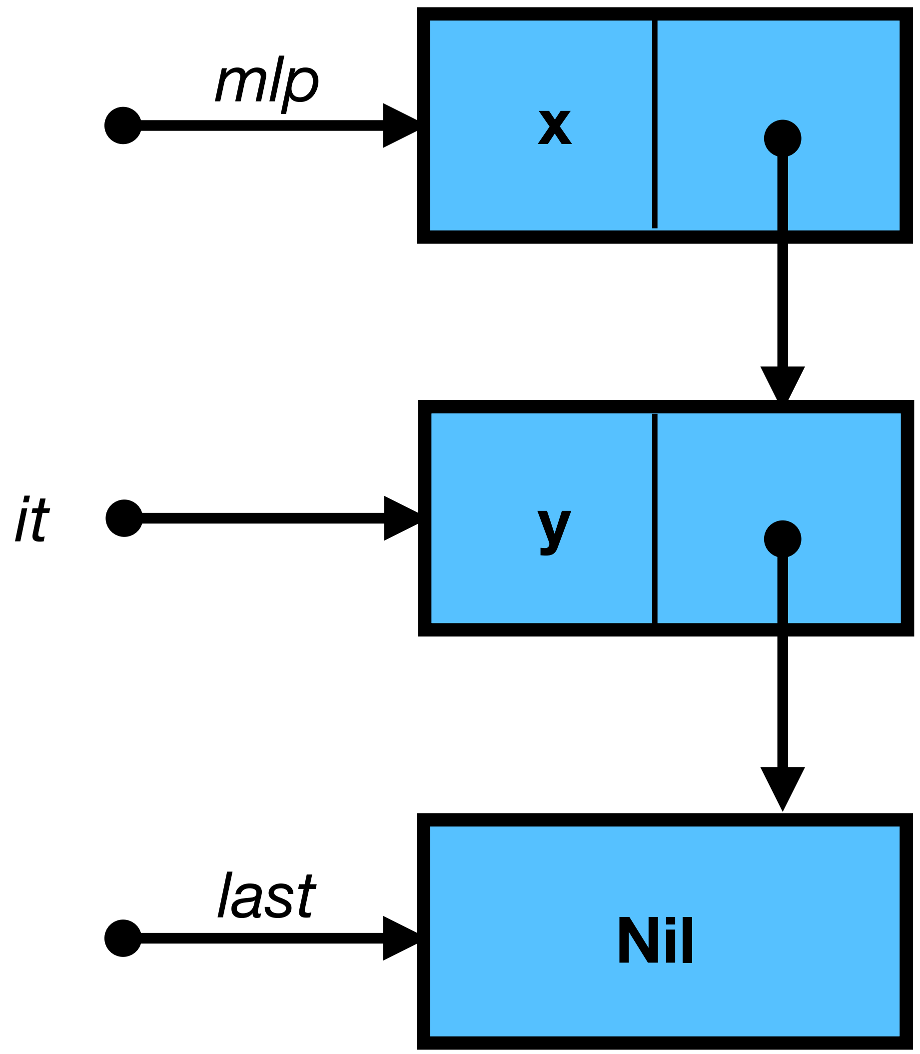
mlp
x
it
y
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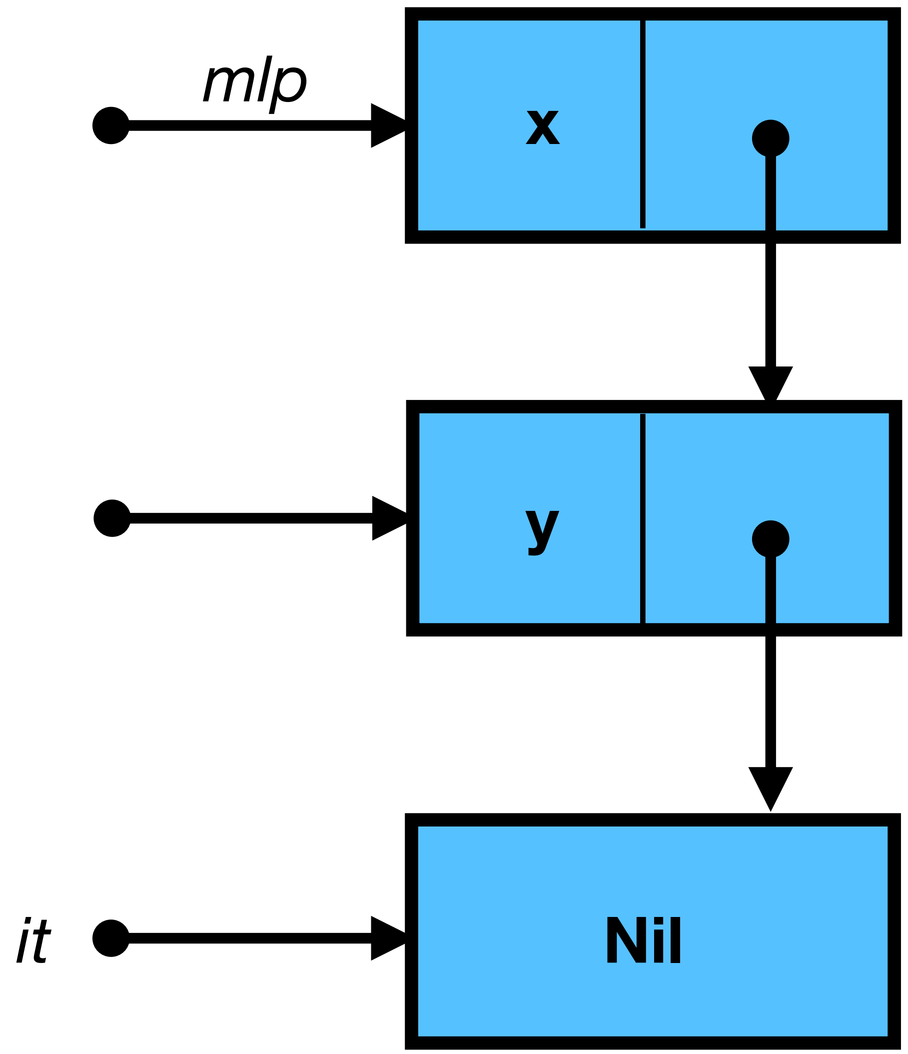
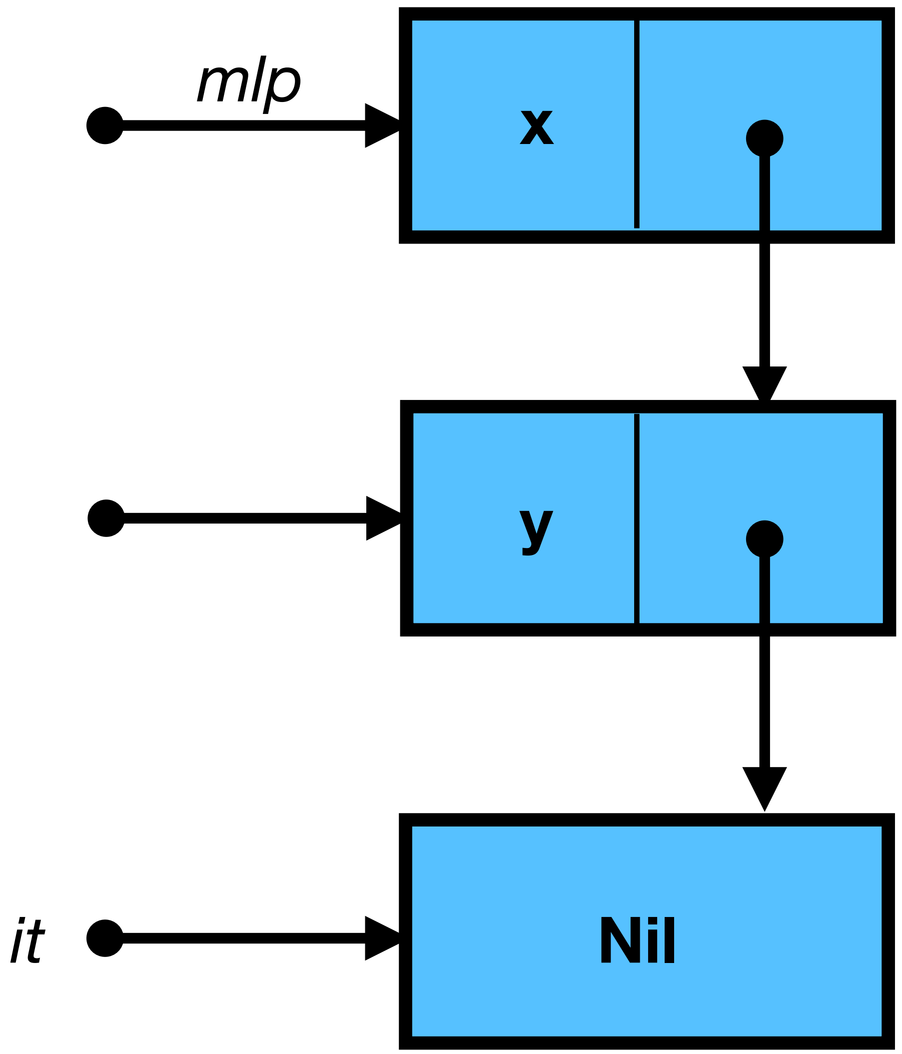
Nil



mlp
x
y
it
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?

Side-Effects

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

```
- : string mlist =
Cons ("a",
 {contents = Cons ("b",
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```