

# MPRI 2.4

## From operational semantics to interpreters

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# The $\lambda$ -calculus

The formal model that underlies all functional programming languages.

Abstract syntax:

$$t, u ::= x \mid \lambda x. t \mid t \ t \quad (\text{terms})$$

Reduction:

$$(\lambda x. t) \ u \longrightarrow t[u/x] \quad (\beta)$$

Mnemonic: read  $t[u/x]$  as “ $t$ , where  $u$  is substituted for  $x$ ”.

Landin, **Correspondence betw. ALGOL 60 and Church's  $\lambda$ -notation**, 1965.

*“It seems possible that the correspondence might form the basis of a formal description of the semantics of Algo 60.”*

## From the $\lambda$ -calculus to a functional programming language

Start from the  $\lambda$ -calculus, and follow several steps:

- Fix a **reduction strategy** (today).
- Develop **efficient execution mechanisms** (today).
- **Enrich the language** with primitive data types and operations, recursion, algebraic data structures, and so on.
- Define a static **type system** (next week).

Landin, **The next 700 programming languages**, 1966.

*“Most programming languages are partly a way of expressing things in terms of other things and partly a basic set of given things.”*

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- Call-by-name
- Call-by-need

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## Operational semantics

An operational semantics describes **the actions of a machine**, in the simplest possible manner / at the most abstract level.

Plotkin, **A Structural Approach to Operational Semantics**, 1981, (2004).

Plotkin, **The Origins of Structural Operational Semantics**, 2004.

Plotkin: — *It is only through having an operational semantics that the  $[\lambda\text{-calculus}]$  can be viewed as a programming language.*

Scott: — *Why call it operational semantics? What is operational about it?*

## Denotational semantics

Scott preferred **denotational** semantics, where the meaning of a program is a mathematical function of an input to an output.

Benton, Kennedy, Varming,

**Some Domain Theory and Denotational Semantics in Coq**, 2009.

Benton, Birkedal, Kennedy, Varming, **Formalizing domains, ultrametric spaces and semantics of programming languages**, 2010.

Dockins, **Formalized, Effective Domain Theory in Coq**, 2014.

# The call-by-value strategy

Values form a subset of terms:

$$\begin{aligned} t, u &::= x \mid \lambda x. t \mid t \ t && \text{(terms)} \\ v &::= x \mid \lambda x. t && \text{(values)} \end{aligned}$$

A value represents the **result** of a computation.

The **call-by-value** reduction relation  $t \longrightarrow_{\text{cbv}} t'$  is inductively defined:

$$\begin{array}{c} \beta_v \\ \hline (\lambda x. t) \textcolor{red}{v} \longrightarrow_{\text{cbv}} t[\textcolor{red}{v}/x] \end{array} \qquad \begin{array}{c} \text{APPL} \\ t \longrightarrow_{\text{cbv}} t' \\ \hline t \ u \longrightarrow_{\text{cbv}} t' \ u \end{array} \qquad \begin{array}{c} \text{APPVR} \\ u \longrightarrow_{\text{cbv}} u' \\ \hline \textcolor{red}{v} \ u \longrightarrow_{\text{cbv}} \textcolor{red}{v} \ u' \end{array}$$

This is known as a **small-step** operational semantics.



# Example

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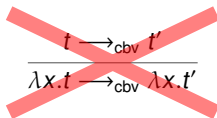
An efficient  
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This is a proof (a.k.a. derivation) that **one** reduction step is permitted:

$$\frac{\frac{\frac{x[1/x] = 1}{(\lambda x.x) \ 1 \longrightarrow_{cbv} 1} \beta_v}{(\lambda x.\lambda y.y \ x) \ ((\lambda x.x) \ 1) \longrightarrow_{cbv} (\lambda x.\lambda y.y \ x) \ 1} \text{AppR}}{(\lambda x.\lambda y.y \ x) \ ((\lambda x.x) \ 1) \ (\lambda x.x) \longrightarrow_{cbv} (\lambda x.\lambda y.y \ x) \ 1 \ (\lambda x.x)} \text{AppL}$$

## Features of call-by-value reduction

- **Weak reduction.** One cannot reduce under a  $\lambda$ -abstraction.

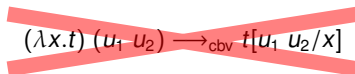

$$\frac{t \rightarrow_{\text{cbv}} t'}{\lambda x. t \rightarrow_{\text{cbv}} \lambda x. t'}$$

Thus, **values do not reduce.**

Also, we are interested in reducing **closed terms** only.

- **Call-by-value.** An actual argument is reduced to a value **before** it is passed to a function.

$$(\lambda x. t) \mathbf{v} \rightarrow_{\text{cbv}} t[\mathbf{v}/x]$$


$$(\lambda x. t) (u_1 u_2) \rightarrow_{\text{cbv}} t[u_1 u_2/x]$$

# Features of call-by-value reduction

- **Left-to-right.** In an application  $t\ u$ , the term  $t$  must be reduced to a value before  $u$  can be reduced at all.

$$\begin{array}{c} \text{APPVR} \\ \frac{u \longrightarrow_{\text{cbv}} u'}{\textcolor{red}{v}\ u \longrightarrow_{\text{cbv}} \textcolor{red}{v}\ u'} \end{array}$$

- **Determinism.** For every term  $t$ , there is at most one term  $t'$  such that  $t \longrightarrow_{\text{cbv}} t'$  holds.

## Reduction sequences

Sequences of reduction steps describe the behavior of a term.

