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Simulating Induction-Recursion for Partial Algorithms

Dominique Larchey-Wendling[1] and Jean-François Monin[2]

[1] Université de Lorraine, CNRS, LORIA
dominique.larchey-wendling@loria.fr
[2] Université Grenoble Alpes, CNRS, Grenoble INP, VERIMAG
jean-francois.monin@univ-grenoble-alpes.fr

Abstract

We describe a generic method to implement and extract partial recursive algorithms in Coq in a purely constructive way, using L. Paulson's if-then-else *normalization as a running example.*

Implementing complicated recursive schemes in a Type Theory such as Coq is a challenging task. A landmark result is the Bove&Capretta approach [BC05] based on accessibility predicates, and in case of nested recursion, simultaneous Inductive-Recursive (IR) definitions of the domain/function [Dyb00]. Limitations to this approach are discussed in e.g. [Set06, BKS16]. We claim that the use of (1) IR, which is still absent from Coq, and (2) an informative predicate (of sort Set or Type) for the domain, preventing its erasing at extraction time, can be circumvented through a suitable *bar inductive predicate*.

```
type Ω = α | ω of Ω ∗ Ω ∗ Ω
let rec nm e = match e with
  | α              ⇒ α
  | ω(α, y, z)      ⇒ ω(α, nm y, nm z)
  | ω(ω(a, b, c), y, z) ⇒ nm(ω(a, nm(ω(b, y, z)), nm(ω(c, y, z))))
```
Figure 1: L. Paulson's if-then-else normalisation algorithm.

We illustrate our technique on L. Paulson's algorithm for if-then-else normalization [Gie97, BC05] displayed in Fig. 1. For concise statements, we use ω to denote the ternary constructor for if␣then␣else␣ expressions, and α as the nullary constructor for atoms. As witnessed in the third match rule $\omega(\omega(a,b,c),y,z)$, nm contains (two) nested recursive calls, making its termination depend on properties of its semantics. This circularity complicates the approach of well-founded recursion and may even render it unfeasible.

Our method allows to show these properties *after* the (partial) function nm is defined, as proposed in [Kra10], but without the use of Hilbert's ε-operator. We proceed purely constructively without any extension to the existing Coq system and

the recursive definition of Fig. 1 can be *extracted as is* from the Coq term that implements nm.

We start with the inductive definition of the graph $\mathbb{G} : \Omega \to \Omega \to \texttt{Prop}$ of nm (Fig. 2) and we show its functionality.[1] Then we define the domain/termination predicate $\mathbb{D} : \Omega \to \texttt{Prop}$ as a bar inductive predicate with the three rules of Fig. 3.

$$\frac{}{\mathbb{G}\,\alpha\,\alpha} \qquad \frac{\mathbb{G}\,y\,n_y \qquad \mathbb{G}\,z\,n_z}{\mathbb{G}\,(\omega\,\alpha\,y\,z)\,(\omega\,\alpha\,n_y\,n_z)}$$

$$\frac{\mathbb{G}\,(\omega\,b\,y\,z)\,n_b \quad \mathbb{G}\,(\omega\,c\,y\,z)\,n_c \quad \mathbb{G}\,(\omega\,a\,n_b\,n_c)\,n_a}{\mathbb{G}\,(\omega\,(\omega\,a\,b\,c)\,y\,z)\,n_a}$$

Figure 2: Rules for the graph $\mathbb{G} : \Omega \to \Omega \to \texttt{Prop}$ of nm.

$$\frac{}{\mathbb{D}\,\alpha} \qquad \frac{\mathbb{D}\,y \qquad \mathbb{D}\,z}{\mathbb{D}\,(\omega\,\alpha\,y\,z)}$$

$$\frac{\mathbb{D}\,(\omega\,b\,y\,z) \qquad \mathbb{D}\,(\omega\,c\,y\,z)}{\forall n_b\,n_c,\,\mathbb{G}\,(\omega\,b\,y\,z)\,n_b \to \mathbb{G}\,(\omega\,c\,y\,z)\,n_c \to \mathbb{D}\,(\omega\,a\,n_b\,n_c)}{\mathbb{D}\,(\omega\,(\omega\,a\,b\,c)\,y\,z)}$$

Figure 3: Rules for the bar inductive definition of $\mathbb{D} : \Omega \to \texttt{Prop}$.

There, we single out recursive calls using $\mathbb{G}$ but proceed by pattern-matching on e following the recursive scheme of nm of Fig. 1. Then we define nm_rec : $\forall e\,(D_e : \mathbb{D}\,e),\,\{n \mid \mathbb{G}\,e\,n\}$ as a fixpoint using D_e to ensure termination. However, the term nm_rec $e\,D_e$ does not use D_e to compute: the value n satisfying $\mathbb{G}\,e\,n$ is computed by pattern-matching on e and recursion, following the scheme of Fig. 1.

