Plan (next 4 weeks)

1. Fast forward
   - Rapid introduction to what’s in OCaml

2. Rewind

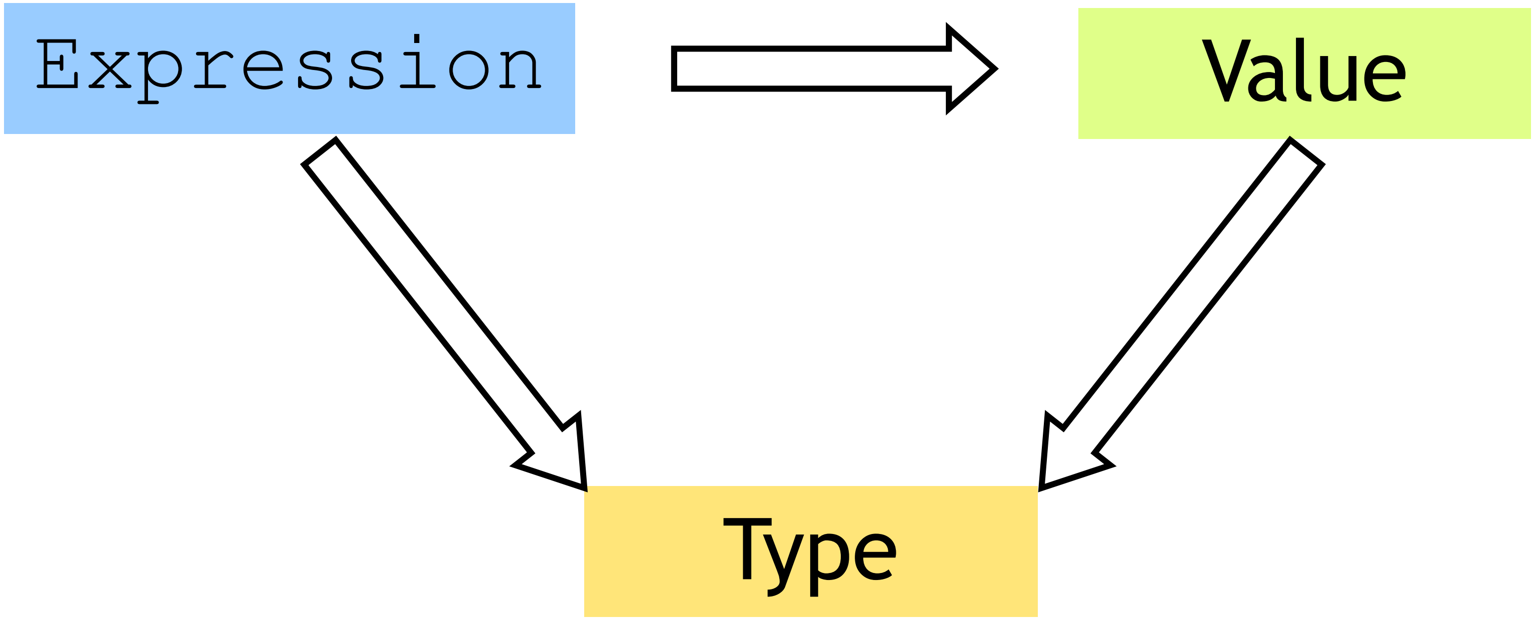
3. Slow motion
   - Go over the pieces individually

History, Variants

“Meta Language”

- Designed by Robin Milner @ Edinburgh
- Language to manipulate Theorems/Proofs
- Several dialects:
  - Standard” ML (of New Jersey)
    - Original syntax
  - “O’Caml: The PL for the discerning hacker”
    - French dialect with support for objects
    - State-of-the-art
    - Extensive library, tool, user support
    - (.NET)

