

The Environment Model

Concepts of Programming Languages

Outline

- » Discuss the difference between **dynamic** and lexical scoping
- » Introduce **closures** as a way of implementing lexical scoping in the environment model
- » Give example **derivations** using closures
- » Discuss **recursion** and closures
- » Demo an **implementation** of the lambda calculus⁺ let expressions using closures

Variable Scoping

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- » immutable
- » binding defined
- » lexically scoped

Mutability

```
let x = 0
let f () =
  let x = 1 in
  ()
print_int x
```

Immutable (OCaml)

```
x = 0
def f():
    global x
    x = 1
print(x)
```

Mutable (Python)

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We think of variables as:

- » **names** if they're immutable
- » **(abstract) memory locations** when they're mutable

Scope

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- » the scope of a function

Dynamic Scoping

```
f() { x=23; g; }  
g() { y=$x; }  
f  
echo $y
```

Bash

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f() { x=23; g; }  
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Dynamic scoping refers to when bindings are determined at runtime based on *computational context*

Dynamic Scoping

x = 23
y = x
print(y)

```
f() { x=23; g; }  
g() { y=$x; }  
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```

Bash

Dynamic scoping refers to when bindings are determined at runtime based on *computational context*

This is a *temporal view*, i.e., what a computation done beforehand which affected the value of a variable

Lexical Scoping

```
x = 0
def f():
    x = 1
    return x
assert(f() == 1)
assert(x == 0)
```

Python

```
let x = 0
let f () =
    let x = 1 in
    x
let _ = assert (f () = 1)
let _ = assert (x = 0)
```

OCaml

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Lexical (static) scoping refers to the use of textual delimiters to define the scope of a binding

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» The binding defines it's own scope (**let-bindings**)

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OCaml

Lexical (static) scoping refers to the use of textual delimiters to define the scope of a binding

There are two common ways lexical scope is determined:

- » The binding defines it's own scope (**let-bindings**)
- » A block defines the scope of a variable (**python functions**)

Tradeoffs

```
f() { x=23; g; }  
g() { y=$x; }  
f  
echo $y
```

dynamic

vs.

```
let x = 0  
let f () =  
  let x = 1 in  
  x  
let _ = assert (f () = 1)  
let _ = assert (x = 0)
```

lexical

Implementing dynamic scoping is *way* easier... (we'll see this in lab)

But **every modern programming language** implements lexical scoping

The Environment Model

Why are we do this?

```
let x = v in ...
```

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We've already implemented lexical scoping using the substitution model (mini-project 1) *Why do it again?*

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Answer. The substitution model is inefficient

Each substitution has to "crawl" through the *entire remainder of the program*

High Level

$$\langle \mathcal{E}, e \rangle \Downarrow v$$

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And evaluate *relative* to the environment, *lazily*
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*The **configurations** in our semantics will have nonempty state*

Environment

\mathcal{E}

environment

$\text{Var} \mapsto \text{Vals}$

partial mapping

dictionary

ex.

$\{x \mapsto 1, y \mapsto 2\}$

\emptyset

empty env.

$\mathcal{E}(x)$ or $\mathcal{E}[x]$

value of x in \mathcal{E}

$x \notin \text{dom}(\mathcal{E})$

x is not mapped in \mathcal{E}

$\mathcal{E}[x \mapsto v]$

add $x \mapsto v$ to \mathcal{E}

Shadowing

$$\{ [x \mapsto v_1] [x \mapsto v_2] \} = \{ [x \mapsto v_2] \}$$

$$\{ x \mapsto 1, y \mapsto 2 \} [x \mapsto 3] = \{ x \mapsto 3, y \mapsto 2 \}$$

Lambda Calculus⁺ (Syntax)

```
<expr> ::= λ<var>.<expr>
          | <var>
          | <expr><expr>
          | let <var> = <expr>
            in <expr>
          | <num>

