Let bindings

We use `let` to bind name (identifier) to a value:

```
# let x = 100;;    (* x is an immutable binding 100 *)
val x : int = 100
```

Since functions are values, just like ints or strings, let is also used to define functions:

```
#let add x y = x + y;;
val add : int -> int -> int
```

Type Annotations

- OCaml compiler infers the types. But type inference is tricky. It gives vague error messages. We can annotate types manually.
- The syntax `(e : t)` asserts that "*e* has type *t*".

```
let (x : int) = 3
let z = (x : int) + 5
```

- Define functions' parameter and return types

```
let add (x:int) (y:int):int = x + y
let id x = x (*  'a → 'a *)
let id (x:int) = x (* int → int *)
```

- Checked by compiler: Very useful for debugging.

CMSC 330: Organization of Programming Languages

Functional Programming with Lists

Lists in OCaml

- The basic data structure in OCaml
  - Lists can be of *arbitrary length*
    - Implemented as a linked data structure
  - Lists must be *homogeneous*
    - All elements have the same type

- Operations
  - Construct lists
  - Destruct them via pattern matching

Constructing Lists: Syntax

Syntax

- `[]` is the empty list (pronounced "nil")
- ***`e1`*** `::` ***`e2`*** prepends element ***`e1`*** to list ***`e2`***
  - ***`e1`*** is the head, ***`e2`*** is the tail

- `[`***`e1`***`;`***`e2`***`;…;`***`en`***`]` is *syntactic sugar* for ***`e1`***`::`***`e2`***`::…::`***`en`***`::[]`

Examples

```
3::[]            (* [3] *)
2::(3::[])       (* [2; 3] *)
[1; 2; 3]        (* 1::(2::(3::[])) *)
```

Constructing Lists: Evaluation

Evaluation

- `[]` is a value
- `[e1;…;en]` evalues to a list of `[v1;…;vn]`
  - **`Where`**
  - `e1` ⇒ `v1`,
  - …,
  - `en` ⇒ `vn`

Constructing Lists: Examples

```
# let y = [1; 1+1; 1+1+1] ;;
val y : int list = [1; 2; 3]

# let x = 4::y ;;
val x : int list = [4; 1; 2; 3]

# let z = 5::y ;;
val z : int list = [5; 1; 2; 3]

# let m = “hello”::”bob”::[];;
val m : string list = [“hello”; “bob”]
```

Constructing Lists: Typing

Nil:

`[]: 'a list` (* empty list *)

Cons:

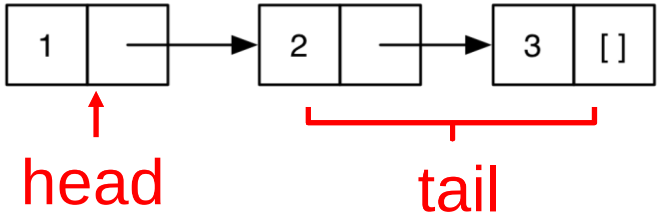
If ***`e1`*** : ***`t`*** and ***`e2`*** : ***`t`*** **`list`** then ***`e1`*** **`::`** ***`e2`*** : ***`t`*** **`list`**

Examples

```
# let x = [1;"world"] ;;
This expression has type string but an expression was
  expected of type int

# let m = [[1];[2;3]];;
val y : int list list = [[1]; [2; 3]]

# let y = 0::[1;2;3] ;;
val y : int list = [0; 1; 2; 3]


# let w = [1;2]::y ;;
This expression has type int list but is here used with
  type int list list
```

