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**Malgorzata Biernacka
Dariusz Biernacki
Olivier Danvy**

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An Operational Foundation for Delimited Continuations *

Małgorzata Biernacka, Dariusz Biernacki, and Olivier Danvy

BRICS[†]

Department of Computer Science

University of Aarhus[‡]

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Abstract

We derive an abstract machine that corresponds to a definitional interpreter for the control operators `shift` and `reset`. Based on this abstract machine, we construct a syntactic theory of delimited continuations.

Both the derivation and the construction scale to the family of control operators `shiftn` and `resetn`. The definitional interpreter for `shiftn` and `resetn` has $n + 1$ layers of continuations, the corresponding abstract machine has $n + 1$ layers of control stacks, and the corresponding syntactic theory has $n + 1$ layers of evaluation contexts.

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[†]Basic Research in Computer Science (www.brics.dk), funded by the Danish National Research Foundation.

[‡]Ny Munkegade, Building 540, DK-8000 Aarhus C, Denmark.
Email: {mbiernac,dabi,danvy}@brics.dk

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1 Introduction

The studies of delimited continuations can be classified in two groups: those that use continuation-passing style (CPS) and those that rely on operational intuitions about control instead. Of the latter, there is a large number [17, 20, 22, 26, 28, 29, 35, 39, 42, 43], with relatively few applications. Of the former, there is the work revolving around the control operators *shift* and *reset* [10, 11], with relatively many applications.

The original motivation for *shift* and *reset* was a continuation-based programming pattern involving several layers of continuations. The original specification relied both on a repeated CPS transformation and on a definitional interpreter with several levels of continuations (as is obtained by repeatedly transforming a direct-style interpreter into continuation-passing style). Only subsequently have *shift* and *reset* been specified operationally, by developing operational analogues of continuation semantics and of CPS transformations [15]. Beyond their original publication, *shift* and *reset* have been studied separately by Danvy and by Filinski [7, 15, 23, 24, 33], and independently by others [4, 25, 31, 36, 46, 47].

The goal of our work is to establish an operational foundation for delimited continuations by using CPS as a guideline. To this end, we start with the original definitional interpreter for *shift* and *reset*. This interpreter uses two layers of continuations: a continuation and a meta-continuation. We then defunctionalize it into an abstract machine [1] and we construct the corresponding syntactic theory [16], as pioneered by Felleisen and Friedman [19]. The construction scales to shift_n and reset_n .

This article is structured as follows. We first review the enabling technology of our work: Reynolds’s defunctionalization, the observation that a defunctionalized CPS program implements an abstract machine, and the observation that Felleisen’s evaluation contexts are the defunctionalized continuations of a continuation-passing evaluator; we also review related work (Section 2). We then defunctionalize the original definitional interpreter for *shift* and *reset* into an abstract machine. This abstract machine is environment-based, and we restate it as an abstract machine based on substitutions (Section 3). We analyze this abstract machine and construct the corresponding syntactic theory (Sections 4 and 5). We also present the abstract machine corresponding to the second level of the CPS hierarchy (Section 6), and we outline how the overall approach scales to higher levels (Section 7).

2 Background and related work

2.1 Defunctionalization

In his seminal work on definitional interpreters [40], Reynolds presented a generalization of closure conversion [32]: defunctionalization. This transformation amounts to representing a functional value not as a function, but as a first-order

sum where each summand corresponds to a lambda-abstraction in a source program. Function introduction is thus represented as an injection, and function elimination as a case dispatch. Therefore, before defunctionalization, functional values are inhabitants of a function space and they are instances of anonymous lambda-abstractions, and after defunctionalization, functional values are inhabitants of a sum. In ML, sums are represented as a data type and injections as data-type constructors.

As a concrete example, let us consider the Fibonacci function in continuation-passing style:

```
(* fib : int * (int -> int) -> int *)
fun fib (0, k)
  = k 0
  | fib (1, k)
  = k 1
  | fib (n, k)
  = fib (n-1,
        fn v1 => fib (n-2,
                    fn v2 => k (v1+v2)))

(* main : int -> int *)
fun main n
  = fib (n, fn v => v)
```