ML's holy trinity



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

Interacting with ML

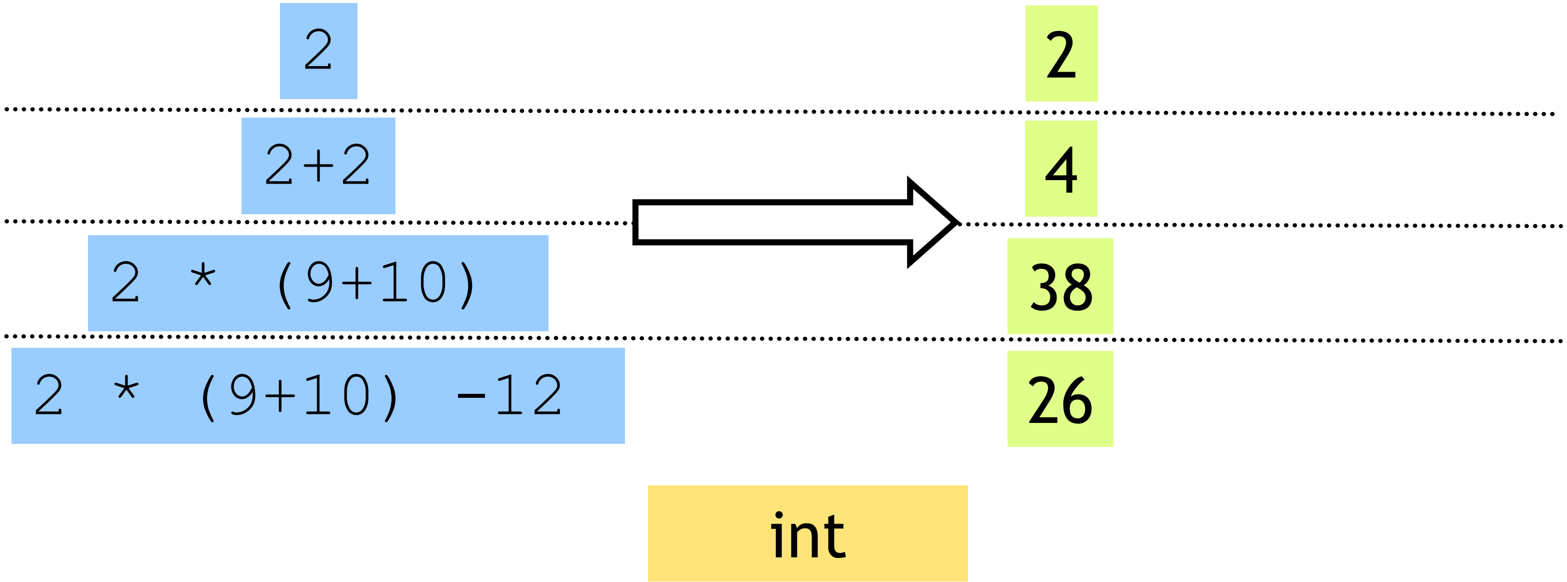
“Read-Eval-Print” Loop

Repeat:

1. System reads expression **e**
2. System evaluates **e** to get value **v**
3. System prints value **v** and type **t**

What are these expressions, values and types ?

