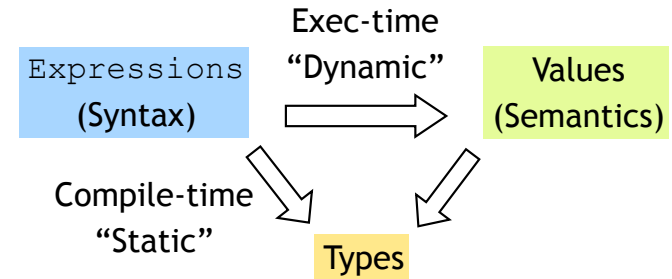


OCaml

The PL for the discerning hacker.

ML Flow



1. Enter expression
2. ML infers a type \mathcal{T}
3. ML crunches expression down to a value
4. Value guaranteed to have type \mathcal{T}

Typing -> Eval Always Works

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Complex types: Lists

<code>[];</code>	<code>[]</code>	<code>'a list</code>
<code>[1;2;3];</code>	<code>[1;2;3]</code>	<code>int list</code>
<code>[1+1;2+2;3+3;4+4];</code>	<code>[2;4;6;8]</code>	<code>int list</code>
<code>["a";"b"; "c"^"d"];</code>	<code>["a";"b"; "cd"]</code>	<code>string list</code>
<code>[(1, "a"^"b"); (3+4, "c")];</code>	<code>[(1, "ab");(7, "c")]</code>	<code>(int*string) list</code>
<code>[[1]; [2;3]; [4;5;6]];</code>	<code>[[1];[2;3];[4;5;6]];</code>	<code>(int list) list</code>

- Unbounded size
- Can have lists of anything (e.g. lists of lists)
- But...

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Complex types: Lists

`[1; "pq"];`

All elements must have same type

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Question 1

Which of these causes a **type error**?

- (a) [1; 2; 3]
- (b) ["1", 2, 3]
- (c) "[1; 2; 3]"
- (d) (1, 2, 3)
- (e) ["1"; 2; 3]

Complex types: Lists

List operator "Cons" `::`

<code>1 :: [];</code>	<code>[1]</code>	int list
<code>1 :: [2;3];</code>	<code>[1;2;3]</code>	int list
<code>"a" :: ["b"; "c"];</code>	<code>["a"; "b"; "c"]</code>	string list

Can only "cons" element to a list of **same type**

`1 :: ["b"; "cd"];`

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Lists: Construct

Nil operator

`[]` `[] : 'a list` `[] => []`

Cons operator

`1 :: [2;3]` int list `[1;2;3]`

$$\frac{e1:T \quad e2: T \text{ list}}{e1::e2 : T \text{ list}} \qquad \frac{e1=>v1 \quad e2=>v2}{e1::e2 =>v1::v2}$$

Complex types: Lists

List operator "Append" `@`

<code>[1;2]@[3;4;5];</code>	<code>[1;2;3;4;5]</code>	int list
<code>["a"]@["b"];</code>	<code>["a"; "b"]</code>	string list
<code>[]@[1];</code>	<code>[1]</code>	int list

Can only append two lists `1 @ [2;3];`

... of the same type `[1] @ ["a"; "b"];`

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Complex types: Lists

List operator “head” `hd`

<code>hd [1;2];</code>	1	int
<code>hd (“a”@“b”);</code>	“a”	string

Only take the head a nonempty list `hd [];`

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Question 2: What is result of?

`(hd [[]; [1;2;3]]) = (hd [[]; [“a”]])`

- (a) Syntax Error
- (b) `true : bool`
- (c) `false : bool`
- (d) Type Error (`hd`)
- (e) Type Error (`=`)

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Complex types: Lists

List operator “tail” `tl`

<code>tl [1;2;3];</code>	[2;3]	int list
<code>tl (“a”@“b”);</code>	["b"]	string list

Only take the tail of nonempty list `tl [];`

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Lists: Deconstruct

Head

$$\frac{e : T \text{ list}}{hd\ e : T} \quad \frac{e \Rightarrow v1::v2}{hd\ e \Rightarrow v1}$$

Tail

$$\frac{e : T \text{ list}}{tl\ e : T \text{ list}} \quad \frac{e \Rightarrow v1::v2}{tl\ e \Rightarrow v2}$$

`(hd [[]; [1;2;3]]) = (hd [[]; [“a”]])`

int list

$$\frac{e_1 : T \quad e_2 : T}{e_1 = e_2 : bool}$$

string list

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Recap: Tuples vs. Lists ?