We defunctionalize this program by representing the continuation as a data structure. All three source lambda-abstractions give rise to inhabitants of the function space `int -> int`. We specify the data structure representing the continuation as an ML data type, and we add an apply function to interpret elements of this data type:

```
datatype cont = CONT0
              | CONT1 of int * cont
              | CONT2 of int * cont

(* apply_cont : cont * int -> int *)
fun apply_cont (CONT0, v)
  = v
  | apply_cont (CONT1 (n, k), v1)
  = fib (n-2, CONT2 (v1, k))
  | apply_cont (CONT2 (v1, k), v2)
  = apply_cont (k, v1+v2)

(* fib : int * cont -> int *)
and fib (0, k)
  = apply_cont (k, 0)
  | fib (1, k)
  = apply_cont (k, 1)
  | fib (n, k)
  = fib (n-1, CONT1 (n, k))
```

```

(* main : int -> int *)
fun main n
  = fib (n, CONT0)

```

The constructor `CONT0` is constant because the initial continuation has no free variables. The constructor `CONT1` holds the values of the two free variables of the outer lambda-abstraction in the induction case, i.e., `n` and `k`, and the constructor `CONT2` holds the values of the two free variables of the inner lambda-abstraction in the induction case, i.e., `v1` and `k`. (One could have chosen to hoist the computation `n-2` from the definition of `apply_cont` to the definition of `fib`. This choice can make a difference in practice [12, 13].)

2.2 This work

The present work builds on two recent observations:

1. a defunctionalized CPS program implements an abstract machine [1, 8];
and
2. Felleisen’s evaluation contexts are defunctionalized continuations [12].

Let us describe each of these observations in more detail.

2.2.1 Abstract machines as defunctionalized CPS programs

Plotkin’s Indifference Theorem [37] states that CPS programs are independent of their evaluation order. In Reynolds’s words [40], all the subterms in applications are ‘trivial’; and in Moggi’s words [34], these subterms are values and not computations. Furthermore, CPS programs are tail recursive [44]. Therefore, a defunctionalized CPS program implements the transition functions of an abstract machine. Each configuration is the name of a function together with its arguments.

Getting back to the example above, the defunctionalized definition of the Fibonacci function can be reformatted as the following abstract machine:

- Expressible values (integers):

$$v ::= n$$

- Evaluation contexts:

$$C ::= \text{CONT0} \mid \text{CONT1}(n, C) \mid \text{CONT2}(v, C)$$

- Initial transition, transition rules, and final transition:

n	\Rightarrow	$\langle n, \text{CONTO} \rangle_{fib}$
$\langle 0, k \rangle_{fib}$	\Rightarrow	$\langle k, 0 \rangle_{app}$
$\langle 1, k \rangle_{fib}$	\Rightarrow	$\langle k, 1 \rangle_{app}$
$\langle n, k \rangle_{fib}$	\Rightarrow	$\langle n - 1, \text{CONT1}(n, k) \rangle_{fib}$
$\langle \text{CONT1}(n, k), v_1 \rangle_{app}$	\Rightarrow	$\langle n - 2, \text{CONT2}(v_1, k) \rangle_{fib}$
$\langle \text{CONT2}(v_1, k), v_2 \rangle_{app}$	\Rightarrow	$\langle k, v_1 + v_2 \rangle_{app}$
$\langle \text{CONTO}, v \rangle_{app}$	\Rightarrow	v

Ager, Biernacki, Danvy, and Midtgaard have built on this observation to establish a functional correspondence between evaluators and abstract machines by relating them using closure conversion, CPS transformation, and defunctionalization [1, 8]. For example, Krivine’s abstract machine corresponds to an ordinary call-by-name evaluator and Felleisen et al.’s CEK machine to an ordinary call-by-value evaluator. (In fact, these two machines can be derived from the *same* vanilla evaluator, resp. using a call-by-name CPS transformation and a call-by-value CPS transformation [9].) The correspondence makes it possible to exhibit the evaluators corresponding to the SECD machine [32], the CLS machine [27], and the Categorical Abstract Machine [6], and it also holds for call-by-need evaluators and lazy abstract machines [2], for computational effects [3], and for logic programming [5]. We apply it here to delimited continuations.

2.2.2 Evaluation contexts as defunctionalized continuations

The realization that Felleisen et al.’s evaluation contexts are defunctionalized continuations makes it possible to mechanically construct evaluation contexts. This mechanical construction contrasts with having to define evaluation contexts on a case-by-case basis [18]. Also, the ubiquitous unique-decomposition lemma follows as a corollary when one starts from a compositional evaluator [9].

2.3 Control operators for delimited continuations

The continuation-based programming pattern that motivated shift and reset has since been found to coincide with layered computational monads [24]. Several implementations have been developed: a definitional interpreter [10], a CPS transformation [11], two embeddings in Standard ML of New Jersey using call/cc and state [15, 23], and native run-time support in a Scheme system [25]. Sustained efforts have also been made to establish an equational theory of delimited continuations [30, 31] with the goal of studying their logical content.