Base type: Integers



`2` → 2

`2+2` → 4

`2 * (9+10)` → 38

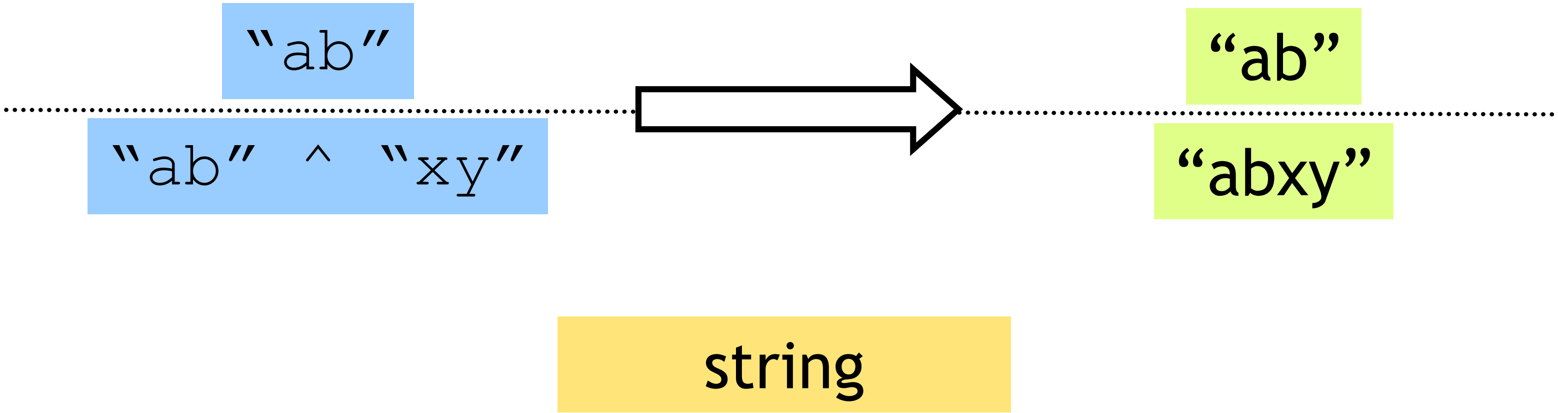
`2 * (9+10) -12` → 26

int

Complex expressions using “operators”: *(why the quotes ?)*

- +, -, *
- div, mod

Base type: Strings



```
"ab"
"ab" ^ "xy"
```

“ab”

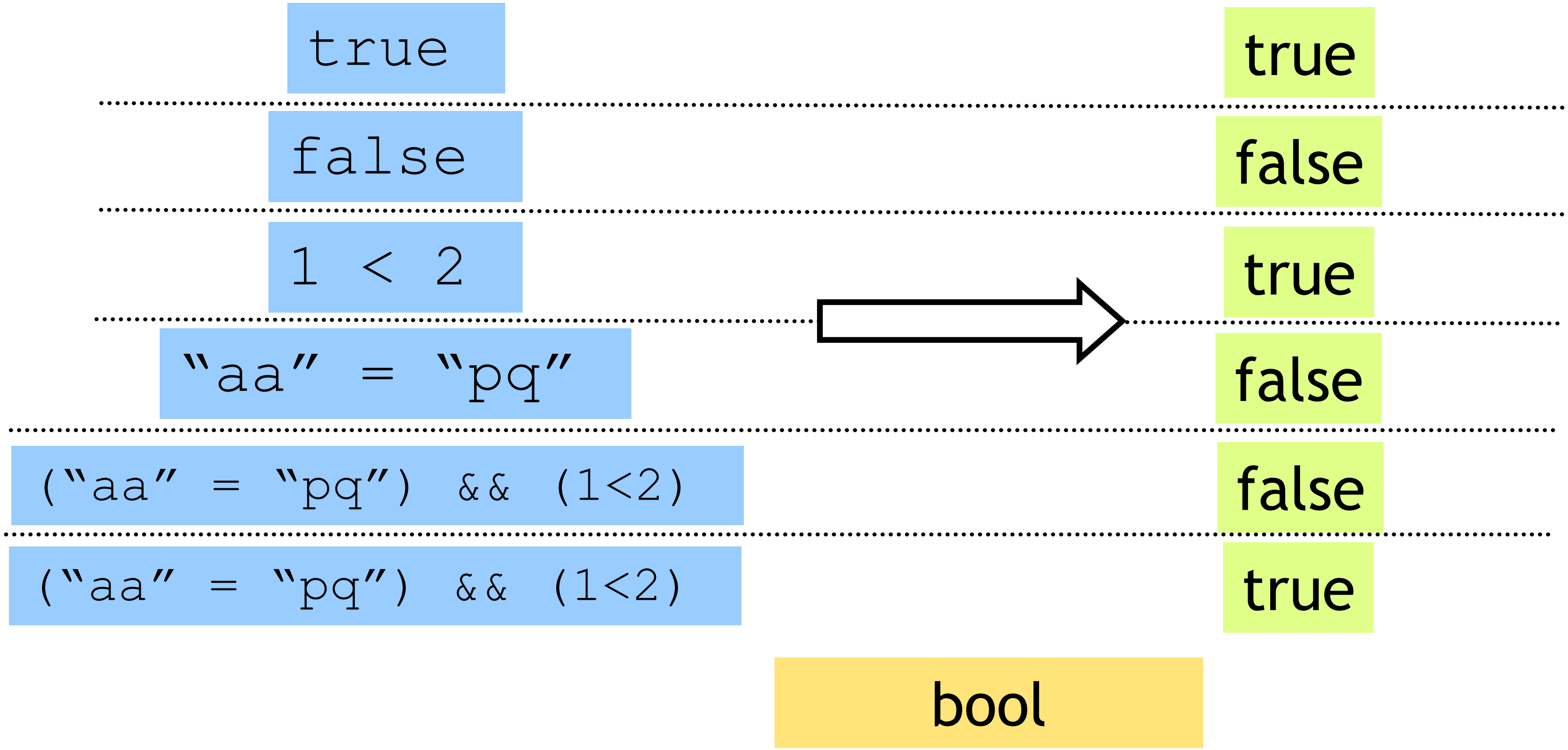
“abxy”