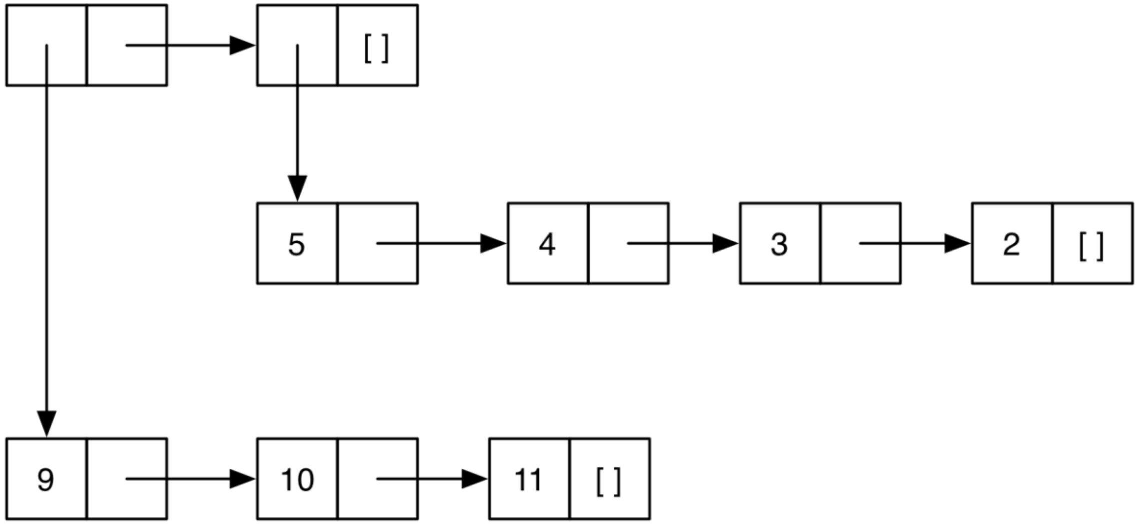
Lists in Ocaml are Linked

[1;2;3] is represented as:



Lists of Lists

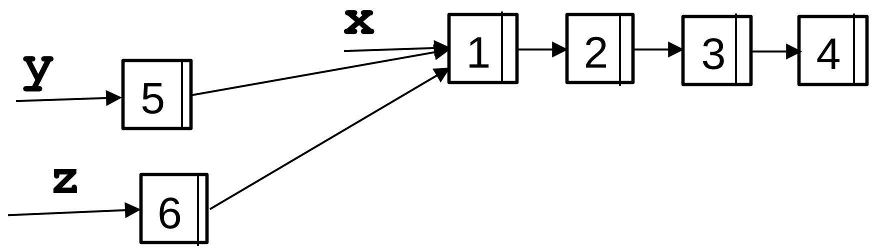
- Lists can be nested arbitrarily
  - Example: `[ [9; 10; 11]; [5; 4; 3; 2] ]`
    - Type `int list list`, also written as (`int list`) `list`



Lists are Immutable

- No way to *mutate* (change) an element of a list
- Instead, build up new lists out of old, e.g., using **::**

```
let x = [1;2;3;4]
let y = 5::x
let z = 6::x
```



Quiz 1

What is the type of the following expression?

```
[1.0; 2.0; 3.0; 4.0]
```

A. `array`

B. `list`

C. `float list`

D. `int list`

Quiz 1

What is the type of the following expression?

```
[1.0; 2.0; 3.0; 4.0]
```

A. `array`

B. `list`

C. `float list`

D. `int list`

Quiz 2

What is the type of the following expression?

```
10::[20]
```

A. `int`

B. `int list`

C. `int list list`

D. `error`

Quiz 2

What is the type of the following expression?

```
10::[20]
```

A. `int`

B. `int list`

C. `int list list`

D. `error`

Quiz 3

What is the type of the following definition?

```
let f a = "umd"::[a]
```

A. `string -> string`

B. `string list`

C. `string list -> string list`

D. `string -> string list`

Quiz 3

What is the type of the following definition?

```
let f a = “umd”::[a]
```

```
A. string -> string
B. string list
C. string list -> string list
D. string -> string list
```

Pattern Matching

- To pull lists apart, use the **`match`** construct
- Syntax

```
    match e with
    | p1 -> e1
    | …
    | pn -> en
```

- ***p1***...***pn*** are *patterns*
- ***e1***...***en*** are *branch expressions*

Pattern Matching Example

```
let is_empty l =
  match l with
    [] -> true
  | (h::t) -> false
```

- Example runs
  - `is_empty []    (* true  *)`
  - `is_empty [1]   (* false *)`
  - `is_empty [1;2] (* false *)`

Pattern Matching Example (cont.)

```
let hd l =
  match l with
   (h::t) -> h
```

- Example runs
  - `hd [1;2;3](* 1 *)`
  - `hd [2;3]   (* 2 *)`
  - `hd [3]     (* 3 *)`
  - `hd []        (* Exception: Match_failure *)`

Pattern Matching Example (cont.)

```
let neg n =
  match n with
    |true-> false
    |_-> true
```

```
let is_empty l =
  match l with
   [] -> true
   |_-> false
```

- An underscore _ is a wildcard pattern. It matches anything

Quiz 4

To what does the following expression evaluate?

```
match [1;2;3] with
    [] -> [0]
| h::t -> t
```

A. `[]`
B. `[0]`
C. `[1]`
D. `[2;3]`

Quiz 4

To what does the following expression evaluate?

```
match [1;2;3] with
   [] -> [0]
| h::t -> t
```