The following three situations are mutually exclusive:

- **Termination:**  $t \longrightarrow_{\text{cbv}} t_1 \longrightarrow_{\text{cbv}} t_2 \longrightarrow_{\text{cbv}} \dots \longrightarrow_{\text{cbv}} v$   
The value  $v$  is the result of evaluating  $t$ .  
The term  $t$  **converges** to  $v$ .
- **Divergence:**  $t \longrightarrow_{\text{cbv}} t_1 \longrightarrow_{\text{cbv}} t_2 \longrightarrow_{\text{cbv}} \dots \longrightarrow_{\text{cbv}} t_n \longrightarrow_{\text{cbv}} \dots$   
The sequence of reductions is infinite.  
The term  $t$  **diverges**.
- **Error:**  $t \longrightarrow_{\text{cbv}} t_1 \longrightarrow_{\text{cbv}} t_2 \longrightarrow_{\text{cbv}} \dots \longrightarrow_{\text{cbv}} t_n \not\longrightarrow_{\text{cbv}} \cdot$   
where  $t_n$  is not a value, yet does not reduce:  $t_n$  is **stuck**.  
The term  $t$  **goes wrong**. This is a **runtime error**.

A strong **type system** rules out errors (Milner, 1978).

Some type systems rule out both errors and divergence.

## Examples of reduction sequences

Termination:

$$\begin{aligned}
 (\lambda x. \lambda y. y \ x) ((\lambda x. x) \ 1) (\lambda x. x) &\longrightarrow_{\text{cbv}} (\lambda x. \lambda y. y \ x) \ 1 (\lambda x. x) \\
 &\longrightarrow_{\text{cbv}} (\lambda y. y \ 1) (\lambda x. x) \\
 &\longrightarrow_{\text{cbv}} (\lambda x. x) \ 1 \\
 &\longrightarrow_{\text{cbv}} 1
 \end{aligned}$$

Divergence:

$$(\lambda x. x \ x) (\lambda x. x \ x) \longrightarrow_{\text{cbv}} (\lambda x. x \ x) (\lambda x. x \ x) \longrightarrow_{\text{cbv}} \dots$$

Error:

$$(\lambda x. x \ x) \ 2 \longrightarrow_{\text{cbv}} 2 \ 2 \not\longrightarrow_{\text{cbv}} \cdot$$

The active redex is highlighted in red.

## An alternative style: evaluation contexts

First, define **head reduction**:

$$\frac{\beta_v}{(\lambda x.t) \ v \longrightarrow_{\text{cbv}}^{\text{head}} t[v/x]}$$

Then, define **reduction** as head reduction under an evaluation context:

$$\frac{\text{CTX} \quad t \longrightarrow_{\text{cbv}}^{\text{head}} t'}{E[t] \longrightarrow_{\text{cbv}} E[t']}$$

where evaluation contexts  $E$  are defined by  $E ::= [] \mid E \ u \mid v \ E$ .

Wright and Felleisen, **A syntactic approach to type soundness**, 1992.

## Unique decomposition

In this alternative style, the determinism of the reduction relation follows from a **unique decomposition** lemma:

### Lemma (Unique Decomposition)

*For every term  $t$ , there exists at most one pair  $(E, u)$  such that*

- $t = E[u]$
- $\exists u' \quad u \longrightarrow_{cbv}^{head} u'.$

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# The call-by-name strategy

The **call-by-name** reduction relation  $t \longrightarrow_{\text{cbn}} t'$  is defined as follows:

$$\frac{\beta}{(\lambda x.t) \textcolor{red}{u} \longrightarrow_{\text{cbn}} t[\textcolor{red}{u}/x]} \qquad \frac{\text{APPL} \quad t \longrightarrow_{\text{cbn}} t'}{t \textcolor{red}{u} \longrightarrow_{\text{cbn}} t' \textcolor{red}{u}}$$

The **unevaluated** actual argument is passed to the function.

It is later reduced if / when / every time the function **demands** its value.

# An example reduction sequence

$$\begin{aligned} (\lambda x. \lambda y. y \ x) ((\lambda x. x) \ 1) (\lambda x. x) &\longrightarrow_{\text{cbn}} (\lambda y. y \ ((\lambda x. x) \ 1)) (\lambda x. x) \\ &\longrightarrow_{\text{cbn}} (\lambda x. x) ((\lambda x. x) \ 1) \\ &\longrightarrow_{\text{cbn}} (\lambda x. x) \ 1 \\ &\longrightarrow_{\text{cbn}} 1 \end{aligned}$$

## Call-by-value versus call-by-name

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If  $t$  terminates under CBV, then it also terminates under CBN (\*).

The converse is **false**:

$$\begin{array}{lcl} (\lambda x.1) \omega & \longrightarrow_{\text{cbn}} & 1 \\ (\lambda x.1) \omega & \longrightarrow_{\text{cbv}}^{\infty} & \end{array}$$

where  $\omega = (\lambda x.x \ x) (\lambda x.x \ x)$  diverges under both strategies.

Call-by-value can perform fewer reduction steps:

$(\lambda x. x + x) \ t$  evaluates  $t$  once under CBV, **twice** under CBN.

Call-by-name can perform fewer reduction steps:

$(\lambda x. 1) \ t$  evaluates  $t$  once under CBV, **not at all** under CBN.

(\*) In fact, the **standardization** theorem implies that  
if  $t$  can be reduced to a value via any strategy,  
then it can be reduced to a value via CBN.  
See **Takahashi (1995)**.