string

Complex expressions using “operators”: *(why the quotes ?)*

- Concatenation ^

Base type: Booleans



`true`	true
`false`	false
`1 < 2`	true
`“aa” = “pq”`	false
`(“aa” = “pq”) && (1<2)`	false
`(“aa” = “pq”) && (1<2)`	true

bool

Complex expressions using “operators”:

- “Relations”: = , <, <=, >=
- &&, ||, not

Type Errors

```
(2+3) || (“a” = “b”)
```

```
“pq” ^ 9
```

```
(2 + “a”)
```

Untypable expression is rejected

- No casting or coercing
- Fancy algorithm to catch errors
- ML’s single most powerful feature

Complex types: Product (tuples)

```
(2+2 , 7>8);
```

→

(4,false)

int * bool

Complex types: Product (tuples)

`(9-3,“ab”^“cd”,(2+2 ,7>8))` ⇒ (6, “abcd”,(4,false))

(int * string * (int * bool))

- Triples,…
- Nesting:
  - Everything is an expression, nest tuples in tuples

Complex types: Lists

`[];`	[]	’a list
`[1;2;3];`	[1;2;3]	int list
`[1+1;2+2;3+3;4+4];`	[2;4;6;8]	int list
`[“a”;“b”; “c”^“d”];`	[“a”;“b”; “cd”]	string list
`[(1,“a”^“b”);(3+4,“c”)];`	[(1,“ab”);(7,“c”)]	(int*string) list
`[[1];[2;3];[4;5;6]];`	[[1];[2;3];[4;5;6]];	(int list) list

- Unbounded size
- Can have lists of anything
- But…

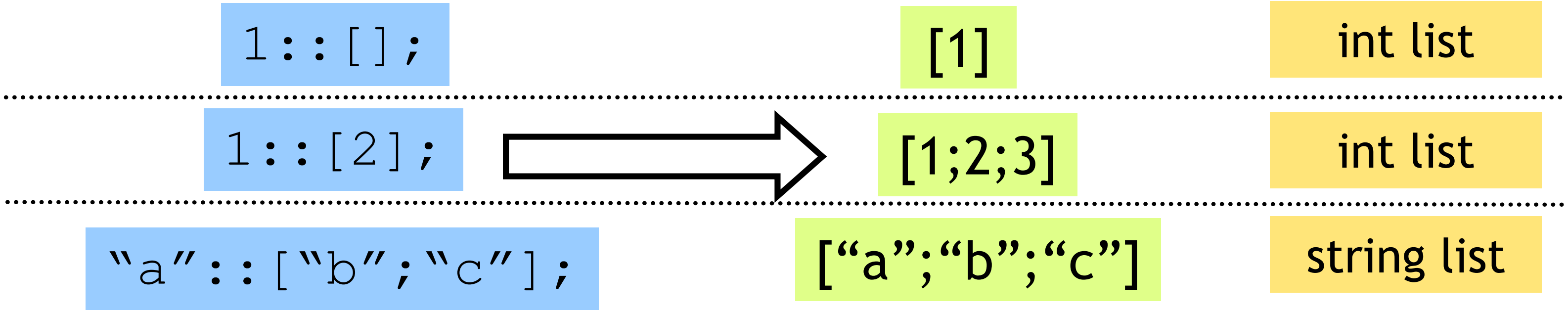
Complex types: Lists

```
[1; “pq”];
```

All elements must have same type

Complex types: Lists

List operator “Cons” `::`



`1::[];`	[1]	int list
`1::[2];`	[1;2;3]	int list
`“a”::[“b”;“c”];`	[“a”;“b”;“c”]	string list

Can only “cons” element to a list of same type

```
1::[“b”; “cd”];
```

Complex types: Lists

List operator “Append” @

`[1;2]@[3;4;5];`	[1;2;3;4;5]	int list
`[“a”]@[“b”];`	[“a”;“b”]	string list
`[]@[1];`	[1]	string list