What's the difference ?

- Tuples:

- Different types, but fixed number:

(3, "abcd") (int * string)

- pair = 2 elts

(3, "abcd", (3.5, 4.2)) (int * string * (float * float))

- triple = 3 elts

- Lists:

- Same type, unbounded number:

[3;4;5;6;7] int list

- Syntax:

- Tuples = comma Lists = semicolon

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So far, a fancy calculator...

... what do we need next ?

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So far, a fancy calculator...

Branches

Question 3: What is result of?

```
if (1 < 2) then true else false
```

- (a) Syntax Error
- (b) true
- (c) false
- (d) Type Error

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Question 4: What is result of?

```
if (1 < 2) then [1;2] else 5
```

- (a) Syntax Error
- (b) [1;2]
- (c) 5
- (d) Type Error

If-then-else expressions

$$\frac{e1 : \text{bool} \quad e2:T \quad e3:T}{\text{if } e1 \text{ then } e2 \text{ else } e3 : T}$$

- Then-subexp, Else-subexp must have same type!
 - Equals type of resulting expression

```
if 1>2 then [1,2] else [] []   if 1<2 then [] else ["a"] []
int list                       string list
```

```
(if 1>2 then [1,2] else [])=(if 1<2 then [] else ["a"])
```

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If-then-else expressions

```
if (1 < 2) then [1;2] else 5
```

```
if false then [1;2] else 5
```

- then-subexp, else-subexp must have same type!
 - ...which is the type of resulting expression

$$\frac{e1 : \text{bool} \quad e2:T \quad e3:T}{\text{if } e1 \text{ then } e2 \text{ else } e3 : T}$$

So far, a fancy calculator...

Variables

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Question 5: I got this @ prompt

```
# [x+x; x*x] ;;  
- : int list = [20; 100]
```

What had I typed before?

- (a) `x = 10;`
- (b) `int x = 10;`
- (c) `x == 10;`
- (d) `let x = 10;`
- (e) `x := 10;`

Variables and bindings

```
let x = e;;
```

“Bind the value of
expression `e` to the variable `x`”

```
# let x = 2+2;;  
val x : int = 4
```

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Variables and bindings

Later declared expressions can use `x`

- Most recent “bound” value used for evaluation

```
# let x = 2+2;;  
val x : int = 4  
# let y = x * x * x;;  
val y : int = 64  
# let z = [x;y;x+y];;  
val z : int list = [4;64;68]  
#
```

Variables and bindings

Undeclared variables

(i.e. without a value binding)

are not accepted !

```
# let p = a + 1;  
Characters 8-9:  
  let p = a + 1 ;;  
           ^  
Unbound value a
```

Catches many bugs due to typos

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Local bindings

... for expressions using “temporary” variables

```
let
  tempVar = x + 2 * y
in
  tempVar * tempVar
;;
```

⇒ 17424 int

- tempVar is bound **only inside** expr body from in ...
- **Not visible** (“not in scope”) outside

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Binding by Pattern-Matching

Simultaneously bind several variables

```
# let (x,y,z) = (2+3, "a"^^"b", 1::[2]);;
val x : int = 5
val y : string = "ab"
val z : int list = [1;2]
```

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Question 6: What is result of?

```
let x = 10 in
  (let z = 10 in x + z) + z
```

- (a) Syntax Error
- (b) 30
- (c) Unbound Error -- x
- (d) Unbound Error -- z
- (e) Type Error

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Binding by Pattern-Matching

But what of:

```
# let h::t = [1;2;3];;
Warning P: this pattern-matching not exhaustive.
val h : int = 1
val t : int list = [2;3]
```

Why is it whining ?

```
# let h::t = [];
Exception: Match_failure
# let XS = [1;2;3];
val xs = [1;2;3]: list
- val h::t = xs;
Warning: Binding not exhaustive
val h = 1 : int
val t = [2;3] : int
```

In general XS may be empty (match failure!)