## Encoding call-by-name in a CBV language

Use **thunks**: functions  $\lambda\_u$  whose purpose is to delay the evaluation of  $u$ .

$$\begin{aligned} \llbracket x \rrbracket &= x () \\ \llbracket \lambda x. t \rrbracket &= \lambda x. \llbracket t \rrbracket \\ \llbracket t \ u \rrbracket &= \llbracket t \rrbracket (\lambda\_ \llbracket u \rrbracket) \end{aligned}$$

**Exercise:** Can you **state** that this encoding is correct? Can you **prove** it?  
— 2017 exam! (**paper assignment and solution**) (**Coq solution**)

## Encoding call-by-name in a CBV language

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In a simply-typed setting, this transformation is **type-preserving**: that is,

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In a simply-typed setting, this transformation is **type-preserving**: that is,

$$\Gamma \vdash t : T \text{ implies } \llbracket \Gamma \rrbracket \vdash \llbracket t \rrbracket : \llbracket T \rrbracket.$$

The translation of types is defined by

## Encoding call-by-name in a CBV language

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In a simply-typed setting, this transformation is **type-preserving**: that is,

$$\Gamma \vdash t : T \quad \text{implies} \quad \llbracket \Gamma \rrbracket \vdash \llbracket t \rrbracket : \llbracket T \rrbracket.$$

The translation of types is defined by

$$\llbracket T_1 \rightarrow T_2 \rrbracket = \text{thunk } \llbracket T_1 \rrbracket \rightarrow \llbracket T_2 \rrbracket$$

where  $\text{thunk } T$  is  $\text{unit} \rightarrow T$ .

The translation of type environments is as follows:

$\llbracket x_1 : T_1; \dots; x_n : T_n \rrbracket$  stands for  $x_1 : \text{thunk } \llbracket T_1 \rrbracket; \dots; x_n : \text{thunk } \llbracket T_n \rrbracket$ .

## Encoding call-by-value in a CBN language

The reverse encoding is somewhat more involved.

The call-by-value **continuation-passing style** (CPS) transformation, studied later on in this course, achieves such an encoding.



## Call-by-push-value

Levy: — *The existence of two separate paradigms is troubling.*

Levy proposes **call-by-push-value**,  
a lower-level calculus into which both CBV and CBN can be encoded,  
thus avoiding a certain amount of duplication between their theories.

Levy, **Call-by-Push-Value: A Subsuming Paradigm**, 1999.

Forster et al., **Call-By-Push-Value in Coq: Operational, Equational, and Denotational Theory**, 2018.

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## Call-by-need

Call-by-need, a.k.a. **lazy evaluation**, eliminates the main inefficiency of call-by-name (namely, repeated computation) by introducing **memoization**.

Its description via an operational semantics involves:

- either **mutable state** and **sharing** ([Ariola and Felleisen, 1997](#); [Maraist, Odersky, Wadler, 1998](#));
- or **nondeterminism**: “call-by-need is clairvoyant call-by-value” ([Hackett and Hutton, 2019](#)).

It is used in Haskell, where it encourages a **modular style** of programming.

Hughes, [Why functional programming matters](#), 1990.

Also see [Harper's](#) and [Augustsson's](#) blog posts on laziness.

## Newton-Raphson iteration (after Hughes)

This is pseudo-Haskell code. The colon `:` is “cons”.

An approximation of the square root of `n` can be computed as follows:

```
next n x = (x + n / x) / 2
repeat f a = a : (repeat f (f a))
within eps (a : b : rest) =
  if abs (a - b) <= eps then b
  else within eps (b : rest)
sqrt a0 eps n =
  within eps (repeat (next n) a0)
```

`repeat (next n) a0` is a **producer** of an infinite stream of numbers.

Its type is just “list of numbers” – look Ma, **no iterators** à la Java!

The **consumer** `within eps` decides how many elements to demand.

The two are programmed **independently**.

## Encoding call-by-need in a CBV language

Call-by-need can be encoded into CBV by using **memoizing thunks**:

$$\begin{aligned}\llbracket x \rrbracket &= \text{force } x \\ \llbracket \lambda x. t \rrbracket &= \lambda x. \llbracket t \rrbracket \\ \llbracket t \ u \rrbracket &= \llbracket t \rrbracket (\text{suspend } (\lambda \_ . \llbracket u \rrbracket))\end{aligned}$$

Such a thunk evaluates  $u$  when **first** forced,  
then memoizes the result,  
so no computation is required if the thunk is forced **again**.

Thunks can be thought of as an abstract type with this API or signature:

```
type 'a thunk
val suspend: (unit -> 'a) -> 'a thunk
val force: 'a thunk -> 'a
```

## Encoding call-by-need in a CBV language

**Exercise:** implement the thunk API in OCaml. (**Solution.**)

In reality, this exercise is unnecessary, as OCaml has built-in thunks:

- “suspend  $(\lambda_.u)$ ” is written **lazy**  $u$ .
- “force  $x$ ” is written **Lazy**.force  $x$ .

**Exercise:** port Newton-Raphson iteration to OCaml.

Make sure that **each element is computed at most once** and **no more elements than necessary** are computed.

Write tests to verify these properties. (**Solution.**)

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## A naïve interpreter

An **interpreter** executes a program (represented by its AST).

Let us write one, in OCaml, by paraphrasing the small-step semantics.

# Abstract syntax

This is the abstract syntax of the  $\lambda$ -calculus:

```
type var = int (* a de Bruijn index *)
type term =
  | Var of var
  | Lam of (* bind: *) term
  | App of term * term
```

For example, the term  $\lambda x.x$  is represented as follows:

```
let id =
  Lam (Var 0)
```

# Renaming

`lift_ i k` represents the renaming  $\uparrow^i(+k)$ .

```
let rec lift_ i k (t : term) : term =  
  match t with  
  | Var x ->  
    if x < i then t else Var (x + k)  
  | Lam t ->  
    Lam (lift_ (i + 1) k t)  
  | App (t1, t2) ->  
    App (lift_ i k t1, lift_ i k t2)  
  
let lift k t =  
  lift_ 0 k t
```

Thus, `lift k` represents  $+k$ . (This renaming adds  $k$  to every variable.)

It is used when one moves the term  $t$  down into  $k$  binders. (Next slide.)

