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A Denotational Account of Untyped Normalization by Evaluation*

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Abstract

We show that the standard normalization-by-evaluation construction for the simply-typed $\lambda_{\beta\eta}$-calculus has a natural counterpart for the untyped λ_β-calculus, with the central type-indexed logical relation replaced by a "recursively defined" *invariant relation*, in the style of Pitts. In fact, the construction can be seen as generalizing a computational-adequacy argument for an untyped, call-by-name language to normalization instead of evaluation.

In the untyped setting, not all terms have normal forms, so the normalization function is necessarily partial. We establish its correctness in the senses of *soundness* (the output term, if any, is β-equivalent to the input term); *standardization* (β-equivalent terms are mapped to the same result); and *completeness* (the function is defined for all terms that do have normal forms). We also show how the semantic construction enables a simple yet formal correctness proof for the normalization algorithm, expressed as a functional program in an ML-like call-by-value language.

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1 Introduction

1.1 Reduction-Based and Reduction-Free Normalization

Traditional accounts of term normalization are based on a directed notion of *reduction* (such as β-reduction), which can be applied anywhere within a term. A term is said to be a *normal form* if no reductions can be performed on it. If the reduction relation is confluent, normal forms are uniquely determined, so normalization is a (potentially partial) function on terms. Some terms (such as Ω) may not have normal forms at all; or a particular reduction strategy (such as normal-order reduction) may be required to guarantee arrival at a normal form when one exists; such a strategy is called *complete*. There is a very large body of work dealing with normalization in reduction-based settings.

However, in recent years, a rather different notion of normalization has emerged, so-called *reduction-free normalization*. As the name suggests, it is not based on a directed notion of reduction, but rather on an undirected notion of term *equivalence*. Equivalence may be defined as simply the reflexive-transitive-symmetric closure of an existing reduction relation, but it does not have to be: any congruence relation on terms may be used. The task of normalization is then to define a *normalization function* on terms, such that the output of the function is equivalent to the input, and such that any two equivalent terms are mapped to identical outputs [3].

For some notions of equivalence (such as β-convertibility of untyped lambda-terms), it is actually impossible to define a *computable*, total normalization function with both of these properties; we must thus accept that the normalization function may be partial. However, even in that case, we can impose a completeness constraint: if we have an independent syntactic characterization of acceptable *normal forms*, we can require that the function both produce terms in this form as output, and that it be defined on all terms equivalent to a normal form.

1.2 Normalization by Evaluation

A particularly natural way of obtaining a reduction-free normalization function is known as *normalization by evaluation (NBE)*, based on the following idea: Suppose we can construct a denotational model of the term syntax (i.e., such that equivalent terms have the same denotation), with the property that a syntactic representation of the term (up to equivalence) can be be extracted from its denotation; such a model is called *residualizing*. Then the normalization function can be expressed simply as a (compositional) interpretation in the model, followed by extraction.

A priori, such a normalization function is not necessarily effectively computable. It can be given a computational interpretation if the denotational model is constructed in intuitionistic set theory [3], but this gets somewhat complicated for domain-theoretic models, especially those involving reflexive domains. In such cases, it is often easier to establish that the constructions are effective by showing that they can expressed as images of program terms in a language for which the domain-theoretic semantics is already known to be computationally adequate.

(It should be noted that the term NBE is also sometimes used for a related concept, based on reducing – usually in a compositional way – the *normalization problem*, which may in general involve open terms of higher type, to an *evaluation problem*, which involves normalization of only closed terms of base type. The required transformation is often syntactically related to the model-based construction above, but the model itself is not made explicit; and in fact, the subsequent evaluation process may still be specified entirely in terms of reductions.)

1.3 The Berger-Schwichtenberg Normalization Algorithm

Perhaps the best-known NBE algorithm is due to Berger and Schwichtenberg [2]. It finds $\beta\eta$-long normal forms of simply-typed λ-terms. We present here its outline, glossing over inessential details.

Types are of the form $\tau ::= b \mid \tau_1 \to \tau_2$. A natural set-theoretic model interprets each base type b as some set, and the function type as the set of all functions between the interpretations of the types, i.e., $[\![\tau_1 \to \tau_2]\!] = [\![\tau_1]\!] \to [\![\tau_2]\!]$. For a type assignment Γ, we also take $[\![\Gamma]\!] = \prod_{x \in \mathrm{dom}\,\Gamma} [\![\Gamma(x)]\!]$.

Let Λ be the set of syntactic λ-terms (written with explicit constructors for emphasis) over a set of variables V. For a well-typed term $\Gamma \vdash m : \tau$, we can then express its semantics $[\![m]\!] \in [\![\Gamma]\!] \to [\![\tau]\!]$ as follows:

$$
\begin{aligned}
[\![\mathrm{VAR}(x)]\!]\,\rho &= \rho(x) \\
[\![\mathrm{LAM}(x^{\tau}, m_0)]\!]\,\rho &= \lambda a^{[\![\tau]\!]}.\,[\![m_0]\!]\,\rho[x \mapsto a] \\
[\![\mathrm{APP}(m_1, m_2)]\!]\,\rho &= [\![m_1]\!]\,\rho\,([\![m_2]\!]\,\rho)
\end{aligned}
$$

It is easy to check that such a model is sound for conversion, i.e., that when $m \leftrightarrow_{\beta\eta} m'$, then $[\![m]\!] = [\![m']\!]$.

Consider now a model where all base types are interpreted as the set of (open) syntactic λ-terms, i.e., $[\![b]\!] = \Lambda$ for all b. In this model, we can define a pair of type-indexed function families: *reification*, $\downarrow^{\tau} : [\![\tau]\!] \to \Lambda$, and *reflection*, $\uparrow^{\tau} : \Lambda \to [\![\tau]\!]$, by mutual induction on types:

$$
\begin{aligned}
\downarrow^{b} l &= l \\
\downarrow^{\tau_1 \to \tau_2} f &= \mathrm{LAM}(x^{\tau_1}, \downarrow^{\tau_2} (f(\uparrow^{\tau_1} \mathrm{VAR}(x)))) \quad \text{(where } x \text{ is chosen "fresh")} \\
\uparrow^{b} l &= l \\
\uparrow^{\tau_1 \to \tau_2} l &= \lambda a^{[\![\tau_1]\!]}.\uparrow^{\tau_2} (\mathrm{APP}(l, \downarrow^{\tau_1} a))
\end{aligned}
$$

For simplicity, let us only consider normal forms of closed terms. Then reification can serve directly as an extraction function: one can check that, for a term $\vdash m : \tau$ in $\beta\eta$-long normal form, $\downarrow^{\tau} ([\![m]\!]\,\emptyset) \leftrightarrow_{\alpha} m$. Hence, by soundness of the model, for any term m' with $m' \leftrightarrow_{\beta\eta} m$, $\downarrow^{\tau} ([\![m']\!]\,\emptyset) = \downarrow^{\tau} ([\![m]\!]\,\emptyset) \leftrightarrow_{\alpha} m \leftrightarrow_{\beta\eta} m'$. Alternatively, one can show the latter property directly, for an arbitrary m'. Either way, the typical proof ultimately involves a logical-relations argument, even if this argument is pushed entirely into a standard result about the syntax (namely, that every well-typed term has a $\beta\eta$-long normal form). The latter approach, however, generalizes better, especially to systems where not all terms have normal forms.

1.4 A Tentative Algorithm for Untyped Terms

In an untyped (or, more accurately, unityped) setting, we may hope to get a residualizing model by interpreting the single type of terms as a domain $D = \Lambda + (D \to D)$.

(Again, we gloss over domain-theoretic subtleties for expository purposes.) We can then define variants of reification, $\downarrow : D \to \Lambda$, and reflection, $\uparrow : \Lambda \to D$, roughly analogous to the simply-typed case:

$$\begin{aligned}
\downarrow d &= \text{case } d \text{ of } \begin{cases} in_1(l) \to l \\ in_2(f) \to \mathrm{LAM}(x, \downarrow (f(\uparrow \mathrm{VAR}(x)))) \quad (x \text{ "fresh"}) \end{cases} \\
\uparrow l &= in_1(l)
\end{aligned}$$

Note that reification is now defined by general recursion, rather than induction. We can also construct an interpretation, $[\![m]\!] \in (V \to D) \to D$, by

$$\begin{aligned}
[\![\mathrm{VAR}(x)]\!]\,\rho &= \rho(x) \\
[\![\mathrm{LAM}(x, m_0)]\!]\,\rho &= in_2(\lambda d.\,[\![m_0]\!]\,\rho[x \mapsto d]) \\
[\![\mathrm{APP}(m_1, m_2)]\!]\,\rho &= \text{case } [\![m_1]\!]\,\rho \text{ of } \begin{cases} in_1(l) \to \uparrow (\mathrm{APP}(l, \downarrow ([\![m_2]\!]\,\rho))) \\ in_2(f) \to f\,([\![m_2]\!]\,\rho) \end{cases}
\end{aligned}$$

Here, reflection is performed "on demand": when application needs a semantic function, but $[\![m_1]\!]\rho$ is a piece of syntax, it is reflected just enough to allow the application to be performed.

Again, it can be checked that β-convertible terms have the same denotation. It is also fairly easy to verify that, for a closed m in β-normal form, $\downarrow ([\![m]\!]\,\emptyset) \leftrightarrow_\alpha m$. What is not obvious at all, however, is that when $\downarrow ([\![m']\!]\,\emptyset) = m$ for a general m', then m' must be syntactically β-convertible to a normal form. Indeed, the problem is a generalization of the usual computational-adequacy problem for a denotational semantics of a functional language: if the denotation of a closed term is not $\perp$, must the term then evaluate to a value?

For a simply typed language, PCF, adequacy of the natural domain-theoretic semantics was shown by Plotkin, using a logical-relations argument [7]. Pitts showed that essentially the same argument applies to an untyped language, except that the central relation is no longer constructed by induction on types, but as a solution of a more general "relation equation"; he also showed a general method for solving such equations, yielding *invariant relations* [5].

In this paper, we first formalize the construction of the normalization function from above, addressing especially the issues of potential divergence and generation of fresh variable names (Section 2). We then show correctness of this function by a generalized computational-adequacy construction (Section 3). Finally, we show how the domain-theoretic analysis directly validates a functional program implementing the construction (Section 4).

1.5 Related Work

The closest related work to ours is probably the NBE-based (in the alternate sense) algorithm for untyped β-normalization proposed by Aehlig and Joachimski [1]. However, while the functional programs ultimately derived from the analyses are quite similar, the correctness arguments are completely different: theirs are based entirely on syntactic concepts and results from higher-order rewriting theory, rather than on the domain-theoretic constructions underlying ours. In particular, their algorithm is very explicitly reduction-based, departing from the original meaning of NBE as term extraction from a denotational model of a conversion relation.

We believe that the domain-theoretic approach enables a more direct and precise correctness proof for the normalizer, as actually implemented. In Aehlig and Joachimski's work, the abstract algorithm is expressed as a small-step operational semantics for a specialized, two-level λ-calculus with named bound variables; yet the actual normalization program is expressed as a compositional interpreter in Haskell, using de Bruijn indices for bound variables, and a reflexive type for the meanings of higher-typed terms. No connection is made to a formal semantics (operational or otherwise) of the relevant Haskell fragment. While it may well be possible to formally close this gap, it remains as a potentially major undertaking. On the other hand, formally relating the domain-theoretic constructions in the model-based normalizer to the functional terms implementing them is completely straightforward. We expect, but have not formally investigated, that Aehlig and Joachimski's interesting extensions of the basic algorithm to infinite normal forms (Böhm trees) could also be expressed naturally in the denotational setting, and be used to validate a functional program producing such normal forms lazily.

Many of the constructions in the present paper are inspired by the first author's work on type-directed partial evaluation [4]. Apart from the obvious differences arising from typed vs. untyped languages, a significant change is also that the TDPE work considered equivalence defined semantically (equality of denotations for all interpretations of "dynamic" constants), while here we consider syntactic β-convertibility. Accordingly, the central invariant relation ties denotations to syntactic terms, rather than to denotations in another semantics.

Essentially the same program as in Section 4, but expressed in FreshML, can be found in a recent paper by Shinwell et al. [8, Figure 7]. However, the focus there is on a practical application of fresh-name generation, rather than on normalization as such. Indeed, the underlying algorithm is only informally attributed to Coquand, and carries no formal correctness argument. In the present work, generation of fresh names is handled explicitly: since constructed output terms are never subsequently analyzed, using a general framework such as FreshML, or higher-order abstract syntax, is probably overkill. However, we anticipate that a different "back end" for output generation could be used, and have deliberately tried to keep the constructions and proofs modular with respect to the term-generation operations. We thus expect that essentially the same arguments – perhaps even a little simplified – could be used to verify correctness of the FreshML variant of the normalizer as well.

2 A Semantic Normalization Construction

2.1 Syntax and Semantics of the Untyped λ-Calculus

Syntax Let V be a countably infinite set of (object) variables, with x and v ranging over V. Let Λ be the set of λ-terms defined by

$$m ::= \mathrm{VAR}(x) \mid \mathrm{LAM}(x, m_0) \mid \mathrm{APP}(m_1, m_2)$$

The set of free variables of a term, $FV(m)$, is defined in the usual way. For any finite set of variables Δ, we write Λ^Δ for the set of λ-terms over Δ, i.e.,

$$\Lambda^\Delta = \{m \in \Lambda \mid FV(m) \subseteq \Delta\}$$

Substitutions For technical reasons, we take simultaneous (as opposed to single-variable), capture-avoiding substitution as the basic concept. Accordingly, we say that a substitution θ is a finite partial function from variables to terms. We take $FV(\theta) = \bigcup_{x \in \mathrm{dom}\,\theta} FV(\theta(x))$, and define the action of θ on a term m in the usual way, by structural induction on m:

$$
\begin{array}{rcl}
\mathrm{VAR}(x)[\theta] & = & \begin{cases} \theta(x) & \text{if } x \in \mathrm{dom}\,\theta \\ \mathrm{VAR}(x) & \text{otherwise} \end{cases} \\
\mathrm{LAM}(x, m_0)[\theta] & = & \mathrm{LAM}(x', m_0[\theta[x \mapsto \mathrm{VAR}(x')]]) \\
 & & \quad \text{where } x' \notin FV(\theta) \cup (FV(m_0) \backslash \{x\}) \\
\mathrm{APP}(m_1, m_2)[\theta] & = & \mathrm{APP}(m_1[\theta], m_2[\theta])
\end{array}
$$

As a special case, we use the standard notation $m[m'/x]$ to mean $m[\,[x \mapsto m']\,]$. To keep the substitution operation deterministic, we assume that the x' in the LAM-clause is picked as some fixed but arbitrary function of the (finite) set of variables it needs to avoid.