A specificity of our work is that we use CPS as a guideline. For example, pure contexts and general evaluation contexts have long been distinguished [21,41]. In their work [31], Kameyama and Hasegawa required this distinction. In contrast, the distinction between contexts and meta-contexts was imposed on us by CPS.

A forerunner of our work is Murthy’s presentation at CW’92 [36], where he designed an abstract machine for the CPS hierarchy that actually coincides with ours. Murthy also introduced a typing system, proved it correct with respect to the CPS translation, and used it to state local reduction rules. In contrast, we mechanically derived our abstract machine using defunctionalization, and we systematically derived a syntactic theory.

3 From interpreter to abstract machine for shift and reset

We start with defining the language of the first level of the CPS hierarchy of control operators [10].

Source terms consist of integer literals, variables, λ -abstractions, function applications, applications of the successor function, shift expressions, and reset expressions:

$$t ::= \lceil n \rceil \mid x \mid \lambda x.t \mid t_0 t_1 \mid \text{succ } t \mid \xi k.t \mid \langle t \rangle$$

In a shift expression $\xi k.t$, the variable k is bound in t .

Programs are closed terms.

3.1 An environment-based definitional interpreter

Figure 1 displays an interpreter for the language of the first level of the CPS hierarchy. The syntax of terms is implemented in the ML structure `Syntax` as a data type:

```

structure Syntax
= struct
  type ide = string

  datatype term = INT of int
                | VAR of ide
                | LAM of ide * term
                | APP of term * term
                | SUCC of term
                | SHIFT of ide * term
                | RESET of term
end

```

We implement the interpreter as an ML functor parameterized by the representation of an environment instantiating the following signature:

```

functor Definitional_Interpreter (structure Env : ENV)
= struct
  datatype value = INT of int
                | FUNC of cont0
  withtype answer = value
    and cont2 = value -> answer
    and cont1 = value * cont2 -> answer
    and cont0 = value * cont1 * cont2 -> answer

  (* eval : Syntax.term * value Env.env * cont1 * cont2
     -> answer *)
  fun eval (Syntax.INT n, e, k1, k2)
    = k1 (INT n, k2)
  | eval (Syntax.VAR x, e, k1, k2)
    = k1 (Env.lookup (x, e), k2)
  | eval (Syntax.LAM (x, t), e, k1, k2)
    = k1 (FUNC (fn (v, k1, k2)
      => eval (t, Env.extend (x, v, e), k1, k2)),
      k2)
  | eval (Syntax.APP (t0, t1), e, k1, k2)
    = eval (t0, e, fn (v0, k2)
      => eval (t1, e, fn (v1, k2)
        => let val (FUNC f) = v0
          in f (v1, k1, k2)
          end))
  | eval (Syntax.SUCC t, e, k1, k2)
    = eval (t, e, fn (INT n, k2) => k1 (INT (n + 1), k2), k2)
  | eval (Syntax.SHIFT (k, t), e, k1, k2)
    = eval (t,
      Env.extend (k,
        FUNC (fn (v, k1', k2')
          => k1 (v, fn v'
            => k1' (v', k2')))),
        e),
      fn (v, k2) => k2 v,
      k2)
  | eval (Syntax.RESET t, e, k1, k2)
    = eval (t, e, fn (v, k2) => k2 v, fn v => k1 (v, k2))

  (* main : Syntax.term -> value *)
  fun main t
    = eval (t, Env.empty, fn (v, k2) => k2 v, fn v => v)
end

```

Figure 1: A definitional interpreter for the first level of the CPS hierarchy

```

signature ENV
= sig
  type 'a env
  val empty : 'a env
  val extend : Syntax.ide * 'a * 'a env -> 'a env
  val lookup : Syntax.ide * 'a env -> 'a
end

```

The evaluation function is defined by structural induction over the syntax of terms, and uses both a continuation `k1` and a meta-continuation `k2`. The meta-continuation intervenes to interpret reset expressions and to apply captured continuations. Otherwise, it is passively threaded to interpret literals, variables, λ -abstractions, function applications, and applications of the successor function. (If it were not for `shift` and `reset`, and if `eval` were curried, `k2` could be eta-reduced and the interpreter would be in ordinary continuation-passing style.) Stuck (i.e., ill-typed) programs raise an ML pattern-matching error.