# Substitution

`subst_ i sigma` represents the substitution  $\uparrow^i \sigma$ .

```
let rec subst_ i (sigma : var -> term) (t : term) : term =  
  match t with  
  | Var x ->  
    if x < i then t else lift i (sigma (x - i))  
  | Lam t ->  
    Lam (subst_ (i + 1) sigma t)  
  | App (t1, t2) ->  
    App (subst_ i sigma t1, subst_ i sigma t2)  
  
let subst sigma t =  
  subst_ 0 sigma t
```

Thus, `subst sigma` represents  $\sigma$ .

## Substitution

A substitution is encoded as a total function of variables to terms.

```
let singleton (u : term) : var -> term =  
  function 0 -> u | x -> Var (x - 1)
```

`singleton u` represents the substitution  $u \cdot id$ .

# Recognizing values

It is easy to test whether a term is a value:

```
let is_value = function
  | Var _ | Lam _ -> true
  | App _          -> false
```

## Performing one step of reduction

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A direct transcription of Plotkin's definition of call-by-value reduction:

```
let rec step (t : term) : term option =  
  match t with  
  | Lam _ | Var _ -> None  
  (* Plotkin's BetaV *)  
  | App (Lam t, v) when is_value v ->  
    Some (subst (singleton v) t)  
  (* Plotkin's AppL *)  
  | App (t, u) when not (is_value t) ->  
    in_context (fun t' -> App (t', u)) (step t)  
  (* Plotkin's AppVR *)  
  | App (v, u) when is_value v ->  
    in_context (fun u' -> App (v, u')) (step u)  
  (* All cases covered already, but OCaml cannot see it. *)  
  | App (_, _) ->  
    assert false
```

We have guarded AppL so that AppL and AppVR are mutually exclusive.

## Performing one step of reduction

`in_context` is just the `map` combinator of the type `_ option`.

```
let in_context f ox =  
  match ox with  
  | None -> None  
  | Some x -> Some (f x)
```



## Performing many steps of reduction

To evaluate a term, one performs as many reduction steps as possible:

```
let rec eval (t : term) : term =  
  match step t with  
  | None ->  
    t  
  | Some t' ->  
    eval t'
```

The function call `eval t` either diverges or returns an irreducible term, which must be either a value or stuck.

## Sources of inefficiency

Unfortunately, this is a terribly **inefficient** way of interpreting programs.

At each reduction step, one must:

- Find the next redex, that is, decompose the term  $t$  as  $E[\lambda(x.u) \ v]$ .
- Perform the substitution  $u[v/x]$ .
- Construct the term  $E[u[v/x]]$ .

The time required to do this is **not**  $O(1)$ . Why?

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- Construct the term  $E[u[v/x]]$ .

The time required to do this is **not**  $O(1)$ . Why?

There seem to be two main sources of inefficiency:

- We keep **forgetting** the current evaluation context, only to **discover** it again at the next reduction step.
- We perform costly substitutions.

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## Towards an alternative to small steps

A reduction sequence from an application  $t_1 \ t_2$  to a final value  $v$  always has the form:

$$t_1 \ t_2 \longrightarrow_{\text{cbv}}^* (\lambda x. u_1) \ t_2 \longrightarrow_{\text{cbv}}^* (\lambda x. u_1) \ v_2 \longrightarrow_{\text{cbv}} u_1[v_2/x] \longrightarrow_{\text{cbv}}^* v$$

where  $t_1 \longrightarrow_{\text{cbv}}^* \lambda x. u_1$  and  $t_2 \longrightarrow_{\text{cbv}}^* v_2$ . That is,

Evaluate operator; evaluate operand; call; continue execution.

Idea: define a “big-step” relation  $t \downarrow_{\text{cbv}} v$ ,  
which relates a term directly with the **final outcome**  $v$  of its evaluation,  
and whose definition reflects the above structure.

## Natural semantics, a.k.a. big-step semantics

The relation  $t \downarrow_{\text{cbv}} v$  means that evaluating  $t$  terminates and produces  $v$ .

Here is its definition, for call-by-value:

$$\begin{array}{c}
 \text{BIGCBVVALUE} \\
 \hline
 v \downarrow_{\text{cbv}} v
 \end{array}
 \qquad
 \begin{array}{c}
 \text{BIGCBVAPP} \\
 \hline
 \frac{t_1 \downarrow_{\text{cbv}} \lambda x. u_1 \quad t_2 \downarrow_{\text{cbv}} v_2 \quad u_1[v_2/x] \downarrow_{\text{cbv}} v}{t_1 \ t_2 \downarrow_{\text{cbv}} v}
 \end{array}$$

**Exercise:** define  $\downarrow_{\text{cbn}}$ .

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Let us write  $\downarrow$  for  $\downarrow_{\text{cbv}}$ , and “ $v \downarrow \cdot$ ” for “ $v \downarrow v$ ”.

$$\frac{\lambda x. \lambda y. y \ x \downarrow \cdot \quad \frac{\lambda x. x \downarrow \cdot \quad 1 \downarrow \cdot}{1 \downarrow \cdot} \quad \frac{(\lambda x. x) \ 1 \downarrow 1 \quad \lambda y. y \ 1 \downarrow \cdot}{(\lambda x. \lambda y. y \ x) ((\lambda x. x) \ 1) \downarrow \lambda y. y \ 1} \quad \lambda x. x \downarrow \cdot \quad \frac{\lambda x. x \downarrow \cdot \quad 1 \downarrow \cdot}{1 \downarrow \cdot} \quad \frac{(\lambda x. x) \ 1 \downarrow 1}{(\lambda x. x) \ 1 \downarrow 1}}{(\lambda x. \lambda y. y \ x) ((\lambda x. x) \ 1) (\lambda x. x) \downarrow 1}$$

Whereas a proof of  $t \rightarrow_{\text{cbv}} t'$  has **linear structure**,  
a proof of  $t \downarrow_{\text{cbv}} v$  has **tree structure**.

