

## MPRI 2.4

### Operational semantics and reduction strategies

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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.

# 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 (next week).
- Enrich the language with primitive data types and operations, recursion, algebraic data structures, and so on (next week).
- Define a static type system (Rémy's lectures).

## 1 Reduction strategies

## Operational semantics

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

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

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.

# The call-by-value strategy

Values form a subset of terms:

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

A value represents the result of a computation.

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

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

$$\frac{\text{APP}_L \quad t \rightarrow_{\text{cbv}} t'}{t \ u \rightarrow_{\text{cbv}} t' \ u}$$

$$\frac{\text{APP}_R \quad u \rightarrow_{\text{cbv}} u'}{v \ u \rightarrow_{\text{cbv}} v \ u'}$$

This is known as a small-step operational semantics.

## Example

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

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

## Features of call-by-value reduction

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

$$\begin{array}{c} t \xrightarrow{\text{cbv}} t' \\ \cancel{\lambda x.t \xrightarrow{\text{cbv}} \lambda x.t'} \end{array}$$

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.

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

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

## 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.

$$\text{APPVR} \quad \frac{u \longrightarrow_{\text{cbv}} u'}{\textcolor{red}{V} u \longrightarrow_{\text{cbv}} \textcolor{red}{V} u'}$$

- **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:**  $t \rightarrow_{\text{cbv}} t_1 \rightarrow_{\text{cbv}} t_2 \rightarrow_{\text{cbv}} \dots \rightarrow_{\text{cbv}} v$   
The value  $v$  is the result of evaluating  $t$ .  
The term  $t$  converges to  $v$ .
- **Divergence:**  $t \rightarrow_{\text{cbv}} t_1 \rightarrow_{\text{cbv}} t_2 \rightarrow_{\text{cbv}} \dots \rightarrow_{\text{cbv}} t_n \rightarrow_{\text{cbv}} \dots$   
The sequence of reductions is infinite.  
The term  $t$  diverges.
- **Error:**  $t \rightarrow_{\text{cbv}} t_1 \rightarrow_{\text{cbv}} t_2 \rightarrow_{\text{cbv}} \dots \rightarrow_{\text{cbv}} t_n \not\rightarrow_{\text{cbv}} \cdot$   
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:

$$\begin{array}{ll} (\lambda x. \lambda y. y\,x) ((\lambda x. x)\,1) (\lambda x. x) & \xrightarrow{\text{cbv}} (\lambda x. \lambda y. y\,x)\,1\,(\lambda x. x) \\ & \xrightarrow{\text{cbv}} (\lambda y. y\,1)\,(\lambda x. x) \\ & \xrightarrow{\text{cbv}} (\lambda x. x)\,1 \\ & \xrightarrow{\text{cbv}} 1 \end{array}$$

Divergence:

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

Error:

$$(\lambda x. x\,x)\,2 \xrightarrow{\text{cbv}} 2\,2 \not\xrightarrow{\text{cbv}} .$$

The active redex is highlighted in red.

## An alternative style: evaluation contexts

First, define **head reduction**:

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

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

$$\frac{\text{C}_\text{Tx} \quad t \xrightarrow[\text{cbv}]{}^{\text{head}} t'}{E[t] \xrightarrow[\text{cbv}]{} E[t']}$$

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  $t = E[u]$  and  $u \xrightarrow[\text{cbv}]{}^{\text{head}} \dots$*

## The call-by-name strategy

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

$$\frac{\beta}{(\lambda x.t) u \rightarrow_{\text{cbn}} t[u/x]} \qquad \frac{\text{APP}_L}{t \rightarrow_{\text{cbn}} t' \quad t u \rightarrow_{\text{cbn}} t' u}$$

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

$$\begin{array}{lcl} (\lambda x. \lambda y. y\,x) ((\lambda x. x)\,1) (\lambda x. x) & \xrightarrow{\text{cbn}} & (\lambda y. y\,((\lambda x. x)\,1)) (\lambda x. x) \\ & \xrightarrow{\text{cbn}} & (\lambda x. x)\,((\lambda x. x)\,1) \\ & \xrightarrow{\text{cbn}} & (\lambda x. x)\,1 \\ & \xrightarrow{\text{cbn}} & 1 \end{array}$$

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

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

The converse is false:

$$\begin{array}{rcl} (\lambda x.1) \omega & \xrightarrow{\text{cbn}} & 1 \\ (\lambda x.1) \omega & \xrightarrow[\text{cbv}]{}^\infty & \end{array}$$

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  $u$ .

$$\begin{array}{lcl} \llbracket x \rrbracket & = & x () \\ \llbracket \lambda x. t \rrbracket & = & \lambda x. \llbracket t \rrbracket \\ \llbracket t \ u \rrbracket & = & \llbracket t \rrbracket (\lambda_. \llbracket u \rrbracket) \end{array}$$

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

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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 thunk  $T$  is 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

This is somewhat more involved.

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

## 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!**

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](#).)