The reset control operator is used to delimit control. A reset expression `Syntax.RESET t` is interpreted by interpreting `t` with the identity continuation and a meta-continuation on which the current continuation has been “pushed”. (Indeed defunctionalizing the meta-continuation yields the data type of a stack [12].)

The shift control operator is used to abstract (delimited) control. A shift expression `Syntax.SHIFT (k, t)` is superficially similar to Reynolds’s escape expression [40]: the current (delimited) continuation is captured in `k`, and is reset to the identity continuation.

Applying a captured continuation is achieved by “pushing” the current continuation on the meta-continuation and applying the captured continuation to the new meta-continuation.

Resuming a continuation is achieved by reactivating the “pushed” continuation with the corresponding meta-continuation.

3.2 An environment-based abstract machine

The definitional interpreter of Figure 1 is already in continuation-passing style. Therefore, we only need to defunctionalize its expressible values and its continuations to obtain an abstract machine. This abstract machine is displayed in Figure 2.

3.3 A substitution-based abstract machine

We go from the environment-based abstract machine of Figure 2 to a substitution-based abstract machine displayed in Figure 3. The equivalence of these two machines is established with a substitution lemma [45]. The substitution-based abstract machine operates on terms where “quoted” (in the sense of Lisp) contexts can occur.

- Expressible values (integers, closures and captured continuations):

$$v ::= \lceil n \rceil \mid [x, t, e] \mid C_1$$

- Environments:

$$e ::= e_{empty} \mid e[x \mapsto v] \mid e[k \mapsto C_1]$$

- Evaluation contexts and meta-contexts:

$$\begin{aligned} C_1 &::= \bullet \mid C_1(t, e) \mid v C_1 \mid succ C_1 \\ C_2 &::= \bullet \mid C_2 \cdot C_1 \end{aligned}$$

- Initial transition, transition rules, and final transition:

t	\Rightarrow	$\langle t, e_{empty}, \bullet, \bullet \rangle_{eval}$
$\langle \lceil n \rceil, e, C_1, C_2 \rangle_{eval}$	\Rightarrow	$\langle C_1, \lceil n \rceil, C_2 \rangle_{cont_1}$
$\langle x, e, C_1, C_2 \rangle_{eval}$	\Rightarrow	$\langle C_1, e(x), C_2 \rangle_{cont_1}$
$\langle \lambda x.t, e, C_1, C_2 \rangle_{eval}$	\Rightarrow	$\langle C_1, [x, t, e], C_2 \rangle_{cont_1}$
$\langle t_0 t_1, e, C_1, C_2 \rangle_{eval}$	\Rightarrow	$\langle t_0, e, C_1(t_1, e), C_2 \rangle_{eval}$
$\langle succ t, e, C_1, C_2 \rangle_{eval}$	\Rightarrow	$\langle t, e, succ C_1, C_2 \rangle_{eval}$
$\langle \xi k.t, e, C_1, C_2 \rangle_{eval}$	\Rightarrow	$\langle t, e[k \mapsto C_1], \bullet, C_2 \rangle_{eval}$
$\langle \langle t \rangle, e, C_1, C_2 \rangle_{eval}$	\Rightarrow	$\langle t, e, \bullet, C_2 \cdot C_1 \rangle_{eval}$
$\langle \bullet, v, C_2 \rangle_{cont_1}$	\Rightarrow	$\langle C_2, v \rangle_{cont_2}$
$\langle C_1(t, e), v, C_2 \rangle_{cont_1}$	\Rightarrow	$\langle t, e, v C_1, C_2 \rangle_{eval}$
$\langle [x, t, e] C_1, v, C_2 \rangle_{cont_1}$	\Rightarrow	$\langle t, e[x \mapsto v], C_1, C_2 \rangle_{eval}$
$\langle C'_1 C_1, v, C_2 \rangle_{cont_1}$	\Rightarrow	$\langle C'_1, v, C_2 \cdot C_1 \rangle_{cont_1}$
$\langle succ C_1, \lceil n \rceil, C_2 \rangle_{cont_1}$	\Rightarrow	$\langle C_1, \lceil n + 1 \rceil, C_2 \rangle_{cont_1}$
$\langle C_2 \cdot C_1, v \rangle_{cont_2}$	\Rightarrow	$\langle C_1, v, C_2 \rangle_{cont_1}$
$\langle \bullet, v \rangle_{cont_2}$	\Rightarrow	v

Figure 2: An environment-based abstract machine for the first level of the CPS hierarchy