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

… of the same type `[1] @ [“a”;“b”];`

Complex types: Lists

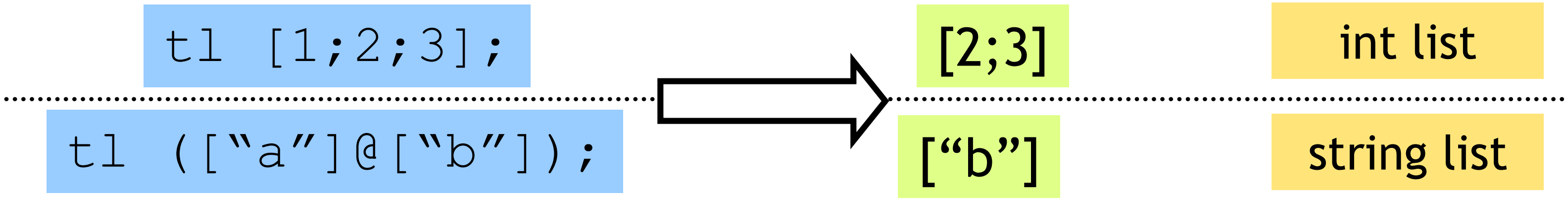
List operator “head” `hd`

`hd [1;2];`	⇒	1	int
`hd ([“a”]@[“b”]);`		“a”	string

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

Complex types: Lists

List operator “tail” `tl`



Expression	Result	Type
`tl [1;2;3];`	[2;3]	int list
`tl ([“a”]@[“b”]);`	[“b”]	string list

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

Recap: Tuples vs. Lists ?

What’s the difference ?

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 * (real * real))

    - triple = 3 elts
- Lists:
  - Same type, unbounded number:

    [3;4;5;6;7]   int list
- Syntax:
  - Tuples = comma   Lists = semicolon

So far, a fancy calculator…

… what do we need next ?

Variables and bindings

```
let x = e;
```

“Bind the value of expression `e`

to the variable `x`”

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

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

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 (“in scope”) outside

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]
```

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]
```

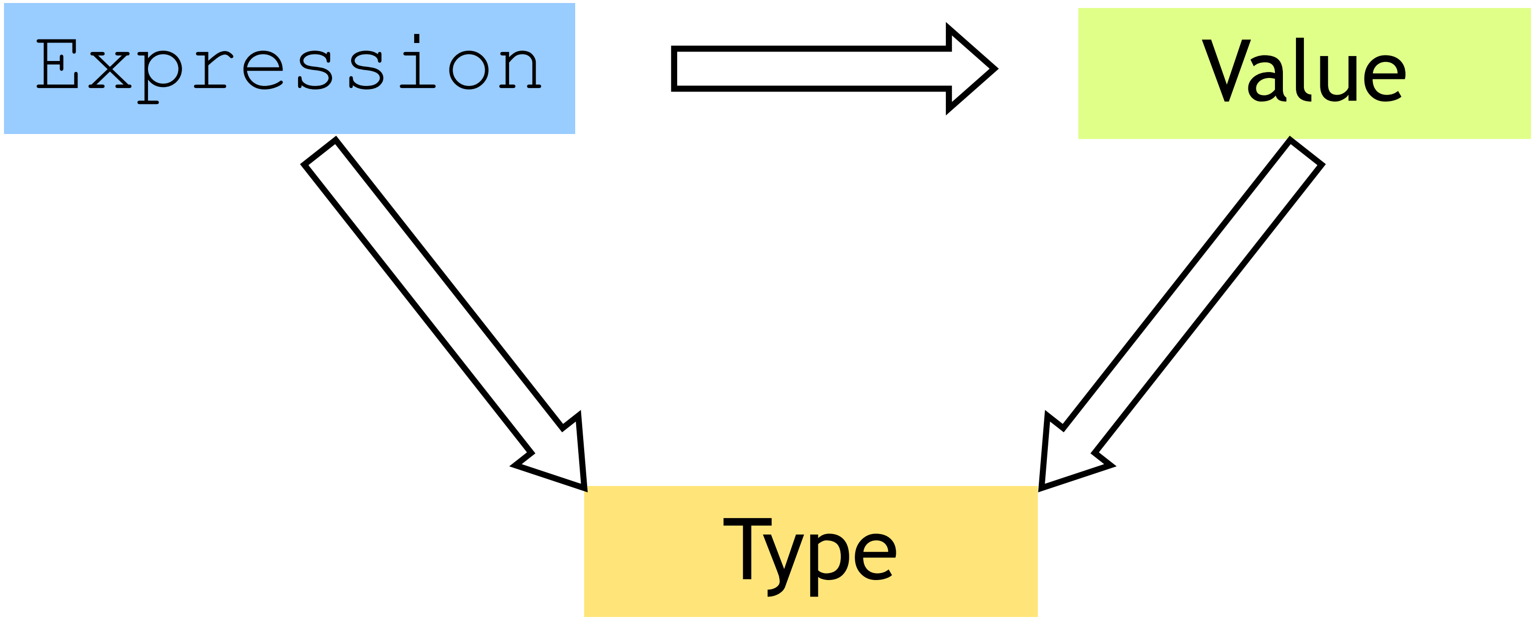
Why is it whining ?