Finally, we define nm $e\,D_e := \pi_1($nm_rec $e\,D_e)$ and get nm_spec $e\,D_e : \mathbb{G}\,e\,($nm $e\,D_e)$ using the second projection π_2. Extraction of OCaml code from nm outputs exactly the algorithm of Fig. 1, illustrating the purely logical (Prop) nature of D_e. In order to reason on $\mathbb{D}/$nm we show that they satisfy the IR specification given in Fig. 4: the constructors of $\mathbb{D}$ are sufficient to establish the simulated constructors d_nm_[012], while nm_spec allows us to derive the fixpoint equations of nm. Us-

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[1] i.e. g_nm_fun : $\forall e\,n_1\,n_2,\,\mathbb{G}\,e\,n_1 \to \mathbb{G}\,e\,n_2 \to n_1 = n_2$.

ing g_nm_fun, we get proof-irrelevance of nm.[2]

```
Inductive Ω : Set := α : Ω | ω : Ω → Ω → Ω → Ω.
Inductive D : Ω → Prop :=
  | d_nm_0                    : D α
  | d_nm_1 y z                : D y → D z → D(ω α y z)
  | d_nm_2 a b c y z D_b D_c  : D(ω a (nm (ω b y z) D_b)
                                     (nm (ω c y z) D_c))
                                → D(ω (ω a b c) y z)
with Fixpoint nm e (D_e : D e) : Ω := match D_e with
  | d_nm_0                    ↦ α
  | d_nm_1 y z D_y D_z        ↦ ω α (nm y D_y) (nm z D_z)
  | d_nm_2 a b c y z D_b D_c D_a ↦ nm (ω a (nm (ω b y z) D_b)
                                     (nm (ω c y z) D_c)) D_a
end.
```

Figure 4: IR spec. of $D : \Omega \to$ Prop and nm $: \forall e, D\, e \to \Omega$.

We show a dependent induction principle for D (see Fig. 5). The term d_nm_ind states that any dependent property $P : \forall e, D\, e \to$ Prop contains D as soon as it is closed under the simulated constructors d_nm_[012] of D. The assumption $\forall e\, D_1\, D_2, P\, e\, D_1 \to P\, e\, D_2$ restricts the principle to *proof-irrelevant* properties about the dependent pair (e, D_e). This is exactly what we need to establish properties of nm. Then we can show partial correctness and termination as in [Gie97] – in this example, nm happens to always terminate on a normal form of its input. In a more relational approach, these properties can alternatively be proved using nm_spec and induction on $G\, x\, n_x$.

```
Theorem d_nm_ind (P : ∀e, D e → Prop) :
    (∀e D_1 D_2, P e D_1 → P e D_2) → (P _ d_nm_0)
  → (∀y z D_y D_z, P _ D_1 → P _ D_z → P _ (d_nm_1 y z D_y D_z))
  → (∀a b c y z D_b D_c D_a, P _ D_b → P _ D_c → P _ D_a …
        … → P _ (d_nm_2 a b c y z D_b D_c D_a))
  → ∀e D_e, P e D_e.
```

Figure 5: Dependent induction principle for $D : \Omega \to$ Prop.

Though our approach is inspired by IR definitions, in contrast with previous work, e.g. [Bov09], the corresponding principles are established *independently* of any consideration on the semantics or termination of the target function (nm), i.e. without proving any properties of D/nm a priori. This postpones the study of termination after both D and nm are defined together with constructors and elimination scheme, fixpoint equations and proof-irrelevance. Moreover, our domain/termination predicate D is *non-informative*, i.e. it does not carry any computational content. Thus the code obtained by extraction is exactly as intended.

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[2]i.e. nm_pirr $: \forall e\, D_1\, D_2,$ nm $e\, D_1 =$ nm $e\, D_2$.

Our Coq code is available under a Free Software license [LWM18]. We have successfully implemented other algorithms using the same technique: F91, unification, depth first search as in [Kra10], quicksort, iterations until 0, partial list map as in [BKS16], Huet&Hullot's list reversal [Gie97], etc. The method is not constrained by nested/mutual induction, partiality or dependent types. On the other hand, spotting recursive sub-calls implies the explicit knowledge of all the algorithms that make such calls, a limitation that typically applies to higher order recursive schemes such as e.g. substitutions under binders. Besides growing our bestiary of examples, we aim at formally defining a class of schemes for which our method is applicable, and more practically propose some automation like what is done in Equations [Soz10].

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