- Source syntax, including values:

$$\begin{aligned}
t & ::= v \mid x \mid t_0 t_1 \mid succ \ t \mid \xi \ k.t \mid \langle t \rangle \\
v & ::= \ulcorner n \urcorner \mid \lambda x.t \mid C_1
\end{aligned}$$

- Evaluation contexts and meta-contexts:

$$\begin{aligned}
C_1 & ::= \bullet \mid C_1 \ t \mid v \ C_1 \mid succ \ C_1 \\
C_2 & ::= \bullet \mid C_2 \cdot C_1
\end{aligned}$$

- Initial transition, transition rules, and final transition:

t	\Rightarrow	$\langle t, \bullet, \bullet \rangle_{eval}$
$\langle \ulcorner n \urcorner, C_1, C_2 \rangle_{eval}$	\Rightarrow	$\langle C_1, \ulcorner n \urcorner, C_2 \rangle_{cont_1}$
$\langle \lambda x.t, C_1, C_2 \rangle_{eval}$	\Rightarrow	$\langle C_1, \lambda x.t, C_2 \rangle_{cont_1}$
$\langle C'_1, C_1, C_2 \rangle_{eval}$	\Rightarrow	$\langle C_1, C'_1, C_2 \rangle_{cont_1}$
$\langle t_0 t_1, C_1, C_2 \rangle_{eval}$	\Rightarrow	$\langle t_0, C_1 \ t_1, C_2 \rangle_{eval}$
$\langle succ \ t, C_1, C_2 \rangle_{eval}$	\Rightarrow	$\langle t, succ \ C_1, C_2 \rangle_{eval}$
$\langle \xi \ k.t, C_1, C_2 \rangle_{eval}$	\Rightarrow	$\langle t\{C_1/k\}, \bullet, C_2 \rangle_{eval}$
$\langle \langle t \rangle, C_1, C_2 \rangle_{eval}$	\Rightarrow	$\langle t, \bullet, C_2 \cdot C_1 \rangle_{eval}$
$\langle \bullet, v, C_2 \rangle_{cont_1}$	\Rightarrow	$\langle C_2, v \rangle_{cont_2}$
$\langle C_1 \ t, v, C_2 \rangle_{cont_1}$	\Rightarrow	$\langle t, v \ C_1, C_2 \rangle_{eval}$
$\langle (\lambda x.t) \ C_1, v, C_2 \rangle_{cont_1}$	\Rightarrow	$\langle t\{v/x\}, C_1, C_2 \rangle_{eval}$
$\langle C'_1 \ C_1, v, C_2 \rangle_{cont_1}$	\Rightarrow	$\langle C'_1, v, C_2 \cdot C_1 \rangle_{cont_1}$
$\langle succ \ C_1, \ulcorner n \urcorner, C_2 \rangle_{cont_1}$	\Rightarrow	$\langle C_1, \ulcorner n + 1 \urcorner, C_2 \rangle_{cont_1}$
$\langle C_2 \cdot C_1, v \rangle_{cont_2}$	\Rightarrow	$\langle C_1, v, C_2 \rangle_{cont_1}$
$\langle \bullet, v \rangle_{cont_2}$	\Rightarrow	v

Figure 3: A substitution-based abstract machine for the first level of the CPS hierarchy

4 Analysis

In this section we analyze the transitions of the substitution-based abstract machine and we identify the ones that correspond to reduction rules in the language.

The abstract machine from Figure 3 is a small-step operational semantics of the language [38]. We can think of a configuration $\langle t, C_1, C_2 \rangle_{eval}$ of the machine as the following decomposition of the initial term into a meta-context C_2 , a context C_1 , and an intermediate term t :

$$C_2 \# C_1[t]$$

where $\#$ separates the context and the meta-context. Notice that in most transitions the meta-context component is not used. (Similarly, most occurrences of the meta-continuation could be eta-reduced in a carried version of the interpreter, in Figure 1.)

Next, we observe that the *eval*-transitions correspond to decomposing a term: depending on its structure, a subpart of the term is chosen to be evaluated next, and the contexts are updated accordingly. Each of the *cont*₁- and *cont*₂-transitions handles a situation when a value is reached. In this case either a reduction is performed or further decomposition takes place.