Conversion and normalization We define convertibility between λ-terms, written $m \leftrightarrow m'$, by the axiom schemas for α- and β-conversion,

$$
\begin{array}{rcll}
\mathrm{LAM}(x, m) & \leftrightarrow & \mathrm{LAM}(x', m[x'/x]) & (x' \notin FV(m) \backslash \{x\}) \\
\mathrm{APP}(\mathrm{LAM}(x, m), m') & \leftrightarrow & m[m'/x] &
\end{array}
$$

together with the standard equivalence and compatibility rules, making $\leftrightarrow$ into a congruence relation on terms.
We further define *atomic* (also known as *neutral*) and *normal* forms, as follows:

$$
\frac{}{\vdash_{\mathrm{at}} \mathrm{VAR}(x)} \qquad \frac{\vdash_{\mathrm{at}} m_1 \quad \vdash_{\mathrm{nf}} m_2}{\vdash_{\mathrm{at}} \mathrm{APP}(m_1, m_2)} \qquad \frac{\vdash_{\mathrm{at}} m}{\vdash_{\mathrm{nf}} m} \qquad \frac{\vdash_{\mathrm{nf}} m_0}{\vdash_{\mathrm{nf}} \mathrm{LAM}(x, m_0)}
$$

We then expect a normalization function on terms to satisfy that the output, if any, is in normal form and convertible to the input (soundness); convertible terms either give the same output, or neither one does (standardization); and if a term has a normal form at all, the normalization function will return one (completeness).

Semantics A natural way of defining a denotational model of convertibility is in terms of a reflexive pointed cpo D. Reflexivity means that the continuous-function space $[D \to D]$ is a retract of D, i.e., that there exist continuous functions

$$
\phi : [D \to D] \to D \quad \text{and} \quad \psi : D \to [D \to D]\,,
$$

such that $\psi \circ \phi = id_{[D \to D]}$. The induced interpretation, $[\![m]\!] \in [[V \to D] \to D]$, is then:

$$
\begin{array}{rcl}
[\![\mathrm{VAR}(x)]\!]\,\rho & = & \rho(x) \\
[\![\mathrm{LAM}(x, m_0)]\!]\,\rho & = & \phi(\lambda d^D.\,[\![m_0]\!]\,\rho[x \mapsto d]) \\
[\![\mathrm{APP}(m_1, m_2)]\!]\,\rho & = & \psi([\![m_1]\!]\,\rho)\,([\![m_2]\!]\,\rho)
\end{array}
$$

Lemma 1 *The interpretation has two expectable properties:*

a. If $\forall x \in FV(m).\, \rho(x) = \rho'(x)$*, then* $[\![m]\!]\,\rho = [\![m]\!]\,\rho'$*.*

b. Let $\theta = [x_1 \mapsto m_1, \ldots, x_n \mapsto m_n]$ *be a substitution.*
Then $[\![m[\theta]]\!]\,\rho = [\![m]\!]\,\rho[x_1 \mapsto [\![m_1]\!]\,\rho, \ldots, x_n \mapsto [\![m_n]\!]\,\rho]$*.*

Proof: Part (a) is a straightforward induction on the structure of m. Part (b) follows by induction on the structure of m, using part (a) in the LAM-case. □

Lemma 2 (model soundness) *If* $m \leftrightarrow m'$ *then* $[\![m]\!] = [\![m']\!]$

Proof: By induction on the derivation of $m \leftrightarrow m'$, using Lemma 1 for α- and β-conversion, and using that $\psi \circ \phi = id_{[D \to D]}$ for β-conversion. □

2.2 Output-Term Generation

We want to account rigorously for the generation of fresh names, and do so in a modular manner. We will therefore construct a set $\widehat{\Lambda}$ (dependent on the name generation scheme) with elements denoted by l, together with *wrapper* functions,

$$\widehat{\mathrm{VAR}} : V \to \widehat{\Lambda}, \quad \widehat{\mathrm{LAM}} : [V \to \widehat{\Lambda}] \to \widehat{\Lambda}, \quad \widehat{\mathrm{APP}} : \widehat{\Lambda} \times \widehat{\Lambda} \to \widehat{\Lambda}$$

where, in particular, $\widehat{\mathrm{LAM}}$ provides a fresh name to be used in constructing the body of the λ-abstraction.

Let $\mathcal{N}$ be a set (discrete cpo) containing at least the natural numbers, with an operation $\cdot + 1 : \mathcal{N} \to \mathcal{N}$, agreeing with the successor operation on naturals. Let $\{g_0, g_1, ...\}$ be a countably infinite subset of V, such that $g_i = g_j$ implies $i = j$, and let $gen : \mathcal{N} \to V$ be such that $gen(n) = g_n$ when $n \in \mathbb{N}$.

We write $\lfloor \cdot \rfloor$ for the inclusion from A to $A_\perp$; and for $f : A \to B$ with B pointed, we write $\cdot \star f$ for f's strict extension to $A_\perp$, i.e., $\perp \star f = \perp_B$ and $\lfloor a \rfloor \star f = f\,a$. We then take $\widehat{\Lambda} = [\mathcal{N} \to \Lambda_\perp]$ and define wrapper functions for constructing λ-terms using de Bruijn-level (not -index!) naming as follows:

$$\begin{aligned}
\widehat{\mathrm{VAR}}(v) &= \lambda n^{\mathcal{N}}.\, \lfloor \mathrm{VAR}(v) \rfloor \\
\widehat{\mathrm{LAM}}(f) &= \lambda n^{\mathcal{N}}.\, f\ gen(n)\ (n+1) \star \lambda m_0^{\Lambda}.\, \lfloor \mathrm{LAM}(gen(n), m_0) \rfloor \\
\widehat{\mathrm{APP}}(l_1, l_2) &= \lambda n^{\mathcal{N}}.\, l_1\, n \star \lambda m_1^{\Lambda}.\, l_2\, n \star \lambda m_2^{\Lambda}.\, \lfloor \mathrm{APP}(m_1, m_2) \rfloor
\end{aligned}$$

Note 1 *If we took freshness as a primitive concept, like in FreshML, we could simply use* $\widehat{\Lambda} = \Lambda_\perp$*;* $\widehat{\mathrm{VAR}}(v) = \lfloor \mathrm{VAR}(v) \rfloor$*;* $\widehat{\mathrm{LAM}}(f) = f\,x \star \lambda m_0.\, \lfloor \mathrm{LAM}(x, m_0) \rfloor$*, with* x fresh *for* f*; and* $\widehat{\mathrm{APP}}(l_1, l_2) = l_1 \star \lambda m_1.\, l_2 \star \lambda m_2.\, \lfloor \mathrm{APP}(m_1, m_2) \rfloor$*.*

2.3 A Residualizing Model

From standard domain-theoretic results (e.g., [5]), we know that there exists a pointed cpo D_r, together with an isomorphism

$$i : D_r \xrightarrow{\cong} (\widehat{\Lambda} + [D_r \to D_r])_\perp$$

Moreover, this solution is a so-called *minimal invariant*, which we will need in the next section.

We first define the reification function $\uparrow : \widehat{\Lambda} \to D_r$ and reflection function $\downarrow : D_r \to \widehat{\Lambda}$, as follows:

$$\begin{aligned}
\downarrow d &= \text{case } i(d) \text{ of } \begin{cases} \lfloor in_1(l) \rfloor \to l \\ \lfloor in_2(f) \rfloor \to \widehat{\mathrm{LAM}}(\lambda x^V. \downarrow (f(\uparrow \widehat{\mathrm{VAR}}(x)))) \\ \quad\perp \quad\; \to \perp_{\widehat{\Lambda}} \end{cases} \\
\uparrow l &= i^{-1}(\lfloor in_1(l) \rfloor)
\end{aligned}$$

where the recursive definition of $\downarrow$ is interpreted in the usual least-fixed-point sense. Using these, we construct appropriate functions $\phi_r : [D_r \to D_r] \to D_r$ and $\psi_r : D_r \to [D_r \to D_r]$:

$$\begin{aligned}
\phi_r(f) &= i^{-1}(\lfloor in_2(f) \rfloor) \\
\psi_r(d) &= \text{case } i(d) \text{ of } \begin{cases} \lfloor in_1(l) \rfloor \to \lambda d'^{D_r}. \uparrow \widehat{\mathrm{APP}}(l, \downarrow d') \\ \lfloor in_2(f) \rfloor \to f \\ \quad\perp \quad\; \to \perp_{[D_r \to D_r]} \end{cases}
\end{aligned}$$

Clearly, we have that $\psi_r \circ \phi_r = id_{[D_r \to D_r]}$, since i was an isomorphism. The induced interpretation is denoted by $[\![\cdot]\!]_r$. We can now define a putative normalization function:

Definition 1 *For any Δ, let $\sharp\Delta = \max(\{n+1 \mid g_n \in \Delta\} \cup \{0\})$ (i.e., the least n such that $\forall n' \geq n.\, g_{n'} \notin \Delta$). We then define the function* $\mathrm{norm}_\Delta : \Lambda^\Delta \to \Lambda_\perp$ *by*

$$\mathrm{norm}_\Delta(m) = \downarrow ([\![m]\!]_r\, (\lambda x^V. \uparrow \widehat{\mathrm{VAR}}(x)))\ \sharp\Delta$$

In particular, when Δ is disjoint from the set of g_i-names (so $\sharp\Delta = 0$), we write just norm *for* norm_Δ.

3 Correctness of the Construction

3.1 Correctness of the Wrappers

Let $s \in \{\mathrm{at}, \mathrm{nf}\}$ be a syntactic-form designator. We first define a quaternary relation, $l \lessapprox_s^\Delta m$, expressing that if l represents a term at all, then that term only has free variables in Δ, is of the syntactic form s, and is convertible to m:

Definition 2 *For $l \in \widehat{\Lambda}$ and $m \in \Lambda^\Delta$, we then define the relation $\lessapprox$ by*

$$l \lessapprox_s^\Delta m \quad \textit{iff} \quad \forall n \geq \sharp\Delta, m' \in \Lambda.\, l\, n = \lfloor m' \rfloor \Rightarrow m' \in \Lambda^\Delta \wedge \vdash_s m' \wedge m' \leftrightarrow m$$

Lemma 3 *For fixed Δ, s, and m, the predicate $P = \{l \mid l \lessapprox_s^\Delta m\}$ is pointed (i.e., $\perp_{\widehat{\Lambda}} \in P$) and inclusive (i.e., closed under limits of ω-chains).*

Proof: Straightforward, noting that $\lessapprox$ is expressed using intersection, inverse image, and a (necessarily inclusive) predicate on the flat domain $\Lambda_\perp$. □

Lemma 4 *The representation relation is closed under weakening and conversion:*

a. *If* $l \lessapprox_s^{\Delta} m$ *and* $\Delta \subseteq \Delta'$*, then also* $l \lessapprox_s^{\Delta'} m$*.*

b. *If* $l \lessapprox_s^{\Delta} m$ *and* $m' \in \Lambda^{\Delta}$ *with* $m \leftrightarrow m'$*, then also* $l \lessapprox_s^{\Delta} m'$*.*

Proof: Both parts are immediate from the definition. □

Lemma 5 *Representations of terms behave much like the terms themselves:*

a. *If* $v \in \Delta$ *then* $\widehat{\mathrm{VAR}}(v) \lessapprox_{\mathrm{at}}^{\Delta} \mathrm{VAR}(v)$*.*

b. *If* $l_1 \lessapprox_{\mathrm{at}}^{\Delta} m_1$ *and* $l_2 \lessapprox_{\mathrm{nf}}^{\Delta} m_2$*, then* $\widehat{\mathrm{APP}}(l_1, l_2) \lessapprox_{\mathrm{at}}^{\Delta} \mathrm{APP}(m_1, m_2)$*.*

c. *If* $l \lessapprox_{\mathrm{at}}^{\Delta} m$*, then also* $l \lessapprox_{\mathrm{nf}}^{\Delta} m$*.*

d. *Let* $f \in [V \to \widehat{\Lambda}]$ *and* $m \in \Lambda^{\Delta \cup \{x\}}$*. If* $\forall v \notin \Delta. f v \lessapprox_{\mathrm{nf}}^{\Delta \cup \{v\}} m[\mathrm{VAR}(v)/x]$*, then* $\widehat{\mathrm{LAM}}(f) \lessapprox_{\mathrm{nf}}^{\Delta} \mathrm{LAM}(x, m)$*.*

Proof: Parts (a), (b), and (c) are straightforward, where (b) uses that convertibility is a congruence wrt. APP. We will now prove (d).

Let f, x, and m, satisfy the condition of the lemma, and let $n \geq \sharp\Delta$ and m' with $\widehat{\mathrm{LAM}}(f)\ n = \lfloor m' \rfloor$ be given; we must show that $m' \in \Lambda^{\Delta}$, $\vdash_{\mathrm{nf}} m'$, and $m' \leftrightarrow \mathrm{LAM}(x, m)$.

From the definition of $\widehat{\mathrm{LAM}}(f)$, we must have that, for some m_0, $f\ g_n\ (n+1) = \lfloor m_0 \rfloor$ and $m' = \mathrm{LAM}(g_n, m_0)$. By definition of $\sharp$, $g_n \notin \Delta$, so by assumption on f, $f\ g_n \lessapprox_{\mathrm{nf}}^{\Delta \cup \{g_n\}} m[\mathrm{VAR}(g_n)/x]$. Further, since $n + 1 \geq \sharp(\Delta \cup \{g_n\})$, the definition of $\lessapprox$ gives us that $m_0 \in \Lambda^{\Delta \cup \{g_n\}}$, $\vdash_{\mathrm{nf}} m_0$, and $m_0 \leftrightarrow m[\mathrm{VAR}(g_n)/x]$. But then clearly $\mathrm{LAM}(g_n, m_0) \in \Lambda^{\Delta}$, $\vdash_{\mathrm{nf}} \mathrm{LAM}(g_n, m_0)$, and

$$\mathrm{LAM}(g_n, m_0) \leftrightarrow \mathrm{LAM}(g_n, m[\mathrm{VAR}(g_n)/x]) \leftrightarrow \mathrm{LAM}(x, m)\,,$$

where the first conversion is by congruence wrt. LAM and the second is a valid α-conversion, since $g_n \notin \Delta$ ensures that $g_n \notin FV(m) \backslash \{x\}$. □

3.2 Adequacy of the Residualizing Model

To construct the central relation between denotations and terms, we first state an abstract version of a result due to Pitts [5]:

Theorem 1 (existence of invariant relations) *Let* A *be a cpo, and let* $i : D \xrightarrow{\cong} (A + [D \to D])_{\perp}$ *be a minimal-invariant solution of the domain equation* $X \cong (A + [X \to X])_{\perp}$*. Let* T *be a set, and let predicates* $P_1 \subseteq A \times T$*,* $P_2 \subseteq T$*, and* $P_3 \subseteq T \times T \times T$ *be given, such that* $\{a \mid P_1(a, t)\}$ *is inclusive for every* $t \in T$*. Then there exists a relation* $\lhd \subseteq D \times T$*, with* $\{d \mid d \lhd t\}$ *inclusive for every* $t \in T$*, and such that, for all* $d \in D$ *and* $t \in T$*:*

$$\begin{aligned} d \lhd t \ \textit{iff}\ \ & i(d) = \perp \\ & \textit{or}\ \exists a.\, i(d) = \lfloor in_1(a) \rfloor \wedge P_1(a, t) \\ & \textit{or}\ \exists f.\, i(d) = \lfloor in_2(f) \rfloor \wedge P_2(t) \wedge \\ & \qquad \forall d' \in D; t', t'' \in T.\ P_3(t, t', t'') \wedge d' \lhd t' \Rightarrow f(d') \lhd t''. \end{aligned}$$