<val>   ::= λ<var>.<expr>
          | <num>
```

This is a grammar for the lambda calculus with let-expressions and numbers

Lambda Calculus⁺ (Semantics)

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"values evaluate to values"

$$\frac{}{\langle \mathcal{E}, \lambda x. e \rangle \Downarrow \lambda x. e}$$

$$\frac{}{\langle \mathcal{E}, n \rangle \Downarrow n}$$

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"variables evaluate to their values in the environment"

$$\frac{\mathcal{E}(x) \neq \perp}{\langle \mathcal{E}, x \rangle \Downarrow \mathcal{E}(x)}$$

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$[v_1 / x] e_2$

$$\frac{\langle \mathcal{E}, e_1 \rangle \Downarrow v_1 \quad \langle \mathcal{E}[x \mapsto v_1], e_2 \rangle \Downarrow v_2}{\langle \mathcal{E}, \text{let } x = e_1 \text{ in } e_2 \rangle \Downarrow v_2}$$

$$\frac{\langle \mathcal{E}, e_1 \rangle \Downarrow \lambda x. e \quad \langle \mathcal{E}, e_2 \rangle \Downarrow v_2 \quad \langle \mathcal{E}[x \mapsto v_2], e \rangle \Downarrow v}{\langle \mathcal{E}, e_1 e_2 \rangle \Downarrow v}$$

$[v_2 / x] e$

"applications and let-expressions store arguments in the environment"

Why are these rules incorrect?

let $x = 0$ in

let $f = \lambda y . x$ in

let $x = 1$ in

$f\ 0$

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let $x = 0$ in

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What's the value of this expression?

Example

$$\overline{\langle \mathcal{E}, \lambda x . e \rangle \Downarrow \lambda x . e}$$

$$\overline{\langle \mathcal{E}, n \rangle \Downarrow n}$$

$$\overline{\langle \mathcal{E}, x \rangle \Downarrow \mathcal{E}(x)}$$

$$\frac{\langle \mathcal{E}, e_1 \rangle \Downarrow \lambda x . e \quad \langle \mathcal{E}, e_2 \rangle \Downarrow v_2 \quad \langle \mathcal{E}[x \mapsto v_2], e \rangle \Downarrow v}{\langle \mathcal{E}, e_1 e_2 \rangle \Downarrow v}$$

$$\frac{\langle \mathcal{E}, e_1 \rangle \Downarrow v_1 \quad \langle \mathcal{E}[x \mapsto v_1], e_2 \rangle \Downarrow v_2}{\langle \mathcal{E}, \text{let } x = e_1 \text{ in } e_2 \rangle \Downarrow v_2}$$

$$\langle \{x \mapsto 0, f \mapsto \lambda y . x\}, \text{let } x = 1 \text{ in } f \ 0 \rangle \Downarrow 1$$

Let's derive the above judgment in the given system

Example

$$\{x \mapsto 0, f \mapsto \lambda y. x\} [x \mapsto 1] = \{x \mapsto 1, f \mapsto \lambda y. x\}$$

$$\frac{}{\langle \mathcal{E}, \lambda x. e \rangle \Downarrow \lambda x. e} \quad \frac{}{\langle \mathcal{E}, n \rangle \Downarrow n}$$

$$\frac{}{\langle \mathcal{E}, x \rangle \Downarrow \mathcal{E}(x)}$$

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$$\frac{}{\langle \{ \dots \}, 0 \rangle \Downarrow 0}$$

$$\{x \mapsto 1, f \mapsto \lambda y. x\} [\gamma \mapsto 0]$$

$$\frac{}{\langle \{x \mapsto 1, f \mapsto \lambda y. x\}, f \rangle \Downarrow \lambda y. x}$$

$$\frac{}{\langle \{x \mapsto 1, \gamma \mapsto 0, f \mapsto \lambda y. x\}, x \rangle \Downarrow 1}$$

$$\frac{}{\langle \{x \mapsto 0, f \mapsto \lambda y. x\}, 1 \rangle \Downarrow 1}$$

$$\frac{}{\langle \{x \mapsto 1, \gamma \mapsto \lambda y. x\}, f 0 \rangle \Downarrow 1}$$

$$\langle \{x \mapsto 0, f \mapsto \lambda y. x\}, \text{let } x = 1 \text{ in } f 0 \rangle \Downarrow 1$$

⋮