Based on the distinction between decomposition and reduction, we single out the following reduction rules from the transitions of the machine:

$$\begin{array}{ll}
 (\text{succ}) & C_2 \# C_1[\text{succ } \ulcorner n \urcorner] \rightarrow C_2 \# C_1[\ulcorner n + 1 \urcorner] \\
 (\beta_\lambda) & C_2 \# C_1[(\lambda x.t) v] \rightarrow C_2 \# C_1[t\{v/x\}] \\
 (\xi_\lambda) & C_2 \# C_1[\xi k.t] \rightarrow C_2 \# \bullet[t\{C_1/k\}] \\
 (\beta_{ctx}) & C_2 \# C_1[C'_1 v] \rightarrow C_2 \cdot C_1 \# C'_1[v] \\
 (\text{val}) & C_2 \cdot C_1 \# \bullet[v] \rightarrow C_2 \# C_1[v] \\
 (\text{val}') & \bullet \# \bullet[v] \rightarrow v
 \end{array}$$

Note that (β_λ) is the usual call-by-value β -reduction. We renamed it to indicate that the applied term is a λ -abstraction, since we can also apply a captured context, as in (β_{ctx}) . The (ξ_λ) rule can be considered as applying an abstraction $\lambda k.t$ to the current context. Moreover, the (β_{ctx}) rule can be seen as performing both a reduction and a decomposition. It is a reduction because an application of a context with a hole to a value is reduced to the value plugged into the hole; and it is a decomposition because it changes the meta-context, as if the application were enclosed in a reset. Finally, the (val) rule allows us to pass the boundary of a context, when the term inside it has been reduced to a value.

The (β_{ctx}) rule and the (ξ_λ) rule give a justification for representing a captured context C_1 as a term $\lambda x.\langle C_1[x] \rangle$, as found in other work on shift and reset [31, 36]. In particular, the need for delimiting the captured context is a consequence of the (β_{ctx}) rule.

What is more, the (β_{ctx}) rule captures the set of extra reduction rules needed by Murthy to prove the representation theorem [36].

5 A syntactic theory

A syntactic theory provides a reduction relation on expressions by defining values, evaluation contexts, and redexes [16, 18, 19, 49]. In the present case,

- the values are already specified in the (substitution-based) abstract machine;
- the evaluation contexts are already specified in the abstract machine, as the data-type part of defunctionalized continuations; and
- we can read the redexes off the transitions of the abstract machine, as done in Section 4.

Furthermore, we can read the decomposition function off the *eval*-transitions of the abstract machine:

$$\begin{aligned}
 \text{decompose}(t) &= \text{decompose}'(t, \bullet, \bullet) \\
 \text{decompose}'(t_0 t_1, C_1, C_2) &= \text{decompose}'(t_0, C_1 t_1, C_2) \\
 \text{decompose}'(\text{succ } t, C_1, C_2) &= \text{decompose}'(t, \text{succ } C_1, C_2) \\
 \text{decompose}'(\langle t \rangle, C_1, C_2) &= \text{decompose}'(t, \bullet, C_2 \cdot C_1) \\
 \text{decompose}'(v, C_1 t, C_2) &= \text{decompose}'(t, v C_1, C_2)
 \end{aligned}$$

The plug function is immediate to write:

$$\begin{aligned}
 \text{plug}(t, \bullet, \bullet) &= t \\
 \text{plug}(t, \bullet, C_2 \cdot C_1) &= \text{plug}(\langle t \rangle, C_1, C_2) \\
 \text{plug}(t, C_1 t', C_2) &= \text{plug}(t t', C_1, C_2) \\
 \text{plug}(t, v C_1, C_2) &= \text{plug}(v t, C_1, C_2) \\
 \text{plug}(t, \text{succ } C_1, C_2) &= \text{plug}(\text{succ } t, C_1, C_2)
 \end{aligned}$$

As a side benefit of starting from a compositional evaluator, the unique-decomposition lemma holds as a corollary.

All the points of this section were already made in Felleisen and Friedman's original article on control operators and abstract machines [19], except for the last one, which is new. We are currently studying how to mechanize the construction of syntactic theories from abstract machines, based on Danvy and Nielsen's converse mechanical construction [14].