Proof: See Appendix A □

We can then establish the existence of a Kripke-style invariant relation, using sets of variables as worlds:

Lemma 6 *There exists a relation $\lesssim$ such that for all Δ, $d \in D_r$ and $m \in \Lambda^\Delta$,*

$$
\begin{aligned}
d \lesssim^\Delta m \text{ iff } & i(d) = \bot \\
& \text{or } \exists l.\, i(d) = \lfloor in_1(l) \rfloor \wedge l \lessapprox^\Delta_{\mathrm{at}} m \\
& \text{or } \exists f.\, i(d) = \lfloor in_2(f) \rfloor \wedge (\exists x \in V, m_0 \in \Lambda^{\Delta \cup \{x\}}.\mathrm{LAM}(x, m_0) \leftrightarrow m) \\
& \quad \wedge \forall \Delta' \supseteq \Delta, d' \in D_r, m' \in \Lambda^{\Delta'}, m_1 \in \Lambda^{\Delta'}. \\
& \qquad m \leftrightarrow m_1 \wedge d' \lesssim^{\Delta'} m' \Rightarrow f(d') \lesssim^{\Delta'} \mathrm{APP}(m_1, m')
\end{aligned}
$$

Proof: By Theorem 1, taking $A = \widehat{\Lambda}$ and $T = \{(\Delta, m) \mid \Delta \subseteq_{\mathrm{fin}} V \wedge m \in \Lambda^\Delta\}$, with the predicates chosen as

$$
\begin{aligned}
P_1 &= \{(l, (\Delta, m)) \mid l \lessapprox^\Delta_{\mathrm{at}} m\} \\
P_2 &= \{(\Delta, m) \mid \exists x \in V, m_0 \in \Lambda^{\Delta \cup \{x\}}.\mathrm{LAM}(x, m_0) \leftrightarrow m\} \\
P_3 &= \{((\Delta, m), (\Delta', m'), (\Delta'', m'')) \mid \\
&\qquad \Delta \subseteq \Delta' = \Delta'' \wedge \exists m_1 \in \Lambda^{\Delta'}.m \leftrightarrow m_1 \wedge m'' = \mathrm{APP}(m_1, m')\}
\end{aligned}
$$

using the equivalence $[\forall x.(\exists y.P(x,y)) \Rightarrow Q(x)] \Leftrightarrow [\forall x.\forall y.P(x,y) \Rightarrow Q(x)]$. P_1 is inclusive in its first argument by Lemma 3. We write $d \lesssim^\Delta m$ instead of $d \lhd (\Delta, m)$. $\square$

Lemma 7 *The relation $\lesssim$ shares two key properties with $\lessapprox$:*

a. If $d \lesssim^\Delta m$ and $\Delta \subseteq \Delta'$, then also $d \lesssim^{\Delta'} m$.

b. If $d \lesssim^\Delta m$ and $m' \in \Lambda^\Delta$ with $m \leftrightarrow m'$, then also $d \lesssim^\Delta m'$.

Proof: We proceed according to the cases for $d \lesssim^\Delta m$ in Lemma 6:

Case $i(d) = \bot$: Both parts are immediate.

Case $i(d) = \lfloor in_1(l) \rfloor$: Both parts follow directly from the corresponding parts of Lemma 4, taking $s = \mathrm{at}$.

Case $i(d) = \lfloor in_2(f) \rfloor$: For (a), if $m_0 \in \Lambda^{\Delta \cup \{x\}}$, then also $m_0 \in \Lambda^{\Delta' \cup \{x\}}$. Likewise, any Δ'' with $\Delta'' \supseteq \Delta'$ in the universal quantification also satisfies $\Delta'' \supseteq \Delta$.

For (b), any m_0 satisfying $\mathrm{LAM}(x, m_0) \leftrightarrow m$ also satisfies $\mathrm{LAM}(x, m_0) \leftrightarrow m'$ by transitivity. Similarly, the terms m_1 satisfying $m \leftrightarrow m_1$ are the same as those that satisfy $m' \leftrightarrow m_1$.

$\square$

The following two lemmas will combine to establish adequacy of our semantics:

Lemma 8 *For all $l \in \widehat{\Lambda}$, $d \in D_r$, and $m \in \Lambda^\Delta$,*

a. If $l \lessapprox^\Delta_{\mathrm{at}} m$ then $\uparrow l \lesssim^\Delta m$

b. If $d \lesssim^\Delta m$ then $\downarrow d \lessapprox^\Delta_{\mathrm{nf}} m$

Proof: Part (a) follows immediately from Lemma 6($\Leftarrow$) and the definition of $\uparrow$.

For part (b), recall that reification was conceptually defined in terms of the continuous function $\Phi : [D_r \to \widehat{\Lambda}] \to [D_r \to \widehat{\Lambda}]$,

$$\Phi(\varphi) = \lambda d^{D_r}.\,\text{case } i(d) \text{ of } \begin{cases} \lfloor in_1(l) \rfloor & \to l \\ \lfloor in_2(f) \rfloor & \to \widehat{\mathrm{LAM}}(\lambda x^V.\,\varphi(f(\uparrow \widehat{\mathrm{VAR}}(x)))) \\ \quad\bot & \to \bot_{\widehat{\Lambda}} \end{cases}$$

with $\downarrow\, = \text{fix}(\Phi)$. Consider therefore the predicate

$$R = \{\varphi \in [D_r \to \widehat{\Lambda}] \mid \forall d, \Delta, m \in \Lambda^{\Delta}.\, d \lesssim^{\Delta} m \Rightarrow \varphi(d) \lessapprox^{\Delta}_{\text{nf}} m\}$$

It is straightforward to verify that R is pointed and inclusive, using the corresponding properties of $\lessapprox$ (Lemma 3). To show that $\text{fix}(\Phi) \in R$ by fixed-point induction, it therefore suffices to show that for all $\varphi \in R$, $\Phi(\varphi) \in R$.

Accordingly, assume that $\varphi \in R$ and $d \lesssim^{\Delta} m$; we aim to prove that $\Phi(\varphi)(d) \lessapprox^{\Delta}_{\text{nf}} m$. We divide the argument into cases over $i(d)$:

Case $i(d) = \bot$: Then $\Phi(\varphi)(d) = \bot_{\widehat{\Lambda}}$, and clearly $\bot_{\widehat{\Lambda}} \lessapprox^{\Delta}_{\text{nf}} m$.

Case $i(d) = \lfloor in_1(l) \rfloor$: Then $\Phi(\varphi)(d) = l$, and by Lemma 6($\Rightarrow$) and Lemma 5(c), $l \lessapprox^{\Delta}_{\text{nf}} m$.

Case $i(d) = \lfloor in_2(f) \rfloor$: Then $\Phi(\varphi)(d) = \widehat{\mathrm{LAM}}(\lambda x^V.\,\varphi(f(\uparrow \widehat{\mathrm{VAR}}(x))))$. Let $v \notin \Delta$ be arbitrary. By Lemma 5(a), $\widehat{\mathrm{VAR}}(v) \lessapprox^{\Delta\cup\{v\}}_{\text{at}} \mathrm{VAR}(v)$, and so by part (a) above,

$$\uparrow \widehat{\mathrm{VAR}}(v) \lesssim^{\Delta\cup\{v\}} \mathrm{VAR}(v)\,.$$

By assumption on m and Lemma 6($\Rightarrow$), there exist x and $m_0 \in \Lambda^{\Delta\cup\{x\}}$ such that $\mathrm{LAM}(x, m_0) \leftrightarrow m$.

Take $\Delta' = \Delta \cup \{v\}$, $d' = \uparrow \widehat{\mathrm{VAR}}(v)$, $m' = \mathrm{VAR}(v)$, and $m_1 = \mathrm{LAM}(x, m_0)$. By assumption on f, we then get that

$$f(\uparrow \widehat{\mathrm{VAR}}(v)) \lesssim^{\Delta\cup\{v\}} \mathrm{APP}(\mathrm{LAM}(x, m_0), \mathrm{VAR}(v))\,.$$

Since $\mathrm{APP}(\mathrm{LAM}(x, m_0), \mathrm{VAR}(v)) \leftrightarrow m_0[\mathrm{VAR}(v)/x]$, and $\lesssim$ is closed under conversion (Lemma 7(b)), we also have

$$f(\uparrow \widehat{\mathrm{VAR}}(v)) \lesssim^{\Delta\cup\{v\}} m_0[\mathrm{VAR}(v)/x]\,.$$

Hence, by assumption on φ,

$$(\lambda x^V.\varphi(f(\uparrow \widehat{\mathrm{VAR}}(x))))\; v \lessapprox^{\Delta\cup\{v\}}_{\text{nf}} m_0[\mathrm{VAR}(v)/x]\,.$$

And thus, by Lemma 5(d),

$$\widehat{\mathrm{LAM}}(\lambda x^V.\varphi(f(\uparrow \widehat{\mathrm{VAR}}(x)))) \lessapprox^{\Delta}_{\text{nf}} \mathrm{LAM}(x, m_0)\,.$$

Finally, since $\lessapprox$ is closed under conversion (Lemma 4(b)), we get $\Phi(\varphi)(d) \lessapprox^{\Delta}_{\text{nf}} m$, as required.

□

Lemma 9 *Let $m \in \Lambda^{\Gamma}$, and for all $x \in \Gamma$, let $\theta(x) \in \Lambda^{\Delta}$ (in particular, $\Gamma \subseteq \operatorname{dom}\theta$). If $\forall x \in \Gamma.\, \rho(x) \lesssim^{\Delta} \theta(x)$ then $[\![m]\!]_r\, \rho \lesssim^{\Delta} m[\theta]$.*

Proof: By structural induction on m.

Case $m = \mathrm{VAR}(x)$: This follows immediately from the assumption on ρ and θ, since $[\![\mathrm{VAR}(x)]\!]_r\ \rho = \rho(x)$.

Case $m = \mathrm{LAM}(x, m_0)$: Take $f = \lambda d. [\![m_0]\!]_r\ \rho[x \mapsto d]$. Then $i([\![m]\!]_r\, \rho) = \lfloor in_2(f) \rfloor$, so to use Lemma 6($\Leftarrow$), we must establish that f and $m[\theta]$ satisfy the requirements for the third alternative. First, from the definition of substitution, we get that $\mathrm{LAM}(x, m_0)[\theta] = \mathrm{LAM}(x', m_0')$ for some x' and $m_0' = m_0[\theta[x \mapsto \mathrm{VAR}(x')]]$. Clearly $m_0' \in \Lambda^{\Delta \cup \{x'\}}$, and $\mathrm{LAM}(x', m_0') \leftrightarrow m[\theta]$ by reflexivity of $\leftrightarrow$.

Second, let $\Delta' \supseteq \Delta$, d', $m_1 \in \Lambda^{\Delta'}$ and $m' \in \Lambda^{\Delta'}$ be given, with $m[\theta] \leftrightarrow m_1$ and $d' \lesssim^{\Delta'} m'$; we must show that $f(d') \lesssim^{\Delta'} \mathrm{APP}(m_1, m')$. Take $\rho' = \rho[x \mapsto d']$ and $\theta' = \theta[x \mapsto m']$. Using the assumption on d' and m' for x, and monotonicity of $\lesssim$ (Lemma 7(a)) for the remaining variables in Γ, we get that for all $x'' \in \Gamma \cup \{x\}$, $\rho'(x'') \lesssim^{\Delta'} \theta'(x'')$. Hence, by IH on m_0, $f(d') = [\![m_0]\!]_r\, \rho' \lesssim^{\Delta'} m_0[\theta']$. And finally, since

$$
\begin{aligned}
& m_0[\theta'] \\
\leftrightarrow\ & \mathrm{APP}(\mathrm{LAM}(x, m_0), \mathrm{VAR}(x))[\theta'] = \mathrm{APP}(\mathrm{LAM}(x, m_0)[\theta'], \mathrm{VAR}(x)[\theta']) \\
\leftrightarrow\ & \mathrm{APP}(\mathrm{LAM}(x, m_0)[\theta], m') = \mathrm{APP}(m[\theta], m') \\
\leftrightarrow\ & \mathrm{APP}(m_1, m')\,,
\end{aligned}
$$

and $\lesssim$ is closed under conversion (Lemma 7(b)), we get $f(d') \lesssim^{\Delta'} \mathrm{APP}(m_1, m')$, as required.

Case $m = \mathrm{APP}(m_1, m_2)$: Here, $[\![\mathrm{APP}(m_1, m_2)]\!]_r\, \rho = \psi_r([\![m_1]\!]_r\, \rho)\, ([\![m_2]\!]_r\, \rho)$. We divide the argument into subcases over $i([\![m_1]\!]_r\, \rho)$:

Case $i([\![m_1]\!]_r\, \rho) = \bot$: Then $\psi_r([\![m_1]\!]_r\, \rho)([\![m_2]\!]_r\, \rho) = \bot \lesssim^{\Delta} \mathrm{APP}(m_1, m_2)[\theta]$.

Case $i([\![m_1]\!]_r\, \rho) = \lfloor in_1(l) \rfloor$: Then $\psi_r([\![m_1]\!]_r\, \rho)([\![m_2]\!]_r\, \rho) = \uparrow(\widehat{\mathrm{APP}}(l, \downarrow([\![m_2]\!]_r\, \rho)))$. By IH on m_1 and Lemma 6($\Rightarrow$), $l \lessapprox^{\Delta}_{\mathrm{at}} m_1[\theta]$, and by IH on m_2 and Lemma 8(b), $\downarrow([\![m_2]\!]_r\ \rho) \lessapprox^{\Delta}_{\mathrm{nf}} m_2[\theta]$. Hence by Lemma 5(b),

$$\widehat{\mathrm{APP}}(l, \downarrow([\![m_2]\!]_r\ \rho)) \lessapprox^{\Delta}_{\mathrm{at}} \mathrm{APP}(m_1[\theta], m_2[\theta]) = \mathrm{APP}(m_1, m_2)[\theta] = m[\theta]\,.$$

And thus, by Lemma 8(a), $\uparrow(\widehat{\mathrm{APP}}(l, \downarrow [\![m_2]\!]_r\, \rho)) \lesssim^{\Delta} m[\theta]$.

Case $i([\![m_1]\!]_r\, \rho) = \lfloor in_2(f) \rfloor$: Then $\psi_r([\![m_1]\!]_r\, \rho)([\![m_2]\!]_r\, \rho) = f([\![m_2]\!]_r\, \rho)$. By IH on m_1 and Lemma 6($\Rightarrow$), we have, in particular, that if $d' \lesssim^{\Delta} m'$ then $f(d') \lesssim^{\Delta} \mathrm{APP}(m_1[\theta], m')$. Take $d' = [\![m_2]\!]_r\, \rho$ and $m' = m_2[\theta]$. Then, using IH on m_2, $f([\![m_2]\!]_r\, \rho) \lesssim^{\Delta} \mathrm{APP}(m_1[\theta], m_2[\theta]) = m[\theta]$. □

3.3 Correctness of the Normalization Function

Definition 3 *The predicate* $\mathrm{tot}(\cdot) \subseteq \widehat{\Lambda}$ *is given by* $\mathrm{tot}(l) \Leftrightarrow \forall n \in \mathbb{N}.\, l\, n \neq \bot$.