$$\langle \emptyset, \text{let } x = 0 \text{ in let } f = \lambda y. x \text{ in let } x = 1 \text{ in } f 0 \rangle \Downarrow 1$$

Closures

Definition / Notation

$$(\mathcal{E}, e)$$

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The environment *captures* bindings which a function needs

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The environment *captures* bindings which a function needs

Functions need to *remember* what the environment looks like in order to behavior correctly according to lexical scoping

Lambda Calculus⁺ (Values)

$$\text{Val} = \mathbb{Z} \cup \text{Cls}$$

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A value (a member of the set Val) is a **closure** (a member of the set Cls) or a **number** (a member of the set \mathbb{Z})

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Important. Values no longer correspond with *expressions*. We're using the distinction between values and expressions to create a more efficient (and correct) semantics

Lambda Calculus⁺ (Correct Semantics)

values and variables

$$\frac{}{\langle \mathcal{E}, \lambda x. e \rangle \Downarrow (\mathcal{E}, \lambda x. e)} \quad \frac{}{\langle \mathcal{E}, n \rangle \Downarrow n} \quad \frac{\mathcal{E}(x) \neq \perp}{\langle \mathcal{E}, x \rangle \Downarrow \mathcal{E}(x)}$$

application

$$\frac{\langle \mathcal{E}, e_1 \rangle \Downarrow (\mathcal{E}', \lambda x. e) \quad \langle \mathcal{E}, e_2 \rangle \Downarrow v_2 \quad \langle \mathcal{E}'[x \mapsto v_2], e \rangle \Downarrow v}{\langle \mathcal{E}, e_1 e_2 \rangle \Downarrow v}$$

let-expressions

$$\frac{\langle \mathcal{E}, e_1 \rangle \Downarrow v_1 \quad \langle \mathcal{E}[x \mapsto v_1], e_2 \rangle \Downarrow v_2}{\langle \mathcal{E}, \text{let } x = e_1 \text{ in } e_2 \rangle \Downarrow v_2}$$

$$\frac{}{\langle \phi, \lambda x. y \rangle \Downarrow (\phi, \lambda x. y)}$$

$$\frac{}{\langle \phi, z \rangle \Downarrow z}$$

$$\frac{}{\langle \{x \mapsto z\}, y \rangle}$$

$y \notin \text{dom}(\mathcal{E})$

$$\langle \phi, (\lambda x. y) z \rangle$$

Practice Problem

$$\frac{}{\langle \mathcal{E}, \lambda x. e \rangle \Downarrow \{\mathcal{E}, \lambda x. e\}} \quad \frac{}{\langle \mathcal{E}, n \rangle \Downarrow n}$$

(var)

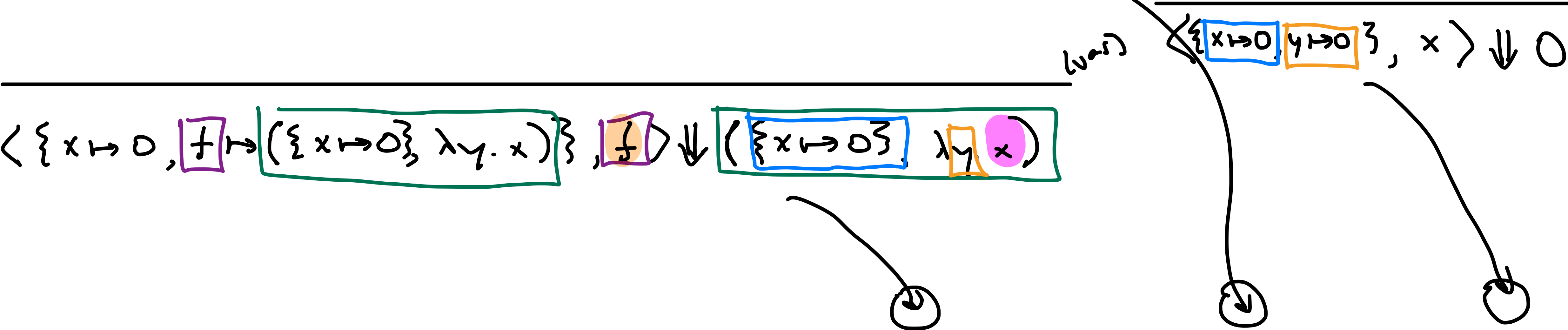
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ε

$$\frac{}{\langle \{ \dots \}, 0 \rangle \Downarrow 0}$$



$$\frac{}{\langle \{ x \mapsto 0 \}, \lambda y. x \rangle \Downarrow (\{ x \mapsto 0 \}, \lambda y. x)}$$

$$\frac{}{\langle \{ x \mapsto 0, f \mapsto (\{ x \mapsto 0, \lambda y. x \}) \}, f 0 \rangle \Downarrow 0}$$

$$\frac{}{\langle \{ x \mapsto 0 \}, \text{let } f = \lambda y. x \text{ in } \text{let } x = 1 \text{ in } f 0 \rangle \Downarrow 0}$$

Practice Problem

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Exercise

$$\frac{}{\langle \{x \mapsto 0\}, f \mapsto (\{x \mapsto 0\}, \lambda y. x) \}, 1 \rangle \Downarrow 1}$$

$$\frac{}{\langle \{x \mapsto 1\}, f \mapsto (\{x \mapsto 0\}, \lambda y. x) \}, f\ 0 \rangle \Downarrow 0}$$

$$\langle \{x \mapsto 0\}, f \mapsto (\{x \mapsto 0\}, \lambda y. x) \}, \text{let } x = 1 \text{ in } f\ 0 \rangle \Downarrow 0$$

⋮

$$\langle \{x \mapsto 0\}, \text{let } f = \lambda y. x \text{ in let } x = 1 \text{ in } f\ 0 \rangle \Downarrow 0$$

Recursion

High-Level