## Some history



Martin-Löf uses big-step semantics, in English:

To execute  $c(a)$ , first execute  $c$ . If you get  $(\lambda x) b$  as result, then continue by executing  $b(a/x)$ .  
Thus  $c(a)$  has value  $d$  if  $c$  has value  $(\lambda x) b$  and  $b(a/x)$  has value  $d$ .

He proposes type theory (1975) as a very high-level programming language in which both **programs** and **specifications** can be written.

Per Martin-Löf,  
**Constructive Mathematics and Computer Programming**, 1984.



# Some history

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Kahn promotes big-step operational semantics:

$\rho \vdash \text{number } N \Rightarrow N$	(1)
$\rho \vdash \text{true} \Rightarrow \text{true}$	(2)
$\rho \vdash \text{false} \Rightarrow \text{false}$	(3)
$\rho \vdash \lambda P. E \Rightarrow [\lambda P. E, \rho]$	(4)
$\frac{\text{val. of } i}{\rho \vdash \text{ident } i \Rightarrow \alpha}$	(5)
$\frac{\rho \vdash E_1 \Rightarrow \text{true} \quad \rho \vdash E_2 \Rightarrow \alpha}{\rho \vdash \text{if } E_1 \text{ then } E_2 \text{ else } E_3 \Rightarrow \alpha}$	(6)
$\frac{\rho \vdash E_1 \Rightarrow \text{false} \quad \rho \vdash E_2 \Rightarrow \alpha}{\rho \vdash \text{if } E_1 \text{ then } E_2 \text{ else } E_3 \Rightarrow \alpha}$	(7)
$\frac{\rho \vdash E_1 \Rightarrow \alpha \quad \rho \vdash E_2 \Rightarrow \beta}{\rho \vdash (E_1, E_2) \Rightarrow (\alpha, \beta)}$	(8)
$\frac{\rho \vdash E_1 \Rightarrow [\lambda P. E, \rho_1] \quad \rho \vdash E_2 \Rightarrow \alpha \quad \rho_1 \cdot P \mapsto \alpha \vdash E \Rightarrow \beta}{\rho \vdash E_1, E_2 \Rightarrow \beta}$	(9)
$\frac{\rho \vdash E_2 \Rightarrow \alpha \quad \rho \cdot P \mapsto \alpha \vdash E_1 \Rightarrow \beta}{\rho \vdash \text{let } P = E_2 \text{ in } E_1 \Rightarrow \beta}$	(10)
$\frac{\rho \cdot P \mapsto \alpha \vdash E_2 \Rightarrow \alpha \quad \rho \cdot P \mapsto \alpha \vdash E_1 \Rightarrow \beta}{\rho \vdash \text{letrec } P = E_2 \text{ in } E_1 \Rightarrow \beta}$	(11)

Figure 2. The dynamic semantics of mini-ML



He gives a big-step operational semantics of MiniML, a static type system, and a compilation scheme towards the CAM.

Gilles Kahn, **Natural semantics**, 1987.

## A big-step interpreter

The call `eval t` attempts to compute a value  $v$  such that  $t \Downarrow_{\text{cbv}} v$  holds.

```
exception RuntimeError
let rec eval (t : term) : term =
  match t with
  | Lam _ | Var _ -> t
  | App (t1, t2) ->
    let v1 = eval t1 in
    let v2 = eval t2 in
    match v1 with
    | Lam u1 -> eval (subst (singleton v2) u1)
    | _       -> raise RuntimeError
```

If `eval` terminates normally, then it **obviously** returns a value;  
but it can also fail to terminate or terminate with a runtime error. (Why?)

This interpreter does not **forget and rediscover** the evaluation context.  
The context is now **implicit** in the interpreter's **stack**!

We **could** prove this interpreter correct, but will first optimize it further.

Equivalence between small-step and  
big-step semantics

## Lemma (From big-step to small-step)

If  $t \downarrow_{cbv} v$ , then  $t \longrightarrow_{cbv}^* v$ .

## Proof.

By induction on the derivation of  $t \downarrow_{cbv} v$ .

Case **BIGCBVVALUE**. We have  $t = v$ . The result is immediate.

Case **BIGCBVAPP**.  $t$  is  $t_1 \ t_2$ , and we have three subderivations:

$$t_1 \downarrow_{cbv} \lambda x. u_1 \qquad t_2 \downarrow_{cbv} v_2 \qquad u_1[v_2/x] \downarrow_{cbv} v$$

Applying the ind. hyp. to them yields three reduction sequences:

$$t_1 \longrightarrow_{cbv}^* \lambda x. u_1 \qquad t_2 \longrightarrow_{cbv}^* v_2 \qquad u_1[v_2/x] \longrightarrow_{cbv}^* v$$

By reducing under an evaluation context and by chaining, we obtain:

$$t_1 \ t_2 \longrightarrow_{cbv}^* (\lambda x. u_1) \ t_2 \longrightarrow_{cbv}^* (\lambda x. u_1) \ v_2 \longrightarrow_{cbv} u_1[v_2/x] \longrightarrow_{cbv}^* v$$

See [LambdaCalculusBigStep/bigcbv\\_star\\_cbv](#).

□

## Equivalence between small-step and big-step semantics

### Lemma (From small-step to big-step, preliminary)

*If  $t_1 \longrightarrow_{cbv} t_2$  and  $t_2 \downarrow_{cbv} v$ , then  $t_1 \downarrow_{cbv} v$ .*

### Proof (Sketch).

By induction on the first hypothesis and case analysis on the second hypothesis. See [LambdaCalculusBigStep/cbv\\_bigcbv\\_bigcbv](#). □

### Lemma (From small-step to big-step)

*If  $t \longrightarrow_{cbv}^* v$ , then  $t \downarrow_{cbv} v$ .*

### Proof.

By induction on the first hypothesis, using  $v \downarrow_{cbv} v$  in the base case and the above lemma in the inductive case.