Another useful early warning

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Binding by Pattern-Matching

But what of:

Wh

In

NEVER USE PATTERN MATCHING LIKE THIS

```
let h::t = ...
```

ALWAYS USE THIS FORM INSTEAD

```
match l with ...
```

(coming up soon, but this is important)

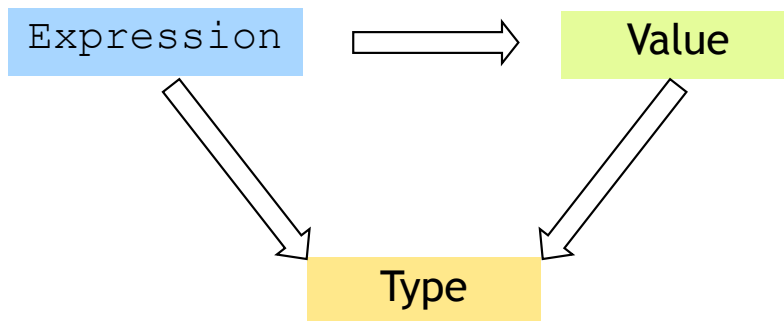
Another useful early warning

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Functions

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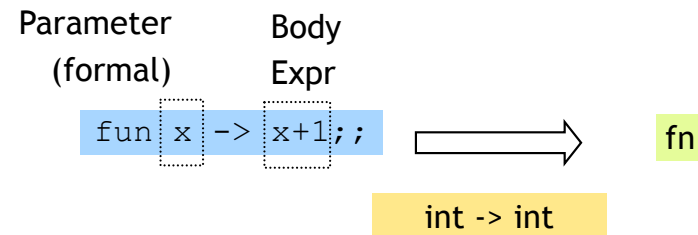
Functions up now, remember ...



Everything is an expression
Everything has a value
Everything has a type

A function is a value!

Complex types: Functions!

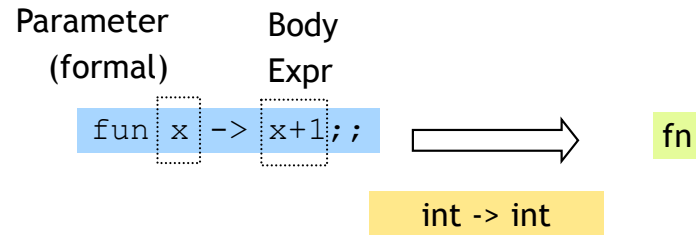


```
# let inc = fun x -> x+1 ;  
val inc : int -> int = fn  
# inc 0;  
val it : int = 1  
# inc 10;  
val it : int = 11
```

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A Problem



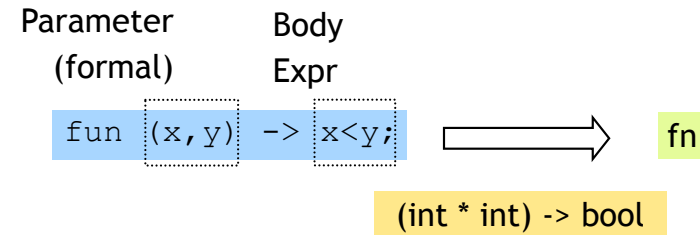
Functions only have
ONE parameter ?!