6 The second level of the CPS hierarchy

We can easily generalize the results from the previous sections to an arbitrary level of the CPS hierarchy. Let us consider the second level. Starting from the standard definitional interpreter with three layers of continuations [10], we derive the corresponding environment-based abstract machine, using the same method as in Section 3.3. The equivalent substitution-based machine is presented in Figure 4. The configurations of the machine are extended with one

- Source syntax, including values:

$$t ::= v \mid x \mid t_0 t_1 \mid succ \ t \mid \xi \ k.t \mid \langle t \rangle \mid \xi_2 \ k.t \mid \langle t \rangle_2$$

$$v ::= \ulcorner n \urcorner \mid \lambda x.t \mid C_1 \mid C_2$$

- Evaluation contexts, meta-contexts and meta-meta-contexts:

$$C_1 ::= \bullet \mid C_1 t \mid v C_1 \mid succ \ C_1$$

$$C_2 ::= \bullet \mid C_2 \cdot C_1$$

$$C_3 ::= \bullet \mid C_3 \cdot (C_2 \cdot C_1)$$

- Initial transition, transition rules, and final transition:

$t \Rightarrow \langle t, \bullet, \bullet, \bullet \rangle_{eval}$
$\langle \ulcorner n \urcorner, C_1, C_2, C_3 \rangle_{eval} \Rightarrow \langle C_1, \ulcorner n \urcorner, C_2, C_3 \rangle_{cont_1}$ $\langle \lambda x.t, C_1, C_2, C_3 \rangle_{eval} \Rightarrow \langle C_1, \lambda x.t, C_2, C_3 \rangle_{cont_1}$ $\langle C'_1, C_1, C_2, C_3 \rangle_{eval} \Rightarrow \langle C_1, C'_1, C_2, C_3 \rangle_{cont_1}$ $\langle t_0 t_1, C_1, C_2, C_3 \rangle_{eval} \Rightarrow \langle t_0, C_1 t_1, C_2, C_3 \rangle_{eval}$ $\langle succ \ t, C_1, C_2, C_3 \rangle_{eval} \Rightarrow \langle t, succ \ C_1, C_2, C_3 \rangle_{eval}$ $\langle \xi \ k.t, C_1, C_2, C_3 \rangle_{eval} \Rightarrow \langle t\{C_1/k\}, \bullet, C_2, C_3 \rangle_{eval}$ $\langle \langle t \rangle, C_1, C_2, C_3 \rangle_{eval} \Rightarrow \langle t, \bullet, C_2 \cdot C_1, C_3 \rangle_{eval}$ $\langle \xi_2 \ k.t, C_1, C_2, C_3 \rangle_{eval} \Rightarrow \langle t\{C_2 \cdot C_1/k\}, \bullet, \bullet, C_3 \rangle_{eval}$ $\langle \langle t \rangle_2, C_1, C_2, C_3 \rangle_{eval} \Rightarrow \langle t, \bullet, \bullet, C_3 \cdot (C_2 \cdot C_1) \rangle_{eval}$
$\langle \bullet, v, C_2, C_3 \rangle_{cont_1} \Rightarrow \langle C_2, v, C_3 \rangle_{cont_2}$ $\langle C_1 t, v, C_2, C_3 \rangle_{cont_1} \Rightarrow \langle t, v C_1, C_2, C_3 \rangle_{eval}$ $\langle (\lambda x.t) C_1, v, C_2, C_3 \rangle_{cont_1} \Rightarrow \langle t\{v/x\}, C_1, C_2, C_3 \rangle_{eval}$ $\langle C'_1 C_1, v, C_2, C_3 \rangle_{cont_1} \Rightarrow \langle C'_1, v, C_2 \cdot C_1, C_3 \rangle_{cont_1}$ $\langle (C'_2 \cdot C'_1) C_1, v, C_2, C_3 \rangle_{cont_1} \Rightarrow \langle C'_1, v, C'_2, C_3 \cdot (C_2 \cdot C_1) \rangle_{cont_1}$ $\langle succ \ C_1, \ulcorner n \urcorner, C_2, C_3 \rangle_{cont_1} \Rightarrow \langle C_1, \ulcorner n + 1 \urcorner, C_2, C_3 \rangle_{cont_1}$
$\langle C_2 \cdot C_1, v, C_3 \rangle_{cont_2} \Rightarrow \langle C_1, v, C_2, C_3 \rangle_{cont_1}$
$\langle \bullet, v, C_3 \rangle_{cont_2} \Rightarrow \langle C_3, v \rangle_{cont_3}$
$\langle C_3 \cdot (C_2 \cdot C_1), v \rangle_{cont_3} \Rightarrow \langle C_1, v, C_2, C_3 \rangle_{cont_1}$
$\langle \bullet, v \rangle_{cont_3} \Rightarrow v$

Figure 4: A substitution-based abstract machine for the second level of the CPS hierarchy

component corresponding to the additional continuation of the interpreter. Observe that the transitions of the machine for Level 1 are “embedded” in the machine for Level 2—the extra component is threaded but not used.