See [LambdaCalculusBigStep/star\\_cbv\\_bigcbv](#). □

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## An alternative to naïve substitution

A basic need is to **record** that  $x$  is bound to  $v$  while evaluating a term  $t$ .

So far, we have used an eager substitution,  $t[v/x]$ , but:

- This is inefficient.
- This does not respect the separation between immutable **code** and mutable **data** imposed by current hardware and operating systems.

Idea: instead of applying the substitution  $[v/x]$  to the code, record the binding  $x \mapsto v$  in a data structure, known as an **environment**.

An environment is a **finite map** of variables to (closed) values.

A first attempt

Let us **try** and define a new big-step evaluation judgement,  $e \vdash t \downarrow_{\text{cbv}} v$ .

(previous definition)

$$\frac{\text{BIGCBVVALUE}}{v \downarrow_{\text{cbv}} v}$$

$$\frac{\begin{array}{c} \text{BIGCBVAPP} \\ t_1 \downarrow_{\text{cbv}} \lambda x. u_1 \\ t_2 \downarrow_{\text{cbv}} v_2 \\ u_1[v_2/x] \downarrow_{\text{cbv}} v \end{array}}{t_1 \ t_2 \downarrow_{\text{cbv}} v}$$

(attempt at a new definition)

$$\frac{\text{EBIGCBVVAR} \quad e(x) = v}{e \vdash x \downarrow_{\text{cbv}} v} \qquad \frac{\text{EBIGCBVLAM}}{e \vdash \lambda x. t \downarrow_{\text{cbv}} \lambda x. t}$$

$$\frac{\begin{array}{c} \text{EBIGCBVAPP} \\ e \vdash t_1 \downarrow_{\text{cbv}} \lambda x. u_1 \\ e \vdash t_2 \downarrow_{\text{cbv}} v_2 \\ e[x \mapsto v_2] \vdash u_1 \downarrow_{\text{cbv}} v \end{array}}{e \vdash t_1 \ t_2 \downarrow_{\text{cbv}} v}$$

What is **wrong** with this definition?

## A first attempt

Let us **try** and define a new big-step evaluation judgement,  $e \vdash t \downarrow_{\text{cbv}} v$ .

(previous definition)

BIGCBVVALUE

$$\frac{}{v \downarrow_{\text{cbv}} v}$$

BIGCBVAPP

$$\frac{\begin{array}{c} t_1 \downarrow_{\text{cbv}} \lambda x. u_1 \\ t_2 \downarrow_{\text{cbv}} v_2 \\ u_1[v_2/x] \downarrow_{\text{cbv}} v \end{array}}{t_1 t_2 \downarrow_{\text{cbv}} v}$$

(attempt at a new definition)

EBIGCBVVAR

$$\frac{e(x) = v}{e \vdash x \downarrow_{\text{cbv}} v}$$

EBIGCBVLAM

$$\frac{}{e \vdash \lambda x. t \downarrow_{\text{cbv}} \lambda x. t}$$

EBIGCBVAPP

$$\frac{\begin{array}{c} e \vdash t_1 \downarrow_{\text{cbv}} \lambda x. u_1 \\ e \vdash t_2 \downarrow_{\text{cbv}} v_2 \\ e[x \mapsto v_2] \vdash u_1 \downarrow_{\text{cbv}} v \end{array}}{e \vdash t_1 t_2 \downarrow_{\text{cbv}} v}$$

What is **wrong** with this definition?

In  $t \downarrow_{\text{cbv}} v$ , both  $t$  and  $v$  are closed.

In  $e \vdash t \downarrow_{\text{cbv}} v$ , we expect  $\text{fv}(t) \subseteq \text{dom}(e)$ . What about  $v$ ? Is it closed?  
What about the values stored in  $e$ ? Are they closed? ...



## Lexical scoping versus dynamic scoping

What value should the following OCaml code produce?

```
let x = 42 in
let f = fun () -> x in
let x = "oops" in
f()
```

## Lexical scoping versus dynamic scoping

What value should the following OCaml code produce?

```
let x = 42 in
let f = fun () -> x in
let x = "oops" in
f()
```

Well,

- The answer is 42. This is **lexical scoping**. This is  $\lambda$ -calculus.
- The answer is not "oops". That would be **dynamic scoping**.

## Lexical scoping versus dynamic scoping

What value should the following OCaml code produce?

```
let x = 42 in
let f = fun () -> x in
let x = "oops" in
f()
```

Well,

- The answer is 42. This is **lexical scoping**. This is  $\lambda$ -calculus.
- The answer is not "oops". That would be **dynamic scoping**.

Thus, the free variables of a  $\lambda$ -abstraction must be evaluated:

- in the environment that exists at the function's **creation site**,
- not in the environment that exists at the function's **call site**.

## A failed attempt

Thus, our first attempt is wrong:

- It implements **dynamic scoping** instead of **lexical scoping**.
- If  $e \vdash t \downarrow_{\text{cbv}} v$  and  $fv(t) \subseteq \text{dom}(e)$  then we would expect that  $v$  is closed and  $t[e] \downarrow_{\text{cbv}} v$  holds — but that is **not** the case.
- The candidate rule  $\text{EBIGCBVLAM}$  obviously **violates** this property. It fails to **record the environment** that exists at function creation time.

How can we **fix** the problem?

## Closures



The result of evaluating a  $\lambda$ -abstraction  $\lambda x.t$ , where  $fv(\lambda x.t)$  may be nonempty, should **not** be  $\lambda x.t$ .