Lemma 10 *The following properties hold of the wrapper functions:*

a. *For all* $v \in V$, $\mathrm{tot}(\widehat{\mathrm{VAR}}(v))$.

b. *If for all* $v \in V$. $\mathrm{tot}(f\, v)$ *then* $\mathrm{tot}(\widehat{\mathrm{LAM}}(f))$.

c. *If* $\mathrm{tot}(l_1)$ *and* $\mathrm{tot}(l_2)$ *then* $\mathrm{tot}(\widehat{\mathrm{APP}}(l_1, l_2))$.

Proof: Straightforward verification in each case. □

Lemma 11 *For all* $m \in \Lambda$ *and* $\rho \in [V \to D_r]$ *such that for all* $x \in FV(m)$, *there exists an* l *with* $\rho(x) = \uparrow l$ *and* $\mathrm{tot}(l)$,

a. *If* $\vdash_{\mathrm{at}} m$ *then* $\exists l \in \widehat{\Lambda}.\, [\![m]\!]_r\, \rho = \uparrow l \wedge \mathrm{tot}(l)$.

b. *If* $\vdash_{\mathrm{nf}} m$ *then* $\mathrm{tot}(\downarrow([\![m]\!]_r\, \rho))$.

Proof: By simultaneous rule induction on $\vdash_{\mathrm{at}} \cdot$ and $\vdash_{\mathrm{nf}} \cdot$. The relevant cases are:

Case $\vdash_{\mathrm{at}} \mathrm{VAR}(x)$: Then $[\![m]\!]_r\, \rho = \rho(x)$, and $x \in FV(m)$, so the result follows directly from the assumption on ρ.

Case $\vdash_{\mathrm{at}} \mathrm{APP}(m_1, m_2)$ because $\vdash_{\mathrm{at}} m_1$ and $\vdash_{\mathrm{nf}} m_2$: By IH(a) on the first premise, there exists an l_1 such that $[\![m_1]\!]_r\, \rho = \uparrow l_1$ and $\mathrm{tot}(l_1)$. Therefore, $[\![m]\!]_r\, \rho = \uparrow(\widehat{\mathrm{APP}}(l_1, \downarrow([\![m_2]\!]_r\, \rho)))$. Take $l_2 = \downarrow([\![m_2]\!]_r\, \rho)$ and $l = \widehat{\mathrm{APP}}(l_1, l_2)$. By IH(b) on the second premise, $\mathrm{tot}(l_2)$, so by Lemma 10(c), $\mathrm{tot}(l)$, as required.

Case $\vdash_{\mathrm{nf}} m$ because $\vdash_{\mathrm{at}} m$: By IH(a) on the premise, $[\![m]\!]_r\, \rho = \uparrow l$, with $\mathrm{tot}(l)$. But $\downarrow(\uparrow l) = l$, so also $\mathrm{tot}(\downarrow [\![m]\!]_r\, \rho)$.

Case $\vdash_{\mathrm{nf}} \mathrm{LAM}(x, m_0)$ because $\vdash_{\mathrm{nf}} m_0$: Expanding the definition of $\downarrow$ for the functional case, we have to show that $\mathrm{tot}(\widehat{\mathrm{LAM}}(\lambda x. \downarrow([\![m_0]\!]_r\, \rho[x \mapsto \uparrow \widehat{\mathrm{VAR}}(x)])))$. By Lemma 10(b), it suffices to show that $\mathrm{tot}(\downarrow([\![m_0]\!]_r\, \rho[x \mapsto \uparrow \widehat{\mathrm{VAR}}(v)]))$, for every $v \in V$. This follows from IH(b) on the premise, if for every $x' \in FV(m_0)$, there exists an l, such that $\rho[x \mapsto \uparrow \widehat{\mathrm{VAR}}(v)](x') = \uparrow l$ and $\mathrm{tot}(l)$. But for $x' \neq x$, we must have $x' \in FV(m)$, so this follows from the assumption on ρ; and for $x' = x$, it follows from Lemma 10(a).

□

Theorem 2 (semantic correctness) norm_Δ *from Definition 1 is a normalization function on* Λ^Δ, *i.e.,*

a. *(soundness) If* $\mathrm{norm}_\Delta(m) = \lfloor m' \rfloor$ *then* $m' \in \Lambda^\Delta$, $\vdash_{\mathrm{nf}} m'$, *and* $m \leftrightarrow m'$.

b. *(standardization) If* $m \leftrightarrow m'$ *then* $\mathrm{norm}_\Delta(m) = \mathrm{norm}_\Delta(m')$.

c. *(completeness) If* $m \leftrightarrow m'$ *with* $\vdash_{\mathrm{nf}} m'$ *then* $\mathrm{norm}_\Delta(m) \neq \bot$.

Proof: *(Soundness)* Let θ_0 be the substitution mapping every x in Δ to $\mathrm{VAR}(x)$, and $\rho_0 = \lambda x^V. \uparrow \widehat{\mathrm{VAR}}(x)$. By Lemma 5(a), for every $x \in \Delta$, $\widehat{\mathrm{VAR}}(x) \lessapprox^\Delta_{\mathrm{at}} \mathrm{VAR}(x) = \theta_0(x)$, and hence by Lemma 8(a), $\rho_0(x) \lesssim^\Delta \theta_0(x)$. By Lemma 9, we then get that $[\![m]\!]_r\, \rho_0 \lesssim^\Delta m[\theta_0] \leftrightarrow m$, and therefore, by Lemma 8(b), $\downarrow([\![m]\!]_r\, \rho_0) \lessapprox^\Delta_{\mathrm{nf}} m$. Assume now that $\mathrm{norm}_\Delta(m) = \lfloor m' \rfloor$. Taking $n = \sharp\Delta$ in Definition 2, we can then immediately read off that m' has the required properties.

(Standardization) This follows directly from model soundness (Lemma 2), since the residualizing model is indeed a model.

(Completeness) Using Lemma 10(a), we see that ρ_0 satisfies the condition on ρ in Lemma 11. Hence, by part (b) of the latter lemma and Definition 3, $\mathrm{norm}_\Delta(m') \neq \bot$. The desired result then follows from (standardization). □

4 An Implementation of the Construction

4.1 Syntax and Semantics of an ML-like Call-by-Value Language

The language is a small fragment of Standard ML where, to sidestep inessential book-keeping, we have hard-coded the inductive representation of λ-terms,

```
datatype term = VAR of string | LAM of string*term | APP of term*term
```

as an additional base type of the language, and simply taken the value sets underlying `string` and `term` to be the sets V and Λ, respectively.

Syntax The fragment is restricted to a single recursive datatype declaration,

$$\texttt{datatype}\ \mathit{dt}\ \texttt{=}\ \mathit{In}_1\ \texttt{of}\ \tau^1\ \texttt{|}\ \cdots\ \texttt{|}\ \mathit{In}_k\ \texttt{of}\ \tau^k$$

where types are given by the grammar

$$\tau ::= \texttt{unit} \mid \texttt{int} \mid \texttt{bool} \mid \texttt{string} \mid \texttt{term} \mid \tau_1 \texttt{ -> } \tau_2 \mid \mathit{dt}$$

The syntax of ML expressions is then

$$\begin{aligned} e ::= \ & x \mid \underline{n} \mid \texttt{"}v\texttt{"} \mid \texttt{()} \mid e_1 \texttt{+} e_2 \mid e_1 \texttt{=} e_2 \mid \texttt{"g"\^{}Int.toString}\ e \mid \\ & \texttt{fn () =>}\ e \mid \texttt{fn}\ x\ \texttt{=>}\ e \mid e_1\ e_2 \mid \texttt{VAR(}e\texttt{)} \mid \texttt{LAM(}e_1\texttt{,}e_2\texttt{)} \mid \texttt{APP(}e_1\texttt{,}e_2\texttt{)} \mid \\ & \texttt{case}\ e\ \texttt{of VAR}\ x_1\ \texttt{=>}\ e_1\ \texttt{|}\ \texttt{LAM(}x_2\texttt{,}x_2'\texttt{)}\ \texttt{=>}\ e_2\ \texttt{|}\ \texttt{APP(}x_3\texttt{,}x_3'\texttt{)}\ \texttt{=>}\ e_3 \mid \\ & \mathit{In}_i(e) \mid \texttt{case}\ e\ \texttt{of}\ \mathit{In}_1\ x_1\ \texttt{=>}\ e_1 \texttt{|}\ \cdots\ \texttt{|}\ \mathit{In}_k\ x_k\ \texttt{=>}\ e_k \mid \\ & \texttt{if}\ e_1\ \texttt{then}\ e_2\ \texttt{else}\ e_3 \mid \texttt{let fun}\ f\ \texttt{(}x\texttt{:}\tau_1\texttt{):}\tau_2\ \texttt{=}\ e_1\ \texttt{in}\ e_2\ \texttt{end} \end{aligned}$$

where x and f range over ML variable names.

Typing We only consider well-typed ML expressions, as captured by the judgement $x_1{:}\tau_1, ..., x_n{:}\tau_n \vdash e : \tau$, asserting that e is of type τ, with free variables $x_1, ..., x_n$ of types $\tau_1, ..., \tau_n$. The typing rules are shown in Figure 1

Operational semantics A *complete program* is a closed expression of type $\tau_1 \texttt{->} \tau_2$, where τ_1 and τ_2 are ground types (i.e., not containing `->` or dt). For such types, let C_τ denote the set of canonical values underlying τ, e.g., $C_{\texttt{int}} = \mathbb{Z}$.

For a complete program $e : \tau_1 \texttt{->} \tau_2$, we can construct a computable partial function $\mathrm{run}_e : C_{\tau_1} \rightharpoonup C_{\tau_2}$, e.g., by

$$\mathrm{run}_e(c_1) = c_2 \ \text{ iff } \ (e\ \underline{c_1}) \Downarrow \underline{c_2}.$$

where $\Downarrow$ is the usual big-step operational semantics of expressions, and $\underline{c}$ denotes the syntactic representation of the value c.

Denotational Semantics For the meaning of ML types, we take

$$\begin{array}{cccc} [\![\texttt{unit}]\!]^{\mathrm{ml}} = \mathbf{1} = \{*\} & [\![\texttt{int}]\!]^{\mathrm{ml}} = \mathbb{Z} & [\![\texttt{bool}]\!]^{\mathrm{ml}} = \mathbb{B} & [\![\texttt{string}]\!]^{\mathrm{ml}} = V \\ [\![\texttt{term}]\!]^{\mathrm{ml}} = \Lambda & [\![\tau_1 \texttt{ -> } \tau_2]\!]^{\mathrm{ml}} = [[\![\tau_1]\!]^{\mathrm{ml}} \to [\![\tau_2]\!]^{\mathrm{ml}}_{\perp}] & [\![\mathit{dt}]\!]^{\mathrm{ml}} = S & \end{array}$$

$$\frac{}{\Gamma, x:\tau \vdash x:\tau} \quad \frac{}{\Gamma \vdash \underline{n} : \texttt{int}} \quad \frac{}{\Gamma \vdash \texttt{"}v\texttt{"} : \texttt{string}} \quad \frac{}{\Gamma \vdash \texttt{()} : \texttt{unit}}$$

$$\frac{\Gamma \vdash e_1 : \texttt{int} \quad \Gamma \vdash e_2 : \texttt{int}}{\Gamma \vdash e_1 \texttt{+} e_2 : \texttt{int}} \quad \frac{\Gamma \vdash e_1 : \texttt{string} \quad \Gamma \vdash e_2 : \texttt{string}}{\Gamma \vdash e_1 \texttt{=} e_2 : \texttt{bool}}$$

$$\frac{\Gamma \vdash e : \texttt{int}}{\Gamma \vdash \texttt{"g"\^{}Int.toString}\ e : \texttt{string}}$$

$$\frac{\Gamma \vdash e : \tau}{\Gamma \vdash \texttt{fn () =>}\ e : \texttt{unit->}\tau} \quad \frac{\Gamma, x:\tau_1 \vdash e:\tau_2}{\Gamma \vdash \texttt{fn}\ x\ \texttt{=>}\ e : \tau_1\texttt{->}\tau_2} \quad \frac{\Gamma \vdash e_1 : \tau_1\texttt{->}\tau_2 \quad \Gamma \vdash e_2 : \tau_1}{\Gamma \vdash e_1\ e_2 : \tau_2}$$

$$\frac{\Gamma \vdash e : \texttt{string}}{\Gamma \vdash \texttt{VAR(}e\texttt{)} : \texttt{term}} \quad \frac{\Gamma \vdash e_1 : \texttt{string} \quad \Gamma \vdash e_2 : \texttt{term}}{\Gamma \vdash \texttt{LAM(}e_1\texttt{,}e_2\texttt{)} : \texttt{term}} \quad \frac{\Gamma \vdash e_1 : \texttt{term} \quad \Gamma \vdash e_2 : \texttt{term}}{\Gamma \vdash \texttt{APP(}e_1\texttt{,}e_2\texttt{)} : \texttt{term}}$$

$$\frac{\begin{array}{c}\Gamma \vdash e : \texttt{term} \quad \Gamma, x_1 : \texttt{string} \vdash e_1 : \tau \\ \Gamma, x_2 : \texttt{string}, x_2' : \texttt{term} \vdash e_2 : \tau \quad \Gamma, x_3 : \texttt{term}, x_3' : \texttt{term} \vdash e_3 : \tau\end{array}}{\Gamma \vdash \texttt{case}\ e\ \texttt{of VAR}\ x_1\ \texttt{=>}\ e_1\ \texttt{| LAM(}x_2\texttt{,}x_2'\texttt{) =>}\ e_2\ \texttt{| APP(}x_3\texttt{,}x_3'\texttt{) =>}\ e_3 : \tau}$$

$$\frac{\Gamma \vdash e : \tau^i}{\Gamma \vdash \mathit{In}_i\texttt{(}e\texttt{)} : \mathit{dt}} \quad \frac{\Gamma \vdash e : \mathit{dt} \quad \Gamma, x_1 : \tau^1 \vdash e_1 : \tau \quad \cdots \quad \Gamma, x_k : \tau^k \vdash e_k : \tau}{\Gamma \vdash \texttt{case}\ e\ \texttt{of}\ \mathit{In}_1\ x_1\ \texttt{=>}\ e_1 \texttt{|}\ \cdots\ \texttt{|}\ \mathit{In}_k\ x_k\ \texttt{=>}\ e_k : \tau}$$

$$\frac{\Gamma \vdash e_1 : \texttt{bool} \quad \Gamma \vdash e_2 : \tau \quad \Gamma \vdash e_3 : \tau}{\Gamma \vdash \texttt{if}\ e_1\ \texttt{then}\ e_2\ \texttt{else}\ e_3 : \tau}$$

$$\frac{\Gamma, f : \tau_1\texttt{->}\tau_2, x : \tau_1 \vdash e_1 : \tau_2 \quad \Gamma, f : \tau_1\texttt{->}\tau_2 \vdash e_2 : \tau}{\Gamma \vdash \texttt{let fun}\ f\ \texttt{(}x\texttt{:}\tau_1\texttt{):}\tau_2\ \texttt{=}\ e\ \texttt{in}\ e_2\ \texttt{end} : \tau}$$

Figure 1: Typing rules of a fragment of ML

where $i_S : S \xrightarrow{\cong} [\![\tau^1]\!]^{\mathrm{ml}} + \cdots + [\![\tau^k]\!]^{\mathrm{ml}}$ is a minimal-invariant solution to the evident predomain equation. We write $in_i : [\![\tau^i]\!]^{\mathrm{ml}} \to [\![\tau^1]\!]^{\mathrm{ml}} + \cdots + [\![\tau^k]\!]^{\mathrm{ml}}$ for the injection functions.