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

In general l may be empty (match failure!)

Another useful early warning

Next : functions, but remember …



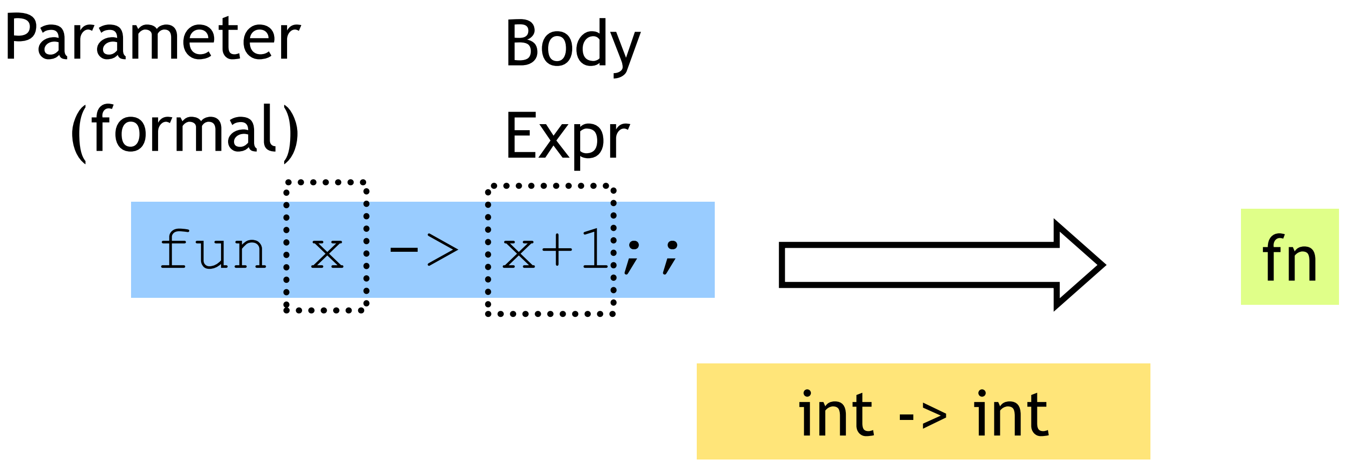
Everything is an expression

Everything has a value

Everything has a type

A function is …

Complex types: Functions!



Parameter (formal)