```
let f x =  
  if x = 0  
  then 1  
  else f (x - 1)  
in f 10
```

High-Level

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let f x =  
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```

What will happen if we evaluate the above program in our environment model (if we've given semantics to if-expressions, subtraction, etc)?

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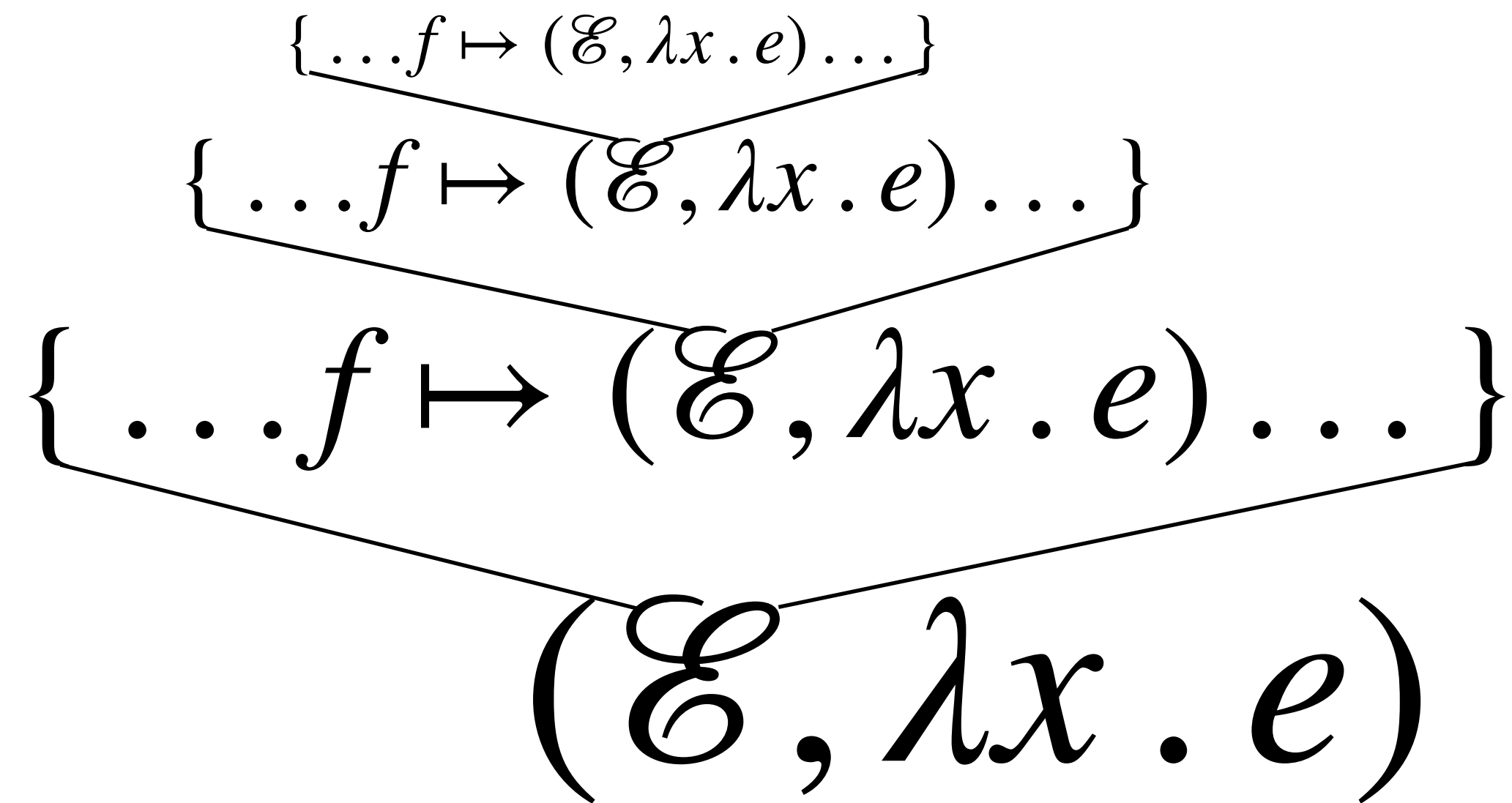
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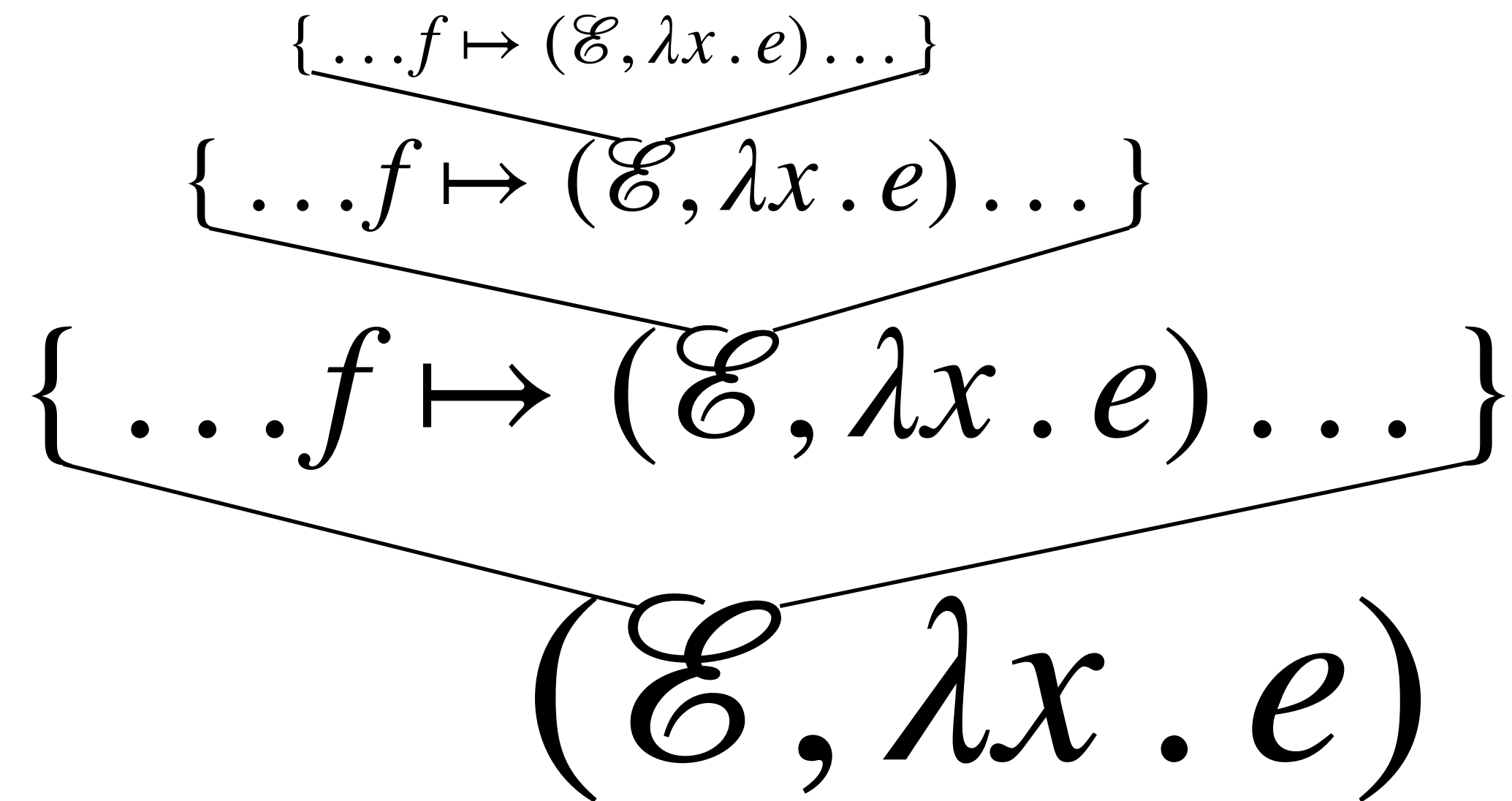
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In the substitution model, there's no natural way to do it (though we can use fix-point combinators...)

The Problem

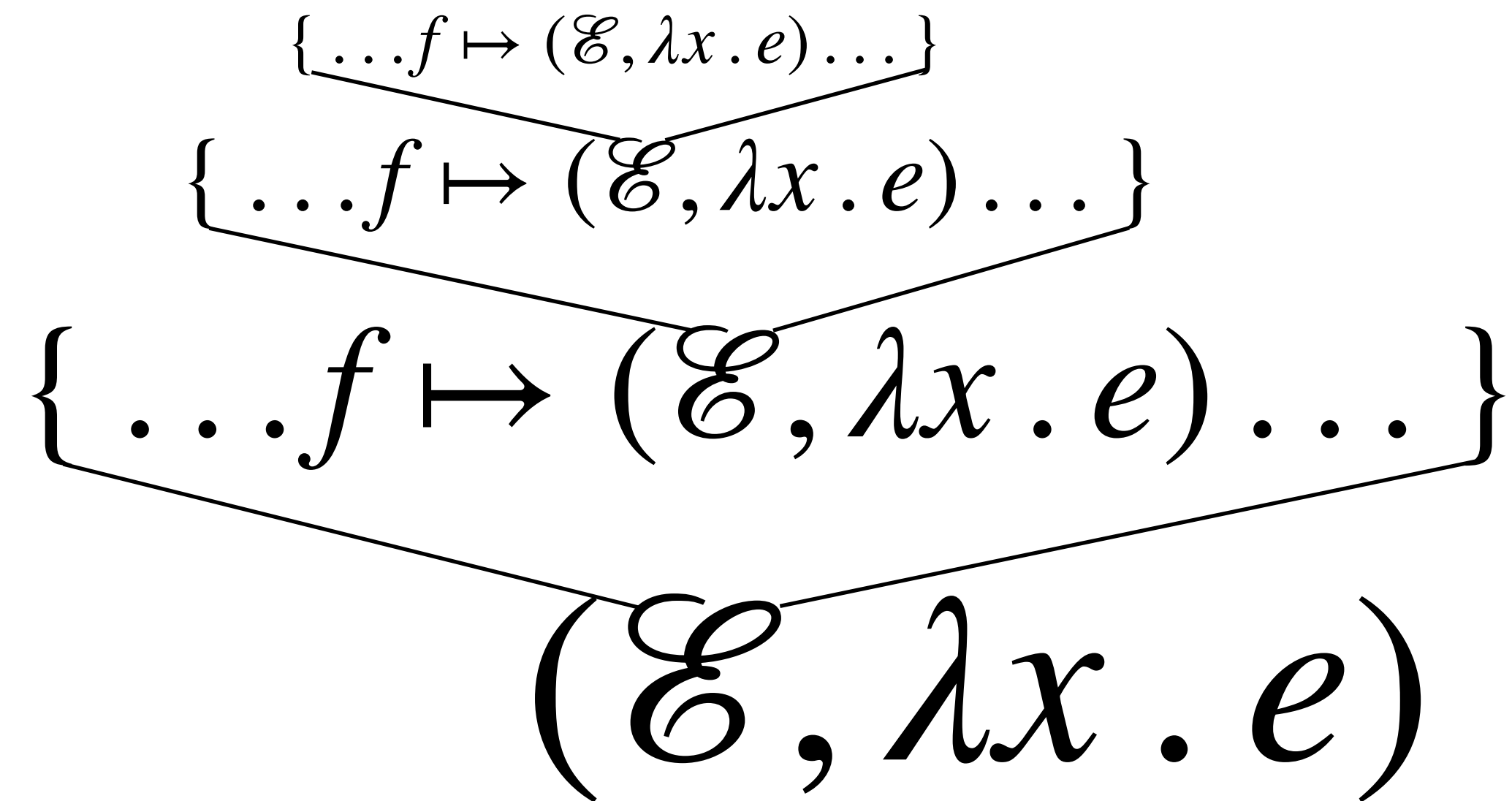