The meaning of ML terms is defined by induction on the typing derivation; for conciseness we write only the terms. The semantics is structured such that if $\Gamma \vdash e : \tau$ and for all $(x : \tau') \in \Gamma$, $\xi(x) \in [\![\tau']\!]^{\mathrm{ml}}$, then $[\![e]\!]^{\mathrm{ml}}\xi \in [\![\tau]\!]^{\mathrm{ml}}_{\perp}$. The full semantics is shown in Figure 2

For notational convenience in the following, we will assume that all function names f in the program are distinct. We can then unambiguously use Θ_f to refer to the semantic function whose fixed point f is mapped to in the environment of the `let`-body, and $\theta_f = \mathrm{fix}(\Theta_f)$.

Theorem 3 (computational adequacy for ML) *For a complete ML program e, $run_e(c_1) = c_2$ iff $[\![e]\!]^{\mathrm{ml}}\,\emptyset \star \lambda f.\, f(c_1) = \lfloor c_2 \rfloor$.*

Proof: Modulo trivial syntactic differences, and an equivalent formulation of the semantics in terms of strict functions between pointed cpos, rather than general ones between cpos, this is shown in, e.g., [6, Section 5]. The primary difficulty is, of course, the definition of the logical relation at type dt, which is again achieved by exploiting the minimal-invariant property of S. □

$$\llbracket x \rrbracket^{\mathrm{ml}}\,\xi = \lfloor \xi(x) \rfloor \quad \llbracket \underline{n} \rrbracket^{\mathrm{ml}}\,\xi = \lfloor n \rfloor \quad \llbracket \texttt{"}v\texttt{"} \rrbracket^{\mathrm{ml}}\,\xi = \lfloor v \rfloor \quad \llbracket \texttt{()} \rrbracket^{\mathrm{ml}}\,\xi = \lfloor * \rfloor$$

$$\llbracket e_1 \texttt{ + } e_2 \rrbracket^{\mathrm{ml}}\,\xi = \llbracket e_1 \rrbracket^{\mathrm{ml}}\,\xi \star \lambda n_1^{\mathbb{Z}}.\, \llbracket e_2 \rrbracket^{\mathrm{ml}}\,\xi \star \lambda n_2^{\mathbb{Z}}.\, \lfloor n_1 + n_2 \rfloor$$

$$\llbracket e_1 \texttt{ = } e_2 \rrbracket^{\mathrm{ml}}\,\xi = \llbracket e_1 \rrbracket^{\mathrm{ml}}\,\xi \star \lambda v_1^{V}.\, \llbracket e_2 \rrbracket^{\mathrm{ml}}\,\xi \star \lambda v_2^{V}.\, \lfloor v_1 = v_2 \rfloor$$

$$\llbracket \texttt{"g"\^{}Int.toString } e \rrbracket^{\mathrm{ml}}\,\xi = \llbracket e \rrbracket^{\mathrm{ml}}\,\xi \star \lambda n^{\mathbb{Z}}.\, \lfloor g_n \rfloor$$

$$\llbracket \texttt{fn () => } e \rrbracket^{\mathrm{ml}}\,\xi = \lfloor \lambda u. \llbracket e \rrbracket^{\mathrm{ml}}\,\xi \rfloor \quad \llbracket \texttt{fn } x \texttt{ => } e \rrbracket^{\mathrm{ml}}\,\xi = \lfloor \lambda a^{\llbracket \tau \rrbracket^{\mathrm{ml}}}. \llbracket e \rrbracket^{\mathrm{ml}}\,\xi[x \mapsto a] \rfloor$$

$$\llbracket e_1\ e_2 \rrbracket^{\mathrm{ml}}\,\xi = \llbracket e_1 \rrbracket^{\mathrm{ml}}\,\xi \star \lambda f^{[\llbracket \tau_1 \rrbracket^{\mathrm{ml}} \to \llbracket \tau_2 \rrbracket^{\mathrm{ml}}_{\perp}]}.\, \llbracket e_2 \rrbracket^{\mathrm{ml}}\,\xi \star \lambda a^{\llbracket \tau_1 \rrbracket^{\mathrm{ml}}}.\, f\,a$$

$$\llbracket \texttt{VAR(}e\texttt{)} \rrbracket^{\mathrm{ml}}\,\xi = \llbracket e \rrbracket^{\mathrm{ml}}\,\xi \star \lambda v^{V}.\, \lfloor \mathrm{VAR}(v) \rfloor$$

$$\llbracket \texttt{LAM(}e_1\texttt{,}e_2\texttt{)} \rrbracket^{\mathrm{ml}}\,\xi = \llbracket e_1 \rrbracket^{\mathrm{ml}}\,\xi \star \lambda v^{V}.\, \llbracket e_2 \rrbracket^{\mathrm{ml}}\,\xi \star \lambda m_0^{\Lambda}.\, \lfloor \mathrm{LAM}(v, m_0) \rfloor$$

$$\llbracket \texttt{APP(}e_1\texttt{,}e_2\texttt{)} \rrbracket^{\mathrm{ml}}\,\xi = \llbracket e_1 \rrbracket^{\mathrm{ml}}\,\xi \star \lambda m_1^{\Lambda}.\, \llbracket e_2 \rrbracket^{\mathrm{ml}}\,\xi \star \lambda m_2^{\Lambda}.\, \lfloor \mathrm{APP}(m_1, m_2) \rfloor$$

$$\llbracket \texttt{case } e \texttt{ of VAR } x_1 \texttt{ => } e_1 \texttt{ | LAM(}x_2\texttt{,}x_2'\texttt{) => } e_2 \texttt{ | APP(}x_3\texttt{,}x_3'\texttt{) => } e_3 \rrbracket^{\mathrm{ml}}\,\xi =$$
$$\llbracket e \rrbracket^{\mathrm{ml}}\,\xi \star \lambda m^{\Lambda}.\,\mathrm{case}\ m\ \mathrm{of} \begin{cases} \mathrm{VAR}(v) & \to \llbracket e_1 \rrbracket^{\mathrm{ml}}\,\xi[x_1 \mapsto v] \\ \mathrm{LAM}(v, m_0) & \to \llbracket e_2 \rrbracket^{\mathrm{ml}}\,\xi[x_2 \mapsto v, x_2' \mapsto m_0] \\ \mathrm{APP}(m_1, m_2) & \to \llbracket e_3 \rrbracket^{\mathrm{ml}}\,\xi[x_3 \mapsto m_1, x_3' \mapsto m_2] \end{cases}$$

$$\llbracket \mathtt{\mathit{In}}_i\texttt{(}e\texttt{)} \rrbracket^{\mathrm{ml}}\,\xi = \llbracket e \rrbracket^{\mathrm{ml}}\,\xi \star \lambda a^{\llbracket \tau^i \rrbracket^{\mathrm{ml}}}.\, \lfloor i_S^{-1}(in_i(a)) \rfloor$$

$$\llbracket \texttt{case } e \texttt{ of } \mathit{In}_1\ x_1 \texttt{ => } e_1 \texttt{|} \cdots \texttt{|} \mathit{In}_k\ x_k \texttt{ => } e_k \rrbracket^{\mathrm{ml}}\,\xi =$$
$$\llbracket e \rrbracket^{\mathrm{ml}}\,\xi \star \lambda s^{S}.\,\mathrm{case}\ i_S(s)\ \mathrm{of} \begin{cases} in_1(a_1) \to \llbracket e_1 \rrbracket^{\mathrm{ml}}\,\xi[x_1 \mapsto a_1] \\ \vdots \\ in_k(a_k) \to \llbracket e_k \rrbracket^{\mathrm{ml}}\,\xi[x_k \mapsto a_k] \end{cases}$$

$$\llbracket \texttt{if } e_1 \texttt{ then } e_2 \texttt{ else } e_3 \rrbracket^{\mathrm{ml}}\,\xi = \llbracket e_1 \rrbracket^{\mathrm{ml}}\,\xi \star \lambda b^{\mathbb{B}}.\,\mathrm{case}\ b\ \mathrm{of} \begin{cases} \mathrm{tt} \to \llbracket e_2 \rrbracket^{\mathrm{ml}}\,\xi \\ \mathrm{ff} \to \llbracket e_3 \rrbracket^{\mathrm{ml}}\,\xi \end{cases}$$

$$\llbracket \texttt{let fun } f\ \texttt{(}x\texttt{:}\tau_1\texttt{):}\tau_2 \texttt{ = } e_1 \texttt{ in } e_2 \texttt{ end} \rrbracket^{\mathrm{ml}}\,\xi =$$
$$\llbracket e_2 \rrbracket^{\mathrm{ml}}\,\xi[f \mapsto \mathrm{fix}(\lambda \theta^{[\llbracket \tau_1 \rrbracket^{\mathrm{ml}} \to \llbracket \tau_2 \rrbracket^{\mathrm{ml}}_{\perp}]}.\lambda a^{\llbracket \tau_1 \rrbracket^{\mathrm{ml}}}. \llbracket e_1 \rrbracket^{\mathrm{ml}}\,\xi[f \mapsto \theta, x \mapsto a])]$$

Figure 2: Denotational semantics of a fragment of ML

4.2 The Normalization Algorithm

The concrete representation of the normalization algorithm, with many of the auxiliary definitions inlined, is shown in Figure 3. We have instantiated ***dt*** as the type `sem`, with two constructors In_1 = `TM` and In_2 = `FUN`. It is easy to check that the top-level expression, *NORM* : `term -> term`, is a well-typed complete program in our sense.

Since ML is a call-by-value language, we must simulate the implicit call-by-name nature of the residualizing semantics using thunking. We have defined `sem` so that $\llbracket \texttt{sem} \rrbracket^{\mathrm{ml}}_{\perp} \cong D_r$; then semantic functions with codomain D_r can be represented directly as ML functions into `sem`, while functions with domain D_r are represented with source type `unit -> sem`. As a further optimization, the *strict* function $\downarrow\, : D_r \to \widehat{\Lambda}$ is represented as simply a function from `sem`.

```
datatype term = VAR of string | LAM of string*term | APP of term*term
datatype sem = TM of int -> term | FUN of (unit -> sem) -> sem;

let fun down (s:sem):int->term = fn n =>
     (case s of
        TM l => l n
      | FUN f => LAM("g"^Int.toString n,
          down (f (fn () => TM(fn n' => VAR("g"^Int.toString n)))) (n+1)))
in let fun eval (m:term):(string->sem)->sem = fn p =>
        (case m of
           VAR x => p x
         | LAM(x,m0) => FUN(fn d => eval m0
                             (fn x' => if x = x' then d () else p x'))
         | APP(m1,m2) => (case (eval m1 p) of
                            TM l => TM(fn n => APP(l n,down (eval m2 p) n))
                          | FUN f => f (fn () => eval m2 p)))
   in let fun norm (m:term):term =
           down (eval m (fn x => TM(fn n => VAR(x)))) 0
      in norm end end end
```

Figure 3: The normalization algorithm, *NORM*, in a fragment of ML

Examples The following examples illustrate how the algorithm works. Let $\Omega \equiv$ APP(LAM("x", VAR("x")), LAM("x", VAR("x"))).

a. $\mathrm{run}_{NORM}(\Omega)$ diverges.

b. run_{NORM}(APP(LAM("x", LAM("x", VAR("x"))), Ω))
   = LAM("g0", VAR("g0"))

c. run_{NORM}(LAM("y", LAM("g4", VAR("z"))))
   = LAM("g0", LAM("g1", VAR("z")))

Let us now properly relate the abstract and concrete constructions. To get a perfect isomorphism between term families and their implementation, we choose $\mathcal{N} = \mathbb{Z}$, with $gen(n) =$ "g$\underline{n}$", e.g., $gen(13) =$ "g13". Let i_D denote the isomorphism $i : D_r \xrightarrow{\cong} ([\mathbb{Z} \to \Lambda_\perp] + [D_r \to D_r])_\perp$ from before. We now also have $i_S : S \xrightarrow{\cong} [\mathbb{Z} \to \Lambda_\perp] + [[\mathbf{1} \to S_\perp] \to S_\perp]$.

Lemma 12 *There exists an isomorphism $i_{DS} : D_r \xrightarrow{\cong} S_\perp$, satisfying*

a. For all $l \in \widehat{\Lambda}$, $i_{DS}(i_D^{-1}(\lfloor in_1(l) \rfloor)) = \lfloor i_S^{-1}(in_1(l)) \rfloor$.

b. For all $f \in [D_r \to D_r]$,
   $i_{DS}(i_D^{-1}(\lfloor in_2(f) \rfloor)) = \lfloor i_S^{-1}(in_2(\lambda t^{\mathbf{1} \to S_\perp}.\ i_{DS}(f(i_{DS}^{-1}(t\ *))))) \rfloor$.

c. $i_{DS}(i_D^{-1}(\perp_{D_r})) = \perp_{S_\perp}$

Proof: See Appendix B. □

We can also state three lemmas, relating the central domain-theoretic functions to the denotations of their syntactic counterparts:

Lemma 13 *For all $d \in D_r$ and $n \in \mathbb{Z}$, $\downarrow d\, n = i_{DS}(d) \star \lambda s^S.\, \theta_{\texttt{down}}\ s \star \lambda l^{\widehat{\Lambda}}.\, l\, n$.*

Proof: By fixed-point induction on $\Phi \times \Theta_{\text{down}}$ (where Φ is as in the proof of Lemma 8), using the predicate $R \subseteq [D_r \to \widehat{\Lambda}] \times [S \to \widehat{\Lambda}_\bot]$ defined by

$$R = \{(\varphi, \theta) \mid \forall d \in D_r, n \in \mathbb{Z}.\, \varphi\ d\ n = i_{DS}(d) \star \lambda s^S.\theta\ s \star \lambda l^{\widehat{\Lambda}}.l\ n\}$$

We aim to establish that $(\text{fix}(\Phi), \text{fix}(\Theta_{\texttt{down}})) \in R$. It is straightforward to verify that R is pointed and inclusive. Assume that $(\varphi, \theta) \in R$; we then must show that $(\Phi(\varphi), \Theta_{\text{down}}(\theta)) \in R$. Accordingly, let arbitrary d and n be given, and consider d:

Case $d = i_D^{-1}(\bot)$: By Lemma 12(c), $i_{DS}(d) = \bot_{S_\bot}$, and so

$$i_{DS}(d) \star \lambda s^S.\Theta_{\text{down}}(\theta)\ s \star \lambda l^{\widehat{\Lambda}}.l\ n = \bot_{\Lambda_\bot}$$

Similarly, $\Phi(\varphi)\ d\ n = \bot_{\widehat{\Lambda}}\ n = \bot_{\Lambda_\bot}$.