Body Expr

```
fun x -> x+1;;
```

fn

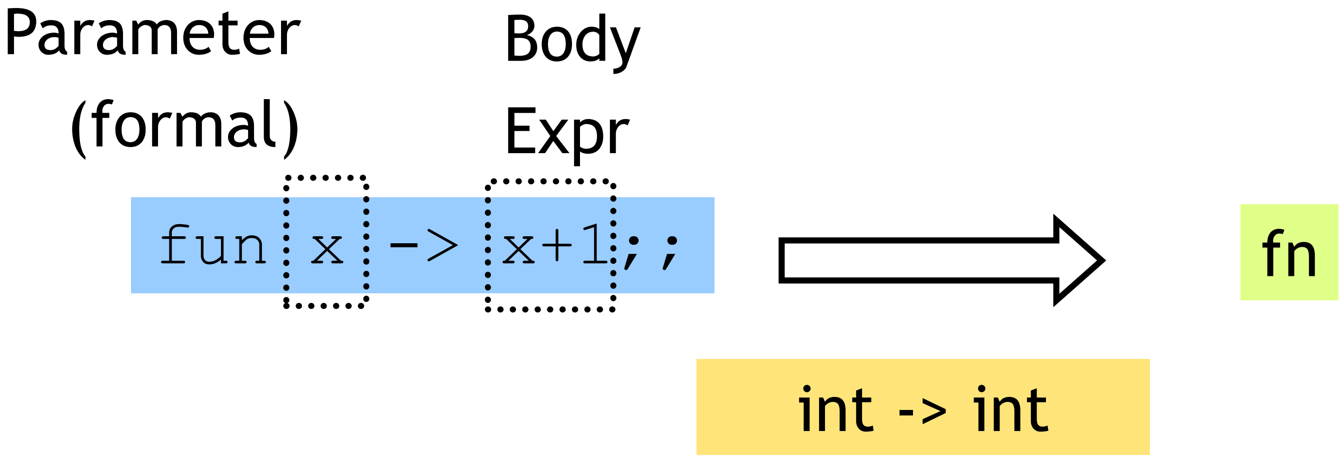
int -> int

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

How a call (“application”) is evaluated:

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

A Problem



Parameter (formal)

Body Expr

```
fun x -> x+1;;
```

fn

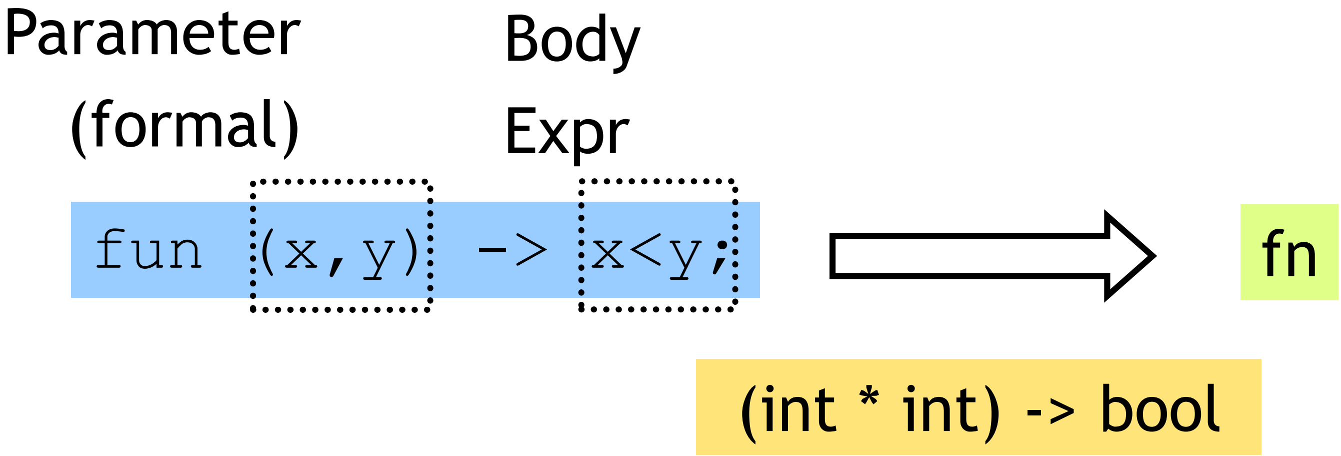
int -> int

Can functions only have a single parameter ?

How a call (“application”) is evaluated:

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

A Solution: Simultaneous Binding



Parameter
(formal)