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In order to implement recursion, a closure has to "*know thyself*"

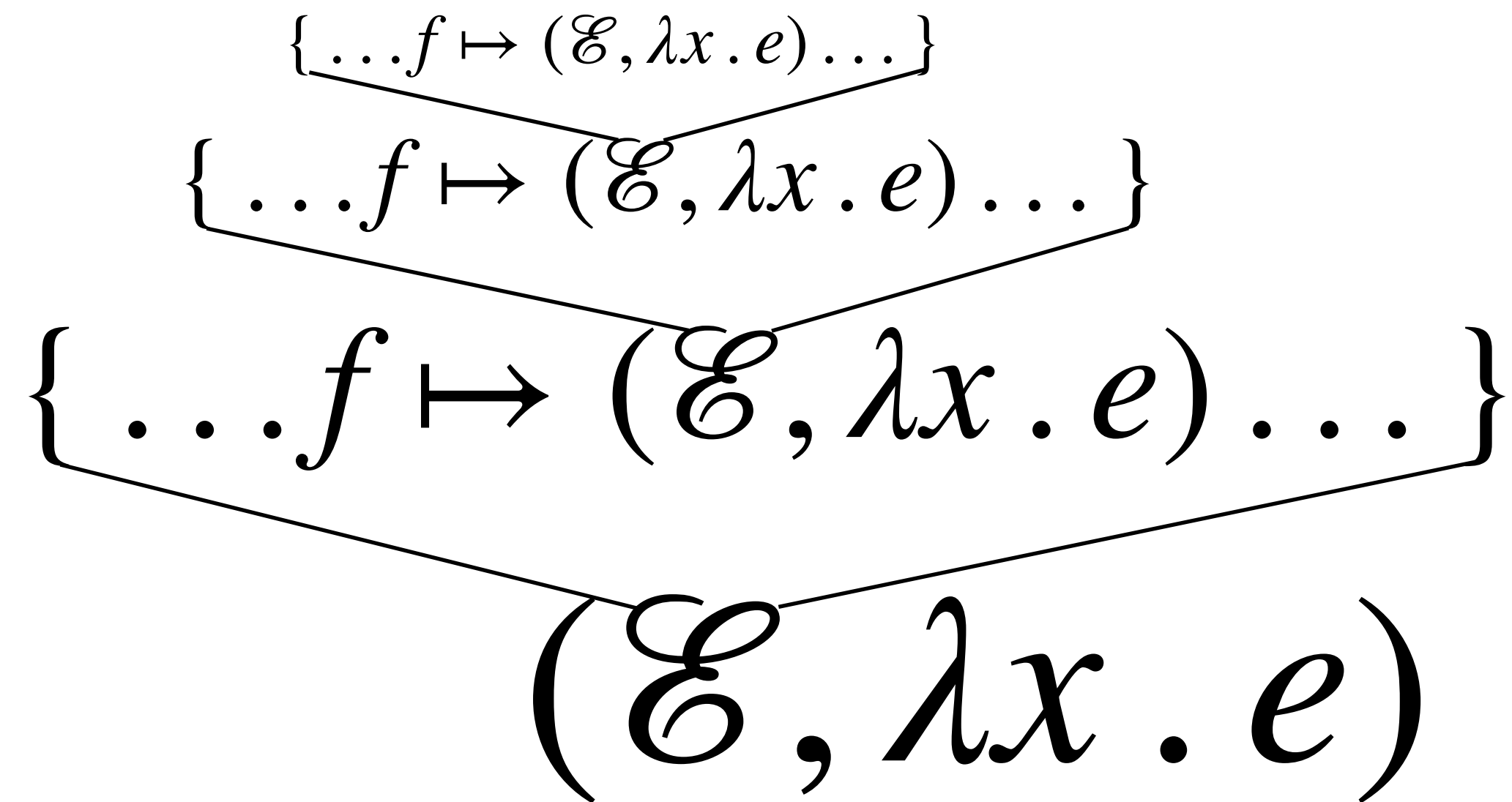
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But we **can't** implement circular structures like this in OCaml

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In order to implement recursion, a closure has to "*know thyself*"

But we **can't** implement circular structures like this in OCaml

We need a way essentially to "simulate" pointers

Solution: Named Closures

$(\text{name}, \mathcal{E}, \lambda x. e)$

We need to be able to *name* closures

The idea. Named closures will put themselves into their environment *when they're called*

Lambda Calculus⁺⁺ (Syntax, Again)