How a call (“application”) is evaluated:

1. Evaluate argument
2. Bind formal to arg value
3. Evaluate “Body expr”

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A Solution: Simultaneous Binding



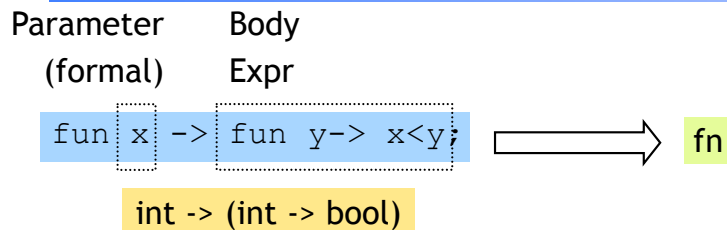
Functions only have
ONE parameter ?

How a call (“application”) is evaluated:

1. Evaluate argument
2. Bind formal to arg value
3. Evaluate “Body expr”

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Another Solution (“Currying”)



Whoa! A function can return a function

```
# let lt = fun x -> fun y -> x < y ;
val lt : int -> int -> bool = fn
# let is5lt = lt 5;
val is5lt : int -> bool = fn;
# is5lt 10;
val it : bool = true;
# is5lt 2;
val it : bool = false;
```

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Question 7: What is result of?

(fun x -> not x)

- (a) Syntax Error
- (b) <fun> : int -> int
- (c) <fun> : int -> bool
- (d) <fun> : bool -> int
- (e) <fun> : bool -> bool

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And how about...

Parameter Body
(formal) Expr

`fun f -> fun x -> not (f x);` \longrightarrow `fn`

`('a -> bool) -> ('a -> bool)`

A function can also take a function argument

```
# let neg = fun f -> fun x -> not (f x);
val lt : int -> int -> bool = fn
# let is5gte = neg is5lt;
val is5gte : int -> bool = fn
# is5gte 10;
val it : bool = false;
# is5gte 2;
val it : bool = true;
(*...odd, even ...*)
```

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Question 8: What is result of?

`(fun f -> (fun x -> (f x)+x))`

- (a) Syntax Error
- (b) Type Error
- (c) `<fun> : int -> int -> int`
- (d) `<fun> : int -> int`
- (e) `<fun> : (int->int)-> int -> int`

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A shorthand for function binding

```
# let neg = fun f -> fun x -> not (f x);
...
# let neg f x = not (f x);
val neg : int -> int -> bool = fn

# let is5gte = neg is5lt;
val is5gte : int -> bool = fn;
# is5gte 10;
val it : bool = false;
# is5gte 2;
val it : bool = true;
```

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Put it together: a “filter” function

If arg “matches” ...then use
this pattern... this Body Expr

```
- let rec filter f xs =
  match xs with
  | [] -> []
  | (x::xs') -> if f x
                 then x::(filter f xs')
                 else (filter f xs');;

val filter : ('a->bool)->'a list->'a list = fn

# let list1 = [1;31;12;4;7;2;10];;
# filter is5lt list1 ;;
val it : int list = [31;12;7;10]
# filter is5gte list1;;
val it : int list = [1;4;2]
# filter even list1;;
val it : int list = [12;4;2;10]
```

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Put it together: a “partition” function

```
# let partition f l = (filter f l, filter (neg f) l);
val partition : ('a->bool)->'a list->'a list * 'a list = fn

# let list1 = [1,31,12,4,7,2,10];
- ...
# partition is5lt list1 ;
val it : (int list * int list) = ([31,12,7,10],[1,2,10])

# partition even list1;
val it : (int list * int list) = ([12,4,2,10],[1,31,7])
```

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A little trick ...

```
# 2 <= 3;; ...
val it : bool = true
# "ba" <= "ab";;
val it : bool = false

# let lt = (<) ;;
val it : 'a -> 'a -> bool = fn

# lt 2 3;;
val it : bool = true;
# lt "ba" "ab" ;;
val it : bool = false;

# let is5Lt = lt 5;
val is5lt : int -> bool = fn;
# is5lt 10;
val it : bool = true;
# is5lt 2;
val it : bool = false;
```

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Put it together: a “quicksort” function

```
let rec sort xs =
  match xs with
  | [] -> []
  | (h::t) -> let (l,r) = partition ((<) h) t in
               (sort l)@(h::(sort r))
```

Now, lets begin at the beginning ...

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