It should be a **closure**  $\langle \lambda x.t \mid e \rangle$ ,

- that is, a **pair** of a  $\lambda$ -abstraction and an environment,
- in other words, a pair of a **code** pointer and a pointer to a heap-allocated **data** structure.

Landin, **The Mechanical Evaluation of Expressions**, 1964.

## Closures and environments

The abstract syntax of closures is:

$$c ::= \langle \lambda x. t \mid e \rangle$$

We expect the evaluation of a term to produce a closure:

$$e \vdash t \Downarrow_{\text{cbv}} c$$

Because evaluating  $x$  produces  $e(x)$ ,  
an environment must be **a finite map of variables to closures**:

$$e ::= [] \mid e[x \mapsto c]$$

Thus, the syntaxes of closures and environments are **mutually inductive**.

## A big-step semantics with environments

Evaluating a  $\lambda$ -abstraction produces a newly allocated **closure**.

$$\text{EBigCbVVar} \quad \frac{e(x) = c}{e \vdash x \downarrow_{\text{cbv}} c}$$

$$\text{EBigCbVLam} \quad \frac{fv(\lambda x.t) \subseteq \text{dom}(e)}{e \vdash \lambda x.t \downarrow_{\text{cbv}} \langle \lambda x.t \mid e \rangle}$$

$$\text{EBigCbVApp} \quad \frac{\begin{array}{l} e \vdash t_1 \downarrow_{\text{cbv}} \langle \lambda x.u_1 \mid e' \rangle \\ e \vdash t_2 \downarrow_{\text{cbv}} c_2 \\ e'[x \mapsto c_2] \vdash u_1 \downarrow_{\text{cbv}} c \end{array}}{e \vdash t_1 t_2 \downarrow_{\text{cbv}} c}$$

Invoking a closure causes the closure's code to be evaluated **in the closure's environment**, extended with a binding of formal to actual.

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How can we relate the judgements  $t \Downarrow_{\text{cbv}} v$  and  $e \vdash t \Downarrow_{\text{cbv}} c$ ?

What lemma should we state?



## Equivalence between big-step semantics without and with environments

How can we relate the judgements  $t \Downarrow_{\text{cbv}} v$  and  $e \vdash t \Downarrow_{\text{cbv}} c$ ?

What lemma should we state?

Assuming  $t$  is closed, we would like to prove that

$$t \Downarrow_{\text{cbv}} v$$

holds if and only if

## Equivalence between big-step semantics without and with environments

How can we relate the judgements  $t \Downarrow_{\text{cbv}} v$  and  $e \vdash t \Downarrow_{\text{cbv}} c$ ?

What lemma should we state?

Assuming  $t$  is closed, we would like to prove that

$$t \Downarrow_{\text{cbv}} v$$

holds if and only if

$$\Box \vdash t \Downarrow_{\text{cbv}} c$$

holds for **some** closure  $c$  such that  $c$  **represents**  $v$  in a certain sense.

## Decoding closures

$c$  represents  $v$  can be defined as  $\lceil c \rceil = v$ , where  $\lceil c \rceil$  is defined by:

$$\lceil \langle \lambda x. t \mid e \rangle \rceil = (\lambda x. t)[\lceil e \rceil]$$

and where the substitution  $\lceil e \rceil$  maps every variable  $x$  in  $\text{dom}(e)$  to  $\lceil e(x) \rceil$ .

( $\lceil c \rceil$  and  $\lceil e \rceil$  are mutually inductively defined.)

# Equivalence between big-step semantics without and with environments

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One implication is easily established:

**Lemma (Soundness of the environment semantics)**

$e \vdash t \downarrow_{cbv} c$  implies  $t[\![e]\!] \downarrow_{cbv} \lceil c \rceil$ .

**Proof (Sketch).**

By induction on the hypothesis.

See [LambdaCalculusBigStep/ebigcbv\\_bigcbv](#). □

In particular,  $[] \vdash t \downarrow_{cbv} c$  implies  $t \downarrow_{cbv} \lceil c \rceil$ .

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The reverse implication requires a more complex statement:

### Lemma (Completeness of the environment semantics)

*If  $t[\ulcorner e \urcorner] \downarrow_{cbv} v$ , where  $fv(t) \subseteq dom(e)$  and  $e$  is well-formed, then there exists  $c$  such that  $e \vdash t \downarrow_{cbv} c$  and  $\ulcorner c \urcorner = v$ .*

### Proof (Sketch).

By induction on the first hypothesis and by case analysis on  $t$ .

See [LambdaCalculusBigStep/bigcbv\\_ebigcbv](#). □

In particular, if  $t$  is closed, then  $t \downarrow_{cbv} v$  implies  $[] \vdash t \downarrow_{cbv} c$ ,  
for some closure  $c$  such that  $\ulcorner c \urcorner = v$ .

## Equivalence between big-step semantics without and with environments

The notion of **well-formedness** on the previous slide is inductively defined:

$$\frac{fv(\lambda x.t) \subseteq dom(e) \quad e \text{ is well-formed}}{\langle \lambda x.t \mid e \rangle \text{ is well-formed}}$$

$$\frac{\forall x, x \in dom(e) \Rightarrow e(x) \text{ is well-formed}}{e \text{ is well-formed}}$$

### Lemma (Well-formedness is an invariant)

*If  $e \vdash t \Downarrow_{cbv} c$  holds and  $e$  is well-formed, then  $c$  is well-formed.*

### Proof.

See [LambdaCalculusBigStep/ebigcbv\\_wf\\_cvalue](#). □

This property is exploited in the proof of the previous lemma.

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## From big-step semantics to interpreter, again

The big-step semantics  $e \vdash t \Downarrow_{\text{cbv}} c$  is a 3-place relation.

We now wish to define a (partial) function of two arguments  $e$  and  $t$ .

We **could** do this in OCaml, as we did earlier today.

Let us do **it in Coq** and prove this interpreter correct and complete!