```
<expr> ::= λ<var>.<expr>
          | <var>
          | <expr><expr>
          | let <var> = <expr>
            in <expr>
          | let rec <var> <var> = <expr>
            in <expr>
          | <num>
```

Lambda Calculus⁺⁺ (Syntax, Again)

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The same grammar as before, but with recursive let-statements

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```

The same grammar as before, but with recursive let-statements

Important. A recursive let **must** take an argument

Lambda Calculus⁺⁺ (Semantics)

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values and variables

$$\frac{}{\langle \mathcal{E}, \lambda x . e \rangle \Downarrow (\mathcal{E}, \lambda x . e)}$$

$$\frac{}{\langle \mathcal{E}, n \rangle \Downarrow n}$$

$$\frac{\mathcal{E}(x) \neq \perp}{\langle \mathcal{E}, x \rangle \Downarrow \mathcal{E}(x)}$$

Lambda Calculus⁺⁺ (Semantics)

values and variables

$$\frac{}{\langle \mathcal{E}, \lambda x. e \rangle \Downarrow (\mathcal{E}, \lambda x. e)} \quad \frac{}{\langle \mathcal{E}, n \rangle \Downarrow n} \quad \frac{\mathcal{E}(x) \neq \perp}{\langle \mathcal{E}, x \rangle \Downarrow \mathcal{E}(x)}$$

application (unnamed closure)

$$\frac{\langle \mathcal{E}, e_1 \rangle \Downarrow (\mathcal{E}', \lambda x. e) \quad \langle \mathcal{E}, e_2 \rangle \Downarrow v_2 \quad \langle \mathcal{E}'[x \mapsto v_2], e \rangle \Downarrow v}{\langle \mathcal{E}, e_1 e_2 \rangle \Downarrow v}$$

Lambda Calculus⁺⁺ (Semantics)

values and variables

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application (named closure)

$$\frac{\langle \mathcal{E}, e_1 \rangle \Downarrow (f, \mathcal{E}', \lambda x. e) \quad \langle \mathcal{E}, e_2 \rangle \Downarrow v_2 \quad \langle \mathcal{E}'[f \mapsto (f, \mathcal{E}', \lambda x. e)][x \mapsto v_2], e \rangle \Downarrow v}{\langle \mathcal{E}, e_1 e_2 \rangle \Downarrow v}$$

Lambda Calculus⁺⁺ (Semantics)

values and variables

$$\frac{}{\langle \mathcal{E}, \lambda x . e \rangle \Downarrow (\mathcal{E}, \lambda x . e)} \quad \frac{}{\langle \mathcal{E}, n \rangle \Downarrow n} \quad \frac{\mathcal{E}(x) \neq \perp}{\langle \mathcal{E}, x \rangle \Downarrow \mathcal{E}(x)}$$

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application (named closure)

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let expressions

$$\frac{\langle \mathcal{E}, e_1 \rangle \Downarrow v_1 \quad \langle \mathcal{E}[x \mapsto v_1], e_2 \rangle \Downarrow v_2}{\langle \mathcal{E}, \text{let } x = e_1 \text{ in } e_2 \rangle \Downarrow v_2}$$

$$\frac{\langle \mathcal{E}[f \mapsto (f, \mathcal{E}, \lambda x . e_1)], e_2 \rangle \Downarrow v_2}{\langle \mathcal{E}, \text{let rec } f x = e_1 \text{ in } e_2 \rangle \Downarrow v_2}$$

Closer Look (Application)

$$\frac{\langle \mathcal{E}, e_1 \rangle \Downarrow (f, \mathcal{E}', \lambda x. e) \quad \langle \mathcal{E}, e_2 \rangle \Downarrow v_2 \quad \langle \mathcal{E}'[f \mapsto (f, \mathcal{E}', \lambda x. e)][x \mapsto v_2], e \rangle \Downarrow v}{\langle \mathcal{E}, e_1 e_2 \rangle \Downarrow v}$$

The only change here is that f is put into environment when f is called

This happens *every time* f is called (even within the body of f)

Closer Look (Recursive Definitions)

$$\frac{\langle \mathcal{E}[f \mapsto (f, \mathcal{E}, \lambda x. e_1)], e_2 \rangle \Downarrow v_2}{\langle \mathcal{E}, \text{let rec } f \ x = e_1 \text{ in } e_2 \rangle \Downarrow v_2}$$

When a recursive function is declared it's given a *named* closure

Remember that we **must** take an argument in the case of a recursive closure

demo

(lambda calculus⁺)

Summary

Functions evaluate to **closures** so that they remember the environment in which they are defined

Recursive function evaluate to **named** closures so that they know how to evaluate themselves(!)