A. `[]`

B. `[0]`

C. `[1]`

D. `[2;3]`

"Deep" pattern matching

- `a::b` matches lists with **at least one** element
- `a::[]` matches lists with **exactly one** element
- `a::b::[]` matches lists with **exactly two** elements
- `a::b::c::d` matches lists with **at least three** elements

Quiz 5

To what does the following expression evaluate?

```
match [1;2;3] with
  | 1::[]     -> [0]
  | _::_      -> [1]
  | 1::_::[] -> []
```

A. `[]`
B. `[0]`
C. `[1]`
D. `[2;3]`

Quiz 5

To what does the following expression evaluate?

```
match [1;2;3] with
  | 1::[]     -> [0]
  | _::_      -> [1]
  | 1::_::[] -> []
```

A. `[]`

B. `[0]`

C. `[1]`

D. `[2;3]`

Pattern Matching – An Abbreviation

- `let f p = e`, where *p* is a pattern
  - is shorthand for `let f x = match x with p -> e`

- Examples
  - `let hd (h::_) = h`
  - `let tl (_::t) = t`
- Useful if there's only one acceptable input

Polymorphic Types

- The **`hd`** function works for *any type of list*
  - `hd [1; 2; 3]              (* 1 *)`
  - `hd ["a"; "b"; "c"]        (* "a" *)`

- OCaml gives such functions polymorphic types
  - `hd : 'a list -> ‘a`

- These are basically generic types in Java
  - `'a list` is like `List<T>`

Examples Of Polymorphic Types

```
let tl (_::t) = t
```

```
# tl [1; 2; 3];;
- : int list = [2; 3]

# tl [1.0; 2.0];;
- : float list = [2.0]
(* tl : 'a list -> 'a list *)
```

Examples Of Polymorphic Types

```
let eq x y = (x = y)
```

-
- `# eq 1 2;;`
  - `: bool = false`

```
# eq “hello” “there”;;
- : bool = false

# eq “hello” 1
```
-- type error

```
(* eq : 'a -> ’a -> bool *)
```

Quiz 6

What is the type of the following function?

```
let f x y =
  if x = y then 1 else 0
```

A. `‘a -> ‘b -> int`

B. `‘a -> ‘a -> bool`

C. `‘a -> ‘a -> int`

D. `int`

Quiz 6

What is the type of the following function?

```
let f x y =
  if x = y then 1 else 0
```

```
A. 'a -> 'b -> int
B. 'a -> 'a -> bool
C. 'a -> 'a -> int
D. int
```

Missing Cases

- Exceptions for inputs that don’t match any pattern
  - OCaml will warn you about non-exhaustive matches

- Example:

```
# let hd l = match l with (h::_) -> h;;
Warning: this pattern-matching is not exhaustive.
Here is an example of a value that is not matched:
[]

# hd [];;
Exception: Match_failure ("", 1, 11).
```

Pattern matching is ***AWESOME***

1. You can’t forget a case
   – Compiler issues inexhaustive pattern-match warning
2. You can’t duplicate a case
   – Compiler issues unused match case warning
3. You can’t get an exception
   – Can’t do something like `List.hd []`
4. Pattern matching leads to elegant, concise, beautiful code

Lists and Recursion

- Lists have a recursive structure
  - And so most functions over lists will be recursive

```
let rec length l = match l with
     [] -> 0
   | (_::t) -> 1 + (length t)
```

  - This is just like an inductive definition
    - *The length of the empty list is zero*
    - *The length of a nonempty list is 1 plus the length of the tail*
  - Type of length?
    - `'a list -> int`

More Examples

- `sum l (* sum of elts in l *)`

```
let rec sum l = match l with
      [] -> 0
    | (x::xs) -> x + (sum xs)
```

- `negate l (* negate elements in list *)`

```
let rec negate l = match l with
      [] -> []
    | (x::xs) -> (-x) :: (negate xs)
```

- `last l  (* last element of l *)`

```
let rec last l = match l with
      [x] -> x
    | (x::xs) -> last xs
```

More Examples (cont.)

```
(* return a list containing all the elements in the list l
  followed by all the elements in list m *)
```

- `append l m`

```
 let rec append l m = match l with
      [] -> m
   | (x::xs) -> x::(append xs m)
```

- `rev l  (* reverse list; hint: use append *)`

```
 let rec rev l = match l with
       [] -> []
    | (x::xs) -> append (rev xs) (x::[])
```

- **`rev`** takes $O(n^2)$ time. Can you do better?