See **[LambdaCalculusInterpreter](#)**.



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The syntax of terms (in de Bruijn's representation) is as before.

The syntax of closures and environments is as shown earlier:

```
Inductive cvalue :=  
| Clo: {bind term} -> list cvalue -> cvalue.
```

```
Definition cenv :=  
  list cvalue.
```

## A first attempt

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```
Fail Fixpoint interpret (e : cenv) (t : term) : cvalue :=
  match t with
  | Var x =>
    nth x e dummy_cvalue
    (* dummy is used when x is out of range *)
  | Lam t =>
    Clo t e
  | App t1 t2 =>
    let cv1 := interpret e t1 in
    let cv2 := interpret e t2 in
    match cv1 with Clo u1 e' =>
      interpret (cv2 :: e') u1
    end
  end.
```

Why is this definition **rejected** by Coq?

## A standard trick: fuel

We parameterize the interpreter with a maximum recursive call depth  $n$ .

```
Fixpoint interpret (n : nat) e t : option cvalue :=
  match n with
  | 0    => None (* not enough fuel *)
  | S n =>
    match t with
    | Var x      => Some (nth x e dummy_cvalue)
    | Lam t      => Some (Clo t e)
    | App t1 t2 =>
      interpret n e t1 >>= fun cv1 =>
      interpret n e t2 >>= fun cv2 =>
      match cv1 with Clo u1 e' =>
        interpret n (cv2 :: e') u1
      end
    end end.
```

The interpreter can now fail, therefore has return type `option cvalue`.

## Equivalence between the big-step semantics and the interpreter

If the interpreter produces a result, then it is a correct result.

### Lemma (Soundness of the interpreter)

*If  $\text{interpret } n \ e \ t = \text{Some } c$  and  $\text{fv}(t) \subseteq \text{dom}(e)$  and  $e$  is well-formed then  $e \vdash t \downarrow_{cbv} c$  holds.*

### Proof (Sketch).

By induction on  $n$ , by case analysis on  $t$ , and by inspection of the first hypothesis. See [LambdaCalculusInterpreter/interpret\\_ebigcbv](#). □

An interpreter that always returns *None* would satisfy this lemma, hence the need for a completeness statement...

## Equivalence between the big-step semantics and the interpreter

If the evaluation of  $t$  is supposed to produce  $c$ , then, **given sufficient fuel**, the interpreter returns  $c$ .

### Lemma (Completeness of the interpreter)

*If  $e \vdash t \Downarrow_{cbv} c$ , then there exists  $n$  such that  $interpret\ n\ e\ t = Some\ c$ .*

### Proof (Sketch).

By induction on the hypothesis, exploiting the fact that *interpret* is monotonic in  $n$ , that is,  $n_1 \leq n_2$  implies  $interpret\ n_1\ e\ t \leq interpret\ n_2\ e\ t$ , where the “definedness” partial order  $\leq$  is generated by  $None \leq Some\ c$ .  
See [LambdaCalculusInterpreter/ebigcbv\\_interpret](#). □

If  $t$  is closed and  $v$  is a value, then the following are equivalent:

$t \longrightarrow_{\text{cbv}}^* v$	small-step substitution semantics
$t \downarrow_{\text{cbv}} v$	big-step substitution semantics
$\exists c \left\{ \begin{array}{l} [] \vdash t \downarrow_{\text{cbv}} c \\ [c] = v \end{array} \right.$	big-step environment semantics
$\exists c \exists n \left\{ \begin{array}{l} \text{interpret } n \ [] \ t = \text{Some } c \\ [c] = v \end{array} \right.$	interpreter

## Cost model

We have represented environments as **lists**. Extension costs  $O(1)$ , but lookup has complexity  $O(n)$ , where  $n$  is the number of variables in scope.

**A better approach** is to represent the environment as an  $n$ -tuple. Then,

- evaluating a variable costs  $O(1)$ ;
- evaluating a  $\lambda$ -abstraction costs  $O(n)$ ;
- evaluating a function call costs  $O(1)$ .

$n$  **can be considered  $O(1)$**  as it depends only on the program's text, not on the input data.

This **simple cost model** is implemented by the OCaml compiler.

## Digression: the cost of garbage collection

The previous slide does not discuss the cost of garbage collection.

Let  $H$  be the total heap size.

Let  $R$  be the total size of the **live** objects. Thus,  $R \leq H$ .

Assuming a copying collector, one collection costs  $O(R)$ .

Collection takes place when the heap is full, so frees up  $H - R$  words.

Thus, the **amortized** cost of collection, per freed-up word, is

$$\frac{O(R)}{H - R}$$

Under the hypothesis  $\frac{R}{H} \leq \frac{1}{2}$ , this cost is  $O(1)$ . That is,

*Provided the heap is not allowed to become more than half full, freeing up an object takes **constant (amortized)** time.*



## Full closures versus minimal closures

In reality, this interpreter has one subtle but serious inefficiency.

When a closure  $\langle \lambda x.t \mid e \rangle$  is allocated,  
the entire environment  $e$  is stored in it,  
even though  $fv(\lambda x.t)$  may be a strict subset of the domain of  $e$ .

We store data that the closure will never need. This is a space leak!

To fix this, one should store a trimmed-down environment in the closure.

**Exercise:** state and prove that, if  $x$  does not occur free in  $t$ , then the evaluation of  $t$  in an environment  $e$  does not depend on the value  $e(x)$ .

**Exercise:** define an optimized interpreter where, at a closure allocation, every unneeded value in  $e$  is replaced with a dummy value. Prove it equivalent to the simpler interpreter.

## A few things to remember

An efficient interpreter uses **environments** and **closures**, not substitutions.

- It can (easily) be proved correct and complete!

There are **several styles** of operational semantics.

- They can (easily) be proved equivalent!