Just as for the first level, the configuration of the machine $(t, C_1, C_2, C_3)_{eval}$ corresponds to the following decomposition of the initial term:

$$C_3 \#_2 C_2 \#_1 C_1[t]$$

where the additional context C_3 represents the rest of the term outside the innermost $reset_2$.

Again, we can read the set of reduction rules off the transitions of the machine. The embedding of the transitions of the previous machine in the current one is materialized in the fact that all the reduction rules for Level 1 are preserved (the first five rules below), and they do not interact with the extra layer of contexts:

$$\begin{array}{ll}
(\text{succ}) & C_3 \#_2 C_2 \#_1 C_1[\text{succ } \ulcorner n \urcorner] \rightarrow C_3 \#_2 C_2 \#_1 C_1[\ulcorner n + 1 \urcorner] \\
(\beta_\lambda) & C_3 \#_2 C_2 \#_1 C_1[(\lambda x.t) v] \rightarrow C_3 \#_2 C_2 \#_1 C_1[t\{v/x\}] \\
(\xi_\lambda) & C_3 \#_2 C_2 \#_1 C_1[\xi k.t] \rightarrow C_3 \#_2 C_2 \#_1 \bullet[t\{C_1/k\}] \\
(\beta_{ctx}) & C_3 \#_2 C_2 \#_1 C_1[C'_1 v] \rightarrow C_3 \#_2 C_2 \cdot C_1 \#_1 C'_1[v] \\
(\text{val}) & C_3 \#_2 C_2 \cdot C_1 \#_1 \bullet[v] \rightarrow C_3 \#_2 C_2 \#_1 C_1[v] \\
(\xi_{2\lambda}) & C_3 \#_2 C_2 \#_1 C_1[\xi_2 k.t] \rightarrow C_3 \#_2 \bullet \#_1 \bullet[t\{C_2 \cdot C_1/k\}] \\
(\beta_{ctx2}) & C_3 \#_2 C_2 \#_1 C_1[C'_2 \cdot C'_1 v] \rightarrow C_3 \cdot (C_2 \cdot C_1) \#_2 C'_2 \#_1 C'_1[v] \\
(\text{val}_2) & C_3 \cdot (C_2 \cdot C_1) \#_2 \bullet \#_1 \bullet[v] \rightarrow C_3 \#_2 C_2 \#_1 C_1[v] \\
(\text{val}'_2) & \bullet \#_2 \bullet \#_1 \bullet[v] \rightarrow v
\end{array}$$

The three new rules $(\xi_{2\lambda})$, (β_{ctx2}) , and (val_2) are straightforward generalizations of their counterparts for shift and reset. Shift_2 captures not one, but two contexts (up to the nearest enclosing $reset_2$), and reset_2 pushes the first two contexts onto the third one. Finally, the (val_2) rule allows us to pass the boundary of a context, when the term inside it has been reduced to a value.

7 Going up in the CPS hierarchy

Having seen that much, one can write reduction rules for an arbitrary level of the hierarchy, or reconstruct the corresponding abstract machine even without repeating the whole procedure.

At the n th level of the hierarchy, all the operators shift_1 , reset_1 , \dots , shift_n , and reset_n are available. The n th level contains $n + 1$ evaluation contexts and each context C_i can be viewed as a stack of nonempty contexts C_{i-1} . The terms are decomposed as

$$C_{n+1} \#_n C_n \#_{n-1} C_{n-1} \#_{n-2} \cdots \#_2 C_2 \#_1 C_1[t],$$

where each $\#_i$ represents a delimited context up to Level i . All the control operators that occur already at the k th level (with $k < n$) of the hierarchy do not use the contexts $k + 2, \dots, n$.

The transitions of the machine for Level k are “embedded” in the machine for Level $k + 1$ —the extra components are threaded but not used. The 0th level corresponds to the CEK machine and the ordinary lambda-calculus under call by value.

8 Conclusion and issues

We have used CPS as a guideline to establish an operational foundation for delimited continuations. Starting from a call-by-value evaluator for λ -terms with shift and reset, we have mechanically constructed the corresponding abstract machine. From this abstract machine, it is straightforward to construct a syntactic theory of delimited control that, by construction, is compatible with CPS—both for one-step reduction and for evaluation.

The whole approach scales seamlessly to account for the shift_n and reset_n family of delimited-control operators.

Defunctionalization provided a key to connect CPS and operational intuitions about control. Indeed most of the time, control stacks are defunctionalized continuations. We do not know whether CPS is the ultimate answer, but the present work shows yet another example of its usefulness. It is like nothing can go wrong with CPS.

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