Body
Expr

```
fun (x,y) -> x<y;
```

fn

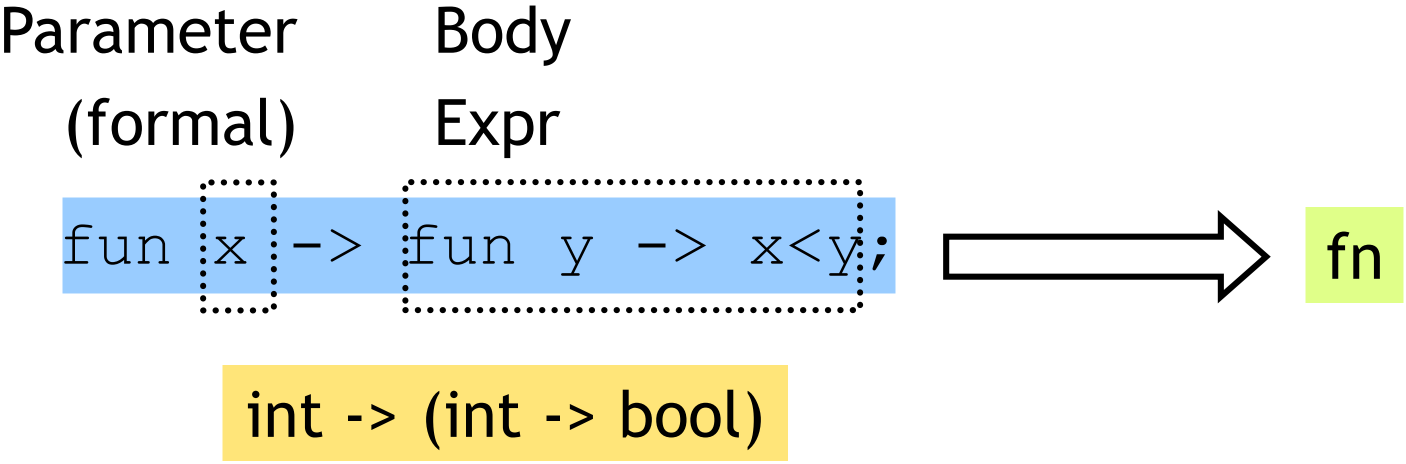
(int * int) -> bool

Can functions only have a single parameter ?

How a call (“application”) is evaluated:

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

Another Solution



Parameter (formal)

Body Expr

```
fun x -> fun y -> x<y;
```

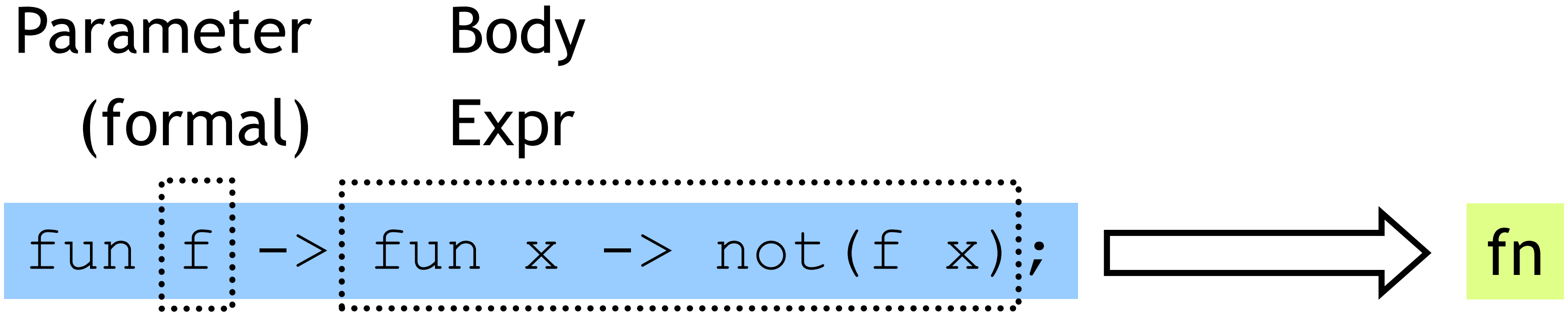
fn

int -> (int -> bool)

Whoa! A function can return a function

```
# let lt = fun x -> fn 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;
```

And how about…



Parameter (formal)

Body Expr

```
fun f -> fun x -> not(f x);
```

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 …*)
```

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;
```

Put it together: a “filter” function

If arg “matches”
this pattern…

…then use
this Body Expr

```
- let rec filter f l =
       match l with
       []  -> []
     | (h::t)->  if f h then h::(filter f t)
                 else (filter f t);;

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 = [1,2,10]
# filter even list1;;
val it : int list = [12,4,2,10]
```

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])
```

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;
```

Put it together: a “quicksort” function

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