Case $d = i_D^{-1}(\lfloor in_1(l) \rfloor)$: Let $\xi = \emptyset[\texttt{down} \mapsto \theta, \texttt{s} \mapsto i_S^{-1}(in_1(l))]$; we calculate:

$$\begin{aligned}
&i_{DS}(d) \star \lambda s^S.\Theta_{\text{down}}(\theta)\ s \star \lambda l^{\widehat{\Lambda}}.l\ n \\
&= i_{DS}(i_D^{-1}(\lfloor in_1(l) \rfloor)) \star \lambda s^S.\Theta_{\text{down}}(\theta)\ s \star \lambda l^{\widehat{\Lambda}}.l\ n \\
&= \lfloor i_S^{-1}(in_1(l)) \rfloor \star \lambda s^S.\Theta_{\text{down}}(\theta)\ s \star \lambda l^{\widehat{\Lambda}}.l\ n && \text{(by Lemma 12(a))} \\
&= [\![\texttt{fn n => (case s of TM l => l n | ...)}]\!]^{\text{ml}}\ \xi \star \lambda l^{\widehat{\Lambda}}.l\ n \\
&= [\![\texttt{l n}]\!]^{\text{ml}}\ \xi[\texttt{n} \mapsto n, \texttt{l} \mapsto l] \\
&= l\ n
\end{aligned}$$

Similarly, $\Phi(\varphi)\ d\ n = \Phi(\varphi)(i_D^{-1}(\lfloor in_1(l) \rfloor))\ n = l\ n$.

Case $d = i_D^{-1}(\lfloor in_2(f) \rfloor)$: Let $\xi = \emptyset[\texttt{down} \mapsto \theta, \texttt{s} \mapsto i_S^{-1}(in_2(\lambda t.\ i_{DS}(f(i_{DS}^{-1}(t\ *)))))]$ and let $\xi' = \xi[\texttt{n} \mapsto n, \texttt{f} \mapsto (\lambda t.\ i_{DS}(f(i_{DS}^{-1}(t\ *))))]$; again,

$$\begin{aligned}
&i_{DS}(d) \star \lambda s^S.\Theta_{\text{down}}(\theta)\ s \star \lambda l^{\widehat{\Lambda}}.l\ n \\
&= i_D(i_D^{-1}(\lfloor in_2(f) \rfloor)) \star \lambda s^S.\Theta_{\text{down}}(\theta)\ s \star \lambda l^{\widehat{\Lambda}}.l\ n \\
&= \lfloor i_S^{-1}(in_2(\lambda t.\, i_{DS}(f(i_{DS}^{-1}(t\,*))))) \rfloor \star \lambda s^S.\Theta_{\text{down}}(\theta)\ s \star \lambda l^{\widehat{\Lambda}}.l\ n \\
& && \text{(by Lemma 12(b))} \\
&= [\![\texttt{fn n => (case s of ...| FUN f => LAM ...)}]\!]^{\text{ml}}\ \xi \star \lambda l^{\widehat{\Lambda}}.l\ n \\
&= [\![\texttt{LAM("g"\^{}Int.toString(n), down (f (fn ...)) (n+1))}]\!]^{\text{ml}}\ \xi' \\
&= [\![\texttt{down (f (fn () => ...)) (n+1)}]\!]^{\text{ml}}\ \xi' \star \lambda m^{\Lambda}.\lfloor \text{LAM}(g_n, m) \rfloor \\
&= [\![\texttt{f (fn () => ...)}]\!]^{\text{ml}}\ \xi' \star \lambda s^S.\theta\ s \star \lambda l^{\widehat{\Lambda}}.l(n+1) \star \lambda m^{\Lambda}.\lfloor \text{LAM}(g_n, m) \rfloor
\end{aligned}$$

Now,

$$\begin{aligned}
&[\![\texttt{f (fn () => TM(fn n' => VAR("g"\^{}Int.toString(n))))}]\!]^{\text{ml}}\ \xi' \\
&= \lfloor (\lambda t.\ i_{DS}(f(i_{DS}^{-1}(t\ *)))) \rfloor \star \lambda g.\lfloor \lambda u.[\![\texttt{TM(fn ...)}]\!]^{\text{ml}}\ \xi' \rfloor \star \lambda a.g\ a \\
&= i_{DS}(f(i_{DS}^{-1}(\lfloor i_S^{-1}(in_1(\lambda n'^{\mathbb{Z}}.\lfloor \text{VAR}(g_n) \rfloor)) \rfloor))) \\
&= i_{DS}(f(i_D^{-1}(\lfloor in_1(\lambda n'^{\mathbb{Z}}.\lfloor \text{VAR}(g_n) \rfloor) \rfloor))) && \text{(by Lemma 12(a))} \\
&= i_{DS}(f(\uparrow \widehat{\text{VAR}}(g_n))) && \text{(by Def. of } \widehat{\text{VAR}} \text{ and } \uparrow)
\end{aligned}$$

By the fixed point assumption on φ and θ, $\forall d', n'.\ \varphi\ d'\ n' = i_{DS}(d') \star \lambda s^S.\theta\ s \star \lambda l^{\widehat{\Lambda}}.l\ n'$. Using the case $d' = f(\uparrow \widehat{\text{VAR}}(g_n))$ and $n' = n + 1$, we continue:

$[\![\texttt{f (fn () => ...)}]\!]^{\mathrm{ml}}\ \xi' \star \lambda s^S.\theta\ s \star \lambda l^{\widehat{\Lambda}}.l(n+1) \star \lambda m^{\Lambda}.\lfloor \mathrm{LAM}(g_n, m)\rfloor$
$= i_{DS}(f(\uparrow \widehat{\mathrm{VAR}}(g_n))) \star \lambda s^S.\theta\ s \star \lambda l^{\widehat{\Lambda}}.l(n+1) \star \lambda m^{\Lambda}.\lfloor \mathrm{LAM}(g_n, m)\rfloor$
$= \varphi(f(\uparrow \widehat{\mathrm{VAR}}(g_n)))\ (n+1) \star \lambda m^{\Lambda}.\lfloor \mathrm{LAM}(g_n, m)\rfloor$

Similarly,

$\Phi(\varphi)\ d\ n$
$= \Phi(\varphi)(i_D^{-1}(\lfloor in_2(f)\rfloor))\ n$
$= \widehat{\mathrm{LAM}}(\lambda x^V.\varphi(f(\uparrow \widehat{\mathrm{VAR}}(x))))\ n$
$= \varphi(f(\uparrow \widehat{\mathrm{VAR}}(g_n)))\ (n+1) \star \lambda m^{\Lambda}.\lfloor \mathrm{LAM}(g_n, m)\rfloor$ (by Def. of $\widehat{\mathrm{LAM}}$) $\square$

Lemma 14 *For all $m \in \Lambda$, $\rho \in [V \to D_r]$, and $\zeta \in [V \to S_\perp]$, such that $\forall x \in FV(m).\, i_{DS}(\rho(x)) = \zeta(x)$, $i_{DS}([\![m]\!]_r\,\rho) = \theta_{\texttt{eval}}\, m \star \lambda g.\, g\,\zeta$.*

Proof: By structural induction on m. Let m, ρ and ζ be given such that $\forall x \in FV(m).i_{DS}(\rho(x)) = \zeta(x)$. Let $\xi = \emptyset[\texttt{down} \mapsto \theta_{\texttt{down}}]$. By the fixed-point equation, since $\theta_{\texttt{eval}} = \mathrm{fix}(\Theta_{\texttt{eval}})$,

$\theta_{\texttt{eval}}\ m \star \lambda g.g\ \zeta$
$= \Theta_{\texttt{eval}}(\theta_{\texttt{eval}})\ m \star \lambda g.g\ \zeta$
$= [\![\texttt{fn p => (case m of ...)}]\!]^{\mathrm{ml}}\ \xi[\texttt{eval} \mapsto \theta_{\texttt{eval}}, \texttt{m} \mapsto m] \star \lambda g.g\ \zeta$
$= [\![\texttt{case m of ...}]\!]^{\mathrm{ml}}\ \xi[\texttt{eval} \mapsto \theta_{\texttt{eval}}, \texttt{m} \mapsto m, \texttt{p} \mapsto \zeta]$

Let $\xi' = \xi[\texttt{eval} \mapsto \theta_{\texttt{eval}}, \texttt{m} \mapsto m, \texttt{p} \mapsto \zeta]$. Consider m:

Case $m = \mathrm{VAR}(x)$: Then,

$\theta_{\texttt{eval}}\ m \star \lambda g.g\ \zeta$
$= [\![\texttt{case m of VAR x => p x | ...}]\!]^{\mathrm{ml}}\ \xi'$
$= [\![\texttt{p x}]\!]^{\mathrm{ml}}\ \xi'[\texttt{x} \mapsto x]$
$= \zeta(x)$

Since clearly $x \in FV(m)$, we have $i_{DS}(\rho(x)) = \zeta(x)$ by assumption on ρ and ζ. Thus similarly,

$i_{DS}([\![m]\!]_r\ \rho)$
$= i_{DS}([\![\mathrm{VAR}(x)]\!]_r\ \rho)$
$= i_{DS}(\rho(x))$
$= \zeta(x)$

Case $m = \mathrm{LAM}(x, m_0)$: Let $\xi'' = \xi'[\texttt{x} \mapsto x, \texttt{m0} \mapsto m_0]$. Then,

$\theta_{\texttt{eval}}\ m \star \lambda g.g\ \zeta$
$= [\![\texttt{case m of ... | LAM(x,m0) => FUN(...) | ...}]\!]^{\mathrm{ml}}\ \xi'$
$= [\![\texttt{FUN(fn d => eval m0 (...))}]\!]^{\mathrm{ml}}\ \xi''$
$= \lfloor i_S^{-1}(in_2(\lambda t^{\mathbf{1}\to S_\perp}.[\![\texttt{eval m0 (fn x' => if ...)}]\!]^{\mathrm{ml}}\ \xi''[\texttt{d} \mapsto t]))\rfloor$
$= \lfloor i_S^{-1}(in_2(\lambda t.\theta_{\texttt{eval}}\ m_0 \star \lambda g.g\ (\lambda x'^V.[\![\texttt{if ...}]\!]^{\mathrm{ml}}\ \xi''[\texttt{d} \mapsto t, \texttt{x'} \mapsto x'])))\rfloor$

Similarly,

$i_{DS}([\![m]\!]_r\ \rho)$
$= i_{DS}([\![\mathrm{LAM}(x, m_0)]\!]_r\ \rho)$
$= i_{DS}(\phi_r(\lambda d^{D_r}.[\![m_0]\!]_r\ \rho[x \mapsto d]))$
$= i_{DS}(i_D^{-1}(\lfloor in_2(\lambda d^{D_r}.[\![m_0]\!]_r\ \rho[x \mapsto d])\rfloor))$
$= \lfloor i_S^{-1}(in_2(\lambda t.i_{DS}((\lambda d^{D_r}.[\![m_0]\!]_r\ \rho[x \mapsto d])\ (i_{DS}^{-1}(t\ *)))))\rfloor$ (by Lemma 12(b))
$= \lfloor i_S^{-1}(in_2(\lambda t.i_{DS}([\![m_0]\!]_r\ \rho[x \mapsto i_{DS}^{-1}(t\ *)])))\rfloor$

We will now prove the two embedded functions equal (in the mathematical sense). Let any $t' : \mathbf{1} \to S_\perp$ be given.

Let $\rho_0 = \rho[x \mapsto i_{DS}^{-1}(t' *)]$ and $\zeta_0 = (\lambda x'^V.[\![\texttt{if ...}]\!]^{\mathrm{ml}}\ \xi''[\texttt{d} \mapsto t', \texttt{x'} \mapsto x'])$. First we verify that ρ_0 and ζ_0 satisfy the requirements of the IH for m_0, namely that for all $x' \in FV(m_0) \subseteq \{x\} \cup FV(m)$, $i_{DS}(\rho_0(x')) = \zeta_0(x')$. This is straightforward; first for $x' = x$:

$$\begin{aligned}
&\zeta_0(x)\\
&= [\![\texttt{if x=x' then d () else p x'}]\!]^{\mathrm{ml}}\ \xi''[\texttt{d} \mapsto t', \texttt{x'} \mapsto x]\\
&= t' *\\
&= i_{DS}(i_{DS}^{-1}(t' *))\\
&= i_{DS}(\rho_0(x))
\end{aligned}$$

Then for any $x'' \in FV(m_0) \setminus \{x\}$:

$$\begin{aligned}
&\zeta_0(x'')\\
&= [\![\texttt{if x=x' then d () else p x'}]\!]^{\mathrm{ml}}\ \xi''[\texttt{d} \mapsto t', \texttt{x'} \mapsto x'']\\
&= \zeta(x'')\\
&= i_{DS}(\rho(x'')) && \text{(by assumption on } \rho \text{ and } \zeta)\\
&= i_{DS}(\rho_0(x''))
\end{aligned}$$

Thus by IH on m_0, $i_{DS}([\![m_0]\!]_r\ \rho_0) = \theta_{\texttt{eval}}\ m_0 \star \lambda g.g\ \zeta_0$. Since t' was arbitrary, we thus have

$$\begin{aligned}
&\theta_{\texttt{eval}}\ m \star \lambda g.g\ \zeta\\
&= \lfloor i_S^{-1}(in_2(\lambda t.\theta_{\texttt{eval}}\ m_0 \star \lambda g.g\ (\lambda x'^V.[\![\texttt{if ...}]\!]^{\mathrm{ml}}\ \xi''[\texttt{d} \mapsto t, \texttt{x'} \mapsto x'])))\rfloor\\
&= \lfloor i_S^{-1}(in_2(\lambda t'.\theta_{\texttt{eval}}\ m_0 \star \lambda g.g\ \zeta_0))\rfloor\\
&= \lfloor i_S^{-1}(in_2(\lambda t'.i_{DS}([\![m_0]\!]_r\ \rho_0)))\rfloor\\
&= \lfloor i_S^{-1}(in_2(\lambda t.i_{DS}([\![m_0]\!]_r\ \rho[x \mapsto i_{DS}^{-1}(t *)])))\rfloor\\
&= i_{DS}([\![m]\!]_r\ \rho)
\end{aligned}$$

Case $m = \mathrm{APP}(m_1, m_2)$: Let $\xi'' = \xi'[\texttt{m1} \mapsto m_1, \texttt{m2} \mapsto m_2]$. Then,

$$\begin{aligned}
&\theta_{\texttt{eval}}\ m \star \lambda g.g\ \zeta\\
&= [\![\texttt{case m of ... | APP(m1,m2) => (case ...)}]\!]^{\mathrm{ml}}\ \xi'\\
&= [\![\texttt{case (eval m1 p) of ...}]\!]^{\mathrm{ml}}\ \xi''
\end{aligned}$$

Now,

$$\begin{aligned}
&[\![\texttt{eval m1 p}]\!]^{\mathrm{ml}}\ \xi''\\
&= \theta_{\texttt{eval}}\ m_1 \star \lambda g.g\ \zeta\\
&= i_{DS}([\![m_1]\!]_r\ \rho) && \text{(by IH on } m_1)
\end{aligned}$$

Consider $[\![m_1]\!]_r\ \rho$:

Case $[\![m_1]\!]_r\ \rho = i_D^{-1}(\perp)$: Then by Lemma 12(c) also $i_{DS}([\![m_1]\!]_r\ \rho) = \perp$, and so $\theta_{\texttt{eval}}\ m \star \lambda g.g\ \zeta = \perp_{S_\perp}$.

Similarly,

$$\begin{aligned}
&i_{DS}([\![m]\!]_r\ \rho)\\
&= i_{DS}([\![\mathrm{APP}(m_1, m_2)]\!]_r\ \rho)\\
&= i_{DS}(\psi_r(i_D^{-1}(\perp))([\![m_2]\!]_r\ \rho))\\
&= i_{DS}(\perp_{[D_r \to D_r]}\ ([\![m_2]\!]_r\ \rho))\\
&= i_{DS}(\perp_{D_r})\\
&= \perp_{S_\perp}
\end{aligned}$$

Case $[\![m_1]\!]_r\ \rho = i_D^{-1}(\lfloor in_1(l)\rfloor)$: Then,

$$\begin{aligned}
&\theta_{\texttt{eval}}\ m \star \lambda g.g\ \zeta\\
&= [\![\texttt{case (eval m1 p) of TM l => TM(fn n ...) | ...}]\!]^{\mathrm{ml}}\ \xi''\\
&= [\![\texttt{TM(fn n => APP (...))}]\!]^{\mathrm{ml}}\ \xi''[\texttt{l} \mapsto l]\\
&= \lfloor i_S^{-1}(in_1(\lambda n^{\mathbb{Z}}.[\![\texttt{APP(l n, down (eval m2 p) n)}]\!]^{\mathrm{ml}}\ \xi''[\texttt{l} \mapsto l, \texttt{n} \mapsto n]))\rfloor
\end{aligned}$$

Similarly,

$$\begin{aligned}
&i_{DS}([\![m]\!]_r\ \rho)\\
&= i_{DS}([\![\mathrm{APP}(m_1, m_2)]\!]_r\ \rho)\\
&= i_{DS}(\psi_r\ (i_D^{-1}(\lfloor in_1(l)\rfloor))\ ([\![m_2]\!]_r\ \rho))\\
&= i_{DS}(\uparrow \widehat{\mathrm{APP}}(l, \downarrow ([\![m_2]\!]_r\ \rho)))\\
&= i_{DS}(\lfloor in_1(\widehat{\mathrm{APP}}(l, \downarrow ([\![m_2]\!]_r\ \rho)))\rfloor) && \text{(by Def. of } \uparrow \text{)}\\
&= \lfloor i_S^{-1}(in_1(\widehat{\mathrm{APP}}(l, \downarrow ([\![m_2]\!]_r\ \rho))))\rfloor && \text{(by Lemma 12(a))}\\
&= \lfloor i_S^{-1}(in_1(\lambda n^{\mathbb{Z}}.l\ n \star \lambda m_1'.\downarrow ([\![m_2]\!]_r\ \rho)\ n \star \lambda m_2'.\lfloor \mathrm{APP}(m_1', m_2')\rfloor))\rfloor
\end{aligned}$$

Again, we will prove the two embedded functions equal. Let any $n' \in \mathbb{Z}$ be given, and let $\xi''' = \xi''[\texttt{l} \mapsto l, \texttt{n} \mapsto n']$. Note also that by IH on m_2, $[\![\texttt{eval m2 p}]\!]^{\mathrm{ml}}\ \xi''' = i_{DS}([\![m_2]\!]_r\ \rho)$. We calculate:

$$\begin{aligned}
&[\![\texttt{APP(l n, down (eval m2 p) n)}]\!]^{\mathrm{ml}}\ \xi'''\\
&= l\ n' \star \lambda m_1'.[\![\texttt{down (eval m2 p)}]\!]^{\mathrm{ml}}\ \xi''' \star \lambda l'.l'\ n' \star \lambda m_2'.\lfloor \mathrm{APP}(m_1', m_2')\rfloor\\
&= l\ n' \star \lambda m_1'.i_{DS}([\![m_2]\!]_r\ \rho) \star \lambda s.\theta_{\texttt{down}}\ s \star \lambda l'.l'\ n' \star \lambda m_2'.\lfloor \mathrm{APP}(m_1', m_2')\rfloor\\
&= l\ n' \star \lambda m_1'.\downarrow ([\![m_2]\!]_r\ \rho)\ n' \star \lambda m_2'.\lfloor \mathrm{APP}(m_1', m_2')\rfloor && \text{(by Lemma 13)}
\end{aligned}$$

Since n' was arbitrary,

$$\begin{aligned}
&\theta_{\texttt{eval}}\ m \star \lambda g.g\ \zeta\\
&= \lfloor i_S^{-1}(in_1(\lambda n^{\mathbb{Z}}.[\![\texttt{APP(l n, down (eval m2 p) n)}]\!]^{\mathrm{ml}}\ \xi''[\texttt{l} \mapsto l, \texttt{n} \mapsto n]))\rfloor\\
&= \lfloor i_S^{-1}(in_1(\lambda n'^{\mathbb{Z}}.[\![\texttt{APP(l n, down (eval m2 p) n)}]\!]^{\mathrm{ml}}\ \xi'''))\rfloor\\
&= \lfloor i_S^{-1}(in_1(\lambda n'^{\mathbb{Z}}.l\ n' \star \lambda m_1'.\downarrow ([\![m_2]\!]_r\ \rho)\ n' \star \lambda m_2'.\lfloor \mathrm{APP}(m_1', m_2')\rfloor))\rfloor\\
&= i_{DS}([\![m]\!]_r\ \rho)
\end{aligned}$$

Case $[\![m_1]\!]_r\ \rho = i_D^{-1}(\lfloor in_2(f)\rfloor)$: Then by Lemma 12(b), we have $i_{DS}([\![m_1]\!]_r\ \rho) = \lfloor i_S^{-1}(in_2(\lambda t^{\mathbf{1}\to S_\perp}.\ i_{DS}(f(i_{DS}^{-1}(t\ *)))))\rfloor$. Thus,

$$\begin{aligned}
&\theta_{\texttt{eval}}\ m \star \lambda g.g\ \zeta\\
&= [\![\texttt{case (eval m1 p) of ... | FUN f => f (fn ...)}]\!]^{\mathrm{ml}}\ \xi''\\
&= [\![\texttt{f (fn () => eval m2 p)}]\!]^{\mathrm{ml}}\ \xi''[\texttt{f} \mapsto (\lambda t.i_{DS}(f(i_{DS}^{-1}(t\ *))))])\\
&= (\lambda t.i_{DS}(f(i_{DS}^{-1}(t\ *))))\ (\lambda u.i_{DS}([\![m_2]\!]_r\ \rho))\\
&= i_{DS}(f\ ([\![m_2]\!]_r\ \rho))
\end{aligned}$$

Similarly,

$$\begin{aligned}
&i_{DS}([\![m]\!]_r\ \rho)\\
&= i_{DS}([\![\mathrm{APP}(m_1, m_2)]\!]_r\ \rho)\\
&= i_{DS}(\psi_r(i_D^{-1}(\lfloor in_2(f)\rfloor))([\![m_2]\!]_r\ \rho))\\
&= i_{DS}(f\ ([\![m_2]\!]_r\ \rho))
\end{aligned}$$

□

Lemma 15 *For all $m \in \Lambda$, $\mathrm{norm}(m) = \theta_{\texttt{norm}}\ m$.*

Proof: Let m be given, and let $\xi = \emptyset[\texttt{down} \mapsto \theta_{\texttt{down}}, \texttt{eval} \mapsto \theta_{\texttt{eval}}, \texttt{norm} \mapsto \theta_{\texttt{norm}}, \texttt{m} \mapsto m]$. Let further $\lfloor \zeta \rfloor = [\![\texttt{fn x => TM(fn n => VAR(x))}]\!]^{\mathrm{ml}}\ \xi$ and $\rho = (\lambda x^V.\uparrow \widehat{\mathrm{VAR}}(x))$.

We first verify that ζ and ρ satisfy the requirements of Lemma 14, namely that for all $x' \in V \supset FV(m)$,

$\zeta(x')$
$= [\![\texttt{fn x => TM(fn n => VAR(x))}]\!]^{\mathrm{ml}}\ \xi \star \lambda f.f(x')$
$= [\![\texttt{TM(fn n => VAR(x))}]\!]^{\mathrm{ml}}\ \xi[\texttt{x} \mapsto x']$
$= \lfloor i_S^{-1}(in_1(\lambda n^{\mathbb{Z}}.\lfloor \mathrm{VAR}(x') \rfloor)) \rfloor$
$= \lfloor i_S^{-1}(in_1(\widehat{\mathrm{VAR}}(x'))) \rfloor$ (by Def. of $\widehat{\mathrm{VAR}}$)
$= i_{DS}(\uparrow \widehat{\mathrm{VAR}}(x'))$ (by Lemma 12(a) and Def. of $\uparrow$)
$= i_{DS}(\rho(x'))$

Hence, by a single unrolling of the fixed-point equation $\theta_{\texttt{norm}} = \Theta_{\texttt{norm}}(\theta_{\texttt{norm}})$,

$\theta_{\texttt{norm}}\ m$
$= [\![\texttt{down (eval m (fn x => TM(fn n => VAR(x)))) 0}]\!]^{\mathrm{ml}}\ \xi$
$= [\![\texttt{eval m (fn x => TM(fn n => VAR(x)))}]\!]^{\mathrm{ml}}\ \xi \star \lambda s.\theta_{\texttt{down}}\ s \star \lambda l.l\ 0$
$= \theta_{\texttt{eval}}\ m \star \lambda g.g\ \zeta \star \lambda s.\theta_{\texttt{down}}\ s \star \lambda l.l\ 0$
$= i_{DS}([\![m]\!]_r\ \rho) \star \lambda s.\theta_{\texttt{down}}\ s \star \lambda l.l\ 0$ (by Lemma 14)
$= \downarrow([\![m]\!]_r\ \rho)\ 0$ (by Lemma 13)
$= \mathrm{norm}(m)$ (by Def. of norm)

□

Theorem 4 (implementation correctness) *The program NORM satisfies that* $\mathrm{run}_{NORM}(m) = m' \Leftrightarrow \mathrm{norm}(m) = \lfloor m' \rfloor$. *That is, NORM computes the normalization function for all λ-terms without free occurrences of* $\texttt{g}\underline{\texttt{n}}$*-variables (including, in particular, all closed terms).*

Proof: A direct consequence of Lemma 15 and Theorem 3. □

5 Conclusions and Perspectives

We have presented a domain-theoretic analysis of a normalization-by-evaluation construction for untyped λ-terms. Compared to the typed case, the main difference is a change from induction on types to general recursion, both for function definitions and for the domains and relations on them. That the correctness proof has a generalized computational-adequacy result at its core, further strengthens the connection between normalization and evaluation. Moreover, the algorithmic content of the construction corresponds very directly to a simple functional program, enabling a precise verification of the normalizer as actually implemented.

There are several possible directions in which to extend the present work. Some were already mentioned in Section 1.5, such as generalizations of the algorithm to Böhm trees. It should also be possible to extend the language and notion of normalization with interpreted constants in a suitable sense. But already the current results indicate that the fundamental ideas of NBE are not incompatible with general recursive types. Thus, reduction-free normalization may provide a complementary view of other equational systems that are currently analyzed using exclusively reduction-based methods. It might even be possible to find unified formulations of rewriting-theoretic and model-theoretic normalization results about particular such systems.

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A Existence of Invariant Relations

For completeness, we review Pitts's technique. For conciseness, let us fix our attention to the recursive domain equation

$$X \cong (A + [X \to X])_\perp$$

where A is a cpo.

A solution to this equation is a pointed cpo D and an isomorphism $i : D \xrightarrow{\cong} (A + [D \to D])_\perp$. Define the continuous function $\delta : [D \to D] \to [D \to D]$ as

$$\delta(e)(d) = \text{case } i(d) \text{ of } \begin{cases} \lfloor in_1(a) \rfloor & \to i^{-1}(\lfloor in_1(a) \rfloor) \\ \lfloor in_2(f) \rfloor & \to i^{-1}(\lfloor in_2(e \circ f \circ e) \rfloor) \\ \quad \perp & \to \perp_D \end{cases}$$

A solution is called a *minimal invariant* if $\mathrm{fix}(\delta) = id_D$.

The following is well-known and can be found in in e.g. Pitts [6]:

Theorem 5 *For any cpo A, there exists a minimal invariant to the recursive domain equation $X \cong (A + [X \to X])_\perp$.*

This section establishes the following result, which is an abstract version of the construction used by Pitts to show computational adequacy for untyped PCF [5]:

Theorem 1 *Let A be a cpo, and let $i : D \xrightarrow{\cong} (A + [D \to D])_\perp$ be a minimal-invariant solution of the domain equation $X \cong (A+[X \to X])_\perp$. Let T be a set, and let predicates $P_1 \subseteq A \times T$, $P_2 \subseteq T$, and $P_3 \subseteq T \times T \times T$ be given, such that $\{a \mid P_1(a,t)\}$ is inclusive for every $t \in T$. Then there exists a relation, $\lhd \subseteq D \times T$, with $\{d \mid d \lhd t\}$ inclusive for every $t \in T$, and such that, for all $d \in D$ and $t \in T$:*

$$\begin{aligned} d \lhd t \textit{ iff } \; & i(d) = \perp \\ \textit{or } & \exists a.\ i(d) = \lfloor in_1(a) \rfloor \wedge P_1(a,t) \\ \textit{or } & \exists f.\ i(d) = \lfloor in_2(f) \rfloor \wedge P_2(t) \wedge \\ & \quad \forall d' \in D, t', t'' \in T.\ P_3(t,t',t'') \wedge d' \lhd t' \Rightarrow f(d') \lhd t''. \end{aligned}$$

To show the theorem, let A, (D,i), and T be given. Define a set Rel of relations on $D \times T$ by

$$R \in Rel \;\text{ iff }\; \text{for all } t \in T,\ \{d \mid (d,t) \in R\} \text{ is a pointed, inclusive subset of } D$$

Then $(Rel, \subseteq)$ is a partial order, where $\subseteq$ is ordinary set inclusion. Since Rel is closed under arbitrary intersection, $(Rel, \subseteq)$ is in fact a complete lattice. (Note, however, that joins in this lattice are not in general set-theoretic unions, since the union of an arbitrary family of inclusive relations need not itself be inclusive. Rather, $\bigsqcup\{R_i \mid i \in I\} = \bigcap\{R \in Rel \mid \forall i \in I.\, R_i \subseteq R\}$, i.e., the smallest *inclusive* relation containing all of the R_i.) In particular, Rel^{op}, i.e., Rel ordered by $\supseteq$, is also a complete lattice, and so is $Rel^{\mathrm{op}} \times Rel$.

Now, let predicates $P_1 \subseteq A \times T$, $P_2 \subseteq T$,and $P_3 \subseteq T \times T \times T$ be given, with $P_1(\cdot, t)$ inclusive for all $t \in T$. Define $\mathcal{R} : Rel^{\mathrm{op}} \times Rel \to Rel$ by

$$\begin{aligned}
&\mathcal{R}(R^-, R^+) = \\
&\quad \{(d,t) \mid i(d) = \bot \\
&\qquad\quad \text{or } \exists a.\, i(d) = \lfloor in_1(a) \rfloor \wedge P_1(a,t) \\
&\qquad\quad \text{or } \exists f.\, i(d) = \lfloor in_2(f) \rfloor \wedge P_2(t) \wedge \\
&\qquad\qquad \forall d' \in D; t', t'' \in T.\ P_3(t,t',t'') \wedge (d',t') \in R^- \Rightarrow (f(d'),t'') \in R^+\}
\end{aligned}$$

It is straightforward to verify that $\mathcal{R}$ is well-defined (by $P_1(\cdot, t)$ being inclusive) and monotonic. To prove Theorem 1, we thus only need to show that there exists a relation $\lhd \in Rel$ such that $\lhd = \mathcal{R}(\lhd, \lhd)$. We first establish a seemingly weaker result:

Lemma 16 *There exist relations $\lhd^-, \lhd^+ \in Rel$, satisfying:*

a. $\lhd^- = \mathcal{R}(\lhd^+, \lhd^-)$ *and* $\lhd^+ = \mathcal{R}(\lhd^-, \lhd^+)$.

b. For all $R^-, R^+ \in Rel$, if $R^- \subseteq \mathcal{R}(R^+, R^-)$ and $\mathcal{R}(R^-, R^+) \subseteq R^+$, then $R^- \subseteq \lhd^-$ and $\lhd^+ \subseteq R^+$.

Proof: Define the symmetric extension of $\mathcal{R}$, $\widehat{\mathcal{R}} : Rel^{\mathrm{op}} \times Rel \to Rel^{\mathrm{op}} \times Rel$, by

$$\widehat{\mathcal{R}}(R^-, R^+) = (\mathcal{R}(R^+, R^-), \mathcal{R}(R^-, R^+))$$

Now $\widehat{\mathcal{R}}$ is a monotonic operator on a complete lattice, so by the Knaster-Tarski fixed-point theorem, $\widehat{\mathcal{R}}$ has a fixed point $(\lhd^-, \lhd^+)$ that is also the least prefixed point of $\widehat{\mathcal{R}}$. That is, we have (a) $(\lhd^-, \lhd^+) = \widehat{\mathcal{R}}(\lhd^-, \lhd^+)$, and (b) if $\widehat{\mathcal{R}}(R^-, R^+) \sqsubseteq_{Rel^{\mathrm{op}} \times Rel} (R^-, R^+)$ then $(\lhd^-, \lhd^+) \sqsubseteq_{Rel^{\mathrm{op}} \times Rel} (R^-, R^+)$. And these are precisely the properties claimed in the statement of the lemma. □

For relations $R, S \in Rel$, we now define a predicate on $e \in [D \to D]$ by:

$$e : R \subset S \ \text{ iff } \ \forall d \in D, t \in T. (d,t) \in R \Rightarrow (e(d), t) \in S$$

Since this predicate is defined as an intersection of inverse images of the inclusive S, it is itself inclusive.

Lemma 17 *If $e : R \subset S$ then $\delta(e) : \mathcal{R}(S, R) \subset \mathcal{R}(R, S)$.*

Proof: Assume $e : R \subset S$, and let $(d,t) \in \mathcal{R}(S,R)$ be given; we must show that $(\delta(e)(d), t) \in \mathcal{R}(R,S)$. Consider $i(d)$. The cases $i(d) = \bot$ and $i(d) = \lfloor in_1(l) \rfloor$ do not depend on R and S and are thus immediate. Assume now $i(d) = \lfloor in_2(f) \rfloor$ where by assumption, $P_2(t)$ and $\forall d', t', t''. P_3(t,t',t'') \wedge (d',t') \in S \Rightarrow (f(d'), t'') \in R$. Then $i(\delta(e)(d)) = \lfloor in_2(e \circ f \circ e) \rfloor$. $P_2(t)$ holds by case. Let d', t', t'' be given, such that $P_3(t,t',t'') \wedge (d',t') \in R$; we must show $(e \circ f \circ e)(d'), t'') \in S$. We calculate: by $e : R \subset S$, $(e(d'), t') \in S$; by case, $(f(e(d')), t'') \in R$; and by $e : R \subset S$ again, $(e(f(e(d'))), t'') \in S$, as required. □

Theorem 6 *The relations $\lhd^-$ and $\lhd^+$ are equal.*

Proof: We show that each relation is included in the other. First, take $R^- = \lhd^+$ and $R^+ = \lhd^-$. By Lemma 16(a) we then get that $R^+ = \mathcal{R}(R^-, R^+)$ and $R^- = \mathcal{R}(R^+, R^-)$. Hence, by Lemma 16(b) (either half), $\lhd^+ \subseteq \lhd^-$.

Conversely, we have by Lemma 16(a) and Lemma 17 that if $e : \lhd^- \subset \lhd^+$ then $\delta(e) : \lhd^- \subset \lhd^+$. Since $(\perp, t) \in \lhd^+$ for any t, we also have $\perp_{[D \to D]} : \lhd^- \subset \lhd^+$. Thus, by fixed-point induction, $\text{fix}(\delta) : \lhd^- \subset \lhd^+$. And since (D, i) is a minimal invariant, $\text{fix}(\delta) = id_D$, and so $id_D : \lhd^- \subset \lhd^+$, i.e. $\lhd^- \subseteq \lhd^+$. □

Taking $\lhd = \lhd^+ = \lhd^-$, and using Lemma 16(a) (either half), we have thus established Theorem 1.

B Existence of Isomorphisms

Let us consider the recursive *pre*domain equation

$$X \cong A + [[\mathbf{1} \to X_\perp] \to X_\perp]$$

where A is a cpo.

A solution to this equation is a (bottomless) cpo S and an isomorphism $j : S \xrightarrow{\cong} A + [[\mathbf{1} \to S_\perp] \to S_\perp]$. Define the continuous function $\gamma : [S \to S_\perp] \to [S \to S_\perp]$ by

$$\gamma(e)(s) = \text{case } j(s) \text{ of } \begin{cases} in_1(a) \to \lfloor j^{-1}(in_1(a)) \rfloor \\ in_2(f) \to \lfloor j^{-1}(in_2(\lambda t^{\mathbf{1} \to S_\perp}.f(\lambda u.(t\ *) \star e) \star e)) \rfloor \end{cases}$$

A solution is called a *minimal invariant* if $\text{fix}(\gamma) = \lambda s.\lfloor s \rfloor$.

Re-expressing the standard inverse-limit construction in the setting of predomains and total continuous functions gives the following result:

Theorem 7 *For any cpo A, there exists a minimal invariant to the recursive predomain equation $X \cong A + [[\mathbf{1} \to X_\perp] \to X_\perp]$.*

We will also need the following simple property about fixed points.

Lemma 18 *Let A and B be pointed cpos, and let $f : A \to A$ and $g : B \to B$ be continuous functions. If $c : A \to B$ is a* strict *continuous function such that $c \circ f = g \circ c$ then $c(\text{fix}(f)) = \text{fix}(g)$.*

Proof: By fixed point induction. Define the admissible predicate $P(a, b) \Leftrightarrow c(a) = b$ as an inverse image of the identity predicate. Since c is strict, we have $P(\perp_A, \perp_B)$ and so P is also pointed. Let now a and b be given such that $P(a, b)$, i.e., $c(a) = b$. By assumption on f and g, also $c(f(a)) = g(c(a)) = g(b)$, namely $P(f(a), g(b))$. Thus by the continuity of f and g, $P(\text{fix}(f), \text{fix}(g))$ or simply $c(\text{fix}(f)) = \text{fix}(g)$. □

We are now in a position to establish the existence of isomorphisms between domains and predomains from minimal invariants for the above equations.

Lemma 19 *Let A be a cpo, let (D, i) be a minimal invariant for the recursive domain equation $X \cong (A + [X \to X])_\perp$, and let (S, j) be a minimal invariant for the recursive predomain equation $X \cong A + [[\mathbf{1} \to X_\perp] \to X_\perp]$. Then there exists an isomorphism $i_{DS} : D \xrightarrow{\cong} S_\perp$, satisfying* *a.* *For all* $a \in A$, $i_{DS}(i^{-1}(\lfloor in_1(a)\rfloor)) = \lfloor j^{-1}(in_1(a))\rfloor$.

b. *For all* $f \in [D \to D]$,
$i_{DS}(i^{-1}(\lfloor in_2(f)\rfloor)) = \lfloor j^{-1}(in_2(\lambda t^{\mathbf{1}\to S_\perp}.\ i_{DS}(f(i_{DS}^{-1}(t\ *)))))\rfloor$.

c. $i_{DS}(i^{-1}(\perp)) = \perp_{S_\perp}$

Proof: By direct construction. For any strict functions $h : D \to S_\perp$ and $k : S_\perp \to D$, define the strict $H(h,k) : D \to S_\perp$ and $K(h,k) : S_\perp \to D$ by

$$\begin{aligned}
H(h,k) &= \lambda d.\text{case } i(d) \text{ of } \begin{cases} \lfloor in_1(a)\rfloor \to \lfloor j^{-1}(in_1(a))\rfloor \\ \lfloor in_2(f)\rfloor \to \lfloor j^{-1}(in_2(\lambda t^{\mathbf{1}\to S_\perp}.\, h(f(k(t\ *)))))\rfloor \\ \quad\perp \quad\ \to \perp_{S_\perp} \end{cases} \\
K(h,k) &= \lambda s'.s' \star \lambda s.\,\text{case } j(s) \text{ of } \begin{cases} in_1(a) \to i^{-1}(\lfloor in_1(a)\rfloor) \\ in_2(f) \to i^{-1}(\lfloor in_2(\lambda d.\, k(f(\lambda u.h\, d)))\rfloor) \end{cases}
\end{aligned}$$

Then define $(i_{DS}, i_{DS}^{-1}) = \text{fix}(\lambda(h,k)^{[D\to S_\perp]\times[S_\perp\to D]}.(H(h,k),K(h,k)))$.

We need to show that i_{DS} and i_{DS}^{-1} are in fact two-sided inverses. Let c be the strict function $\lambda(h,k).k \circ h : [D \to S_\perp] \times [S_\perp \to D] \to [D \to D]$. Now,

$$\begin{aligned}
& c \circ \lambda(h,k).(H(h,k),K(h,k)) \\
&= \lambda(h,k).K(h,k) \circ H(h,k) \\
&= \lambda(h,k).\lambda d.\text{case } i(d) \text{ of } \begin{cases} in_1(a) \to K(h,k)(\lfloor j^{-1}(in_1(a))\rfloor) \\ in_2(f) \to K(h,k)(\lfloor j^{-1}(in_2(\lambda t.\, h(f(k(t\,*)))))\rfloor) \\ \quad\perp \quad\ \to K(h,k)(\perp_{S_\perp}) \end{cases} \\
&= \lambda(h,k).\lambda d.\text{case } i(d) \text{ of } \begin{cases} in_1(a) \to i^{-1}(\lfloor in_1(a)\rfloor) \\ in_2(f) \to i^{-1}(\lfloor in_2(\lambda d.k(\big(\lambda t.\, h(f(k(t\,*)))\big)\,(\lambda u.h\,d)))\rfloor) \\ \quad\perp \quad\ \to \perp_D \end{cases} \\
&= \lambda(h,k).\lambda d.\text{case } i(d) \text{ of } \begin{cases} in_1(a) \to i^{-1}(\lfloor in_1(a)\rfloor) \\ in_2(f) \to i^{-1}(\lfloor in_2(k \circ h \circ f \circ k \circ h)\rfloor) \\ \quad\perp \quad\ \to \perp_D \end{cases} \\
&= (\lambda e.\lambda d.\text{case } i(d) \text{ of } \left\{\begin{matrix} in_1(a) \to i^{-1}(\lfloor in_1(a)\rfloor) \\ in_2(f) \to i^{-1}(\lfloor in_2(e \circ f \circ e)\rfloor) \\ \perp \quad \to \perp_D \end{matrix}\right\}) \circ c \\
&= \delta \circ c
\end{aligned}$$

By Lemma 18 and the minimal invariant property of (D,i),

$$i_{DS}^{-1} \circ i_{DS} = c(\text{fix}(\lambda(h,k).(H(h,k),K(h,k)))) = \text{fix}(\delta) = id_D$$

For the other direction, let c' be the strict function $\lambda(h,k).h \circ k \circ (\lambda s.\lfloor s\rfloor) : [D \to S_\perp] \times [S_\perp \to D] \to [S \to S_\perp]$. We proceed similarly,

$$
\begin{aligned}
& c' \circ \lambda(h,k).(H(h,k), K(h,k)) \\
&= \lambda(h,k).H(h,k) \circ K(h,k) \circ (\lambda s.\lfloor s \rfloor) \\
&= \lambda(h,k).\lambda s.\text{case } j(s) \text{ of } \begin{cases} in_1(a) \to H(h,k)(i^{-1}(\lfloor in_1(a) \rfloor)) \\ in_2(f) \to H(h,k)(i^{-1}(\lfloor in_2(\lambda d.k(f(\lambda u.h\, d))) \rfloor)) \end{cases} \\
&= \lambda(h,k).\lambda s.\text{case } j(s) \text{ of } \begin{cases} in_1(a) \to \lfloor j^{-1}(in_1(a)) \rfloor \\ in_2(f) \to \lfloor j^{-1}(in_2(\lambda t.h(\big(\lambda d.k(f(\lambda u.h\, d))\big)\ (k(t\,*))))) \rfloor \end{cases} \\
&= \lambda(h,k).\lambda s.\text{case } j(s) \text{ of } \begin{cases} in_1(a) \to \lfloor j^{-1}(in_1(a)) \rfloor \\ in_2(f) \to \lfloor j^{-1}(in_2(\lambda t.h(k(f(\lambda u.h(k(t\,*))))))) \rfloor \end{cases} \\
&= \lambda(h,k).\lambda s.\text{case } j(s) \text{ of } \begin{cases} in_1(a) \to \lfloor j^{-1}(in_1(a)) \rfloor \\ in_2(f) \to \lfloor j^{-1}(in_2(\lambda t.\begin{pmatrix} f(\lambda u.(t\,*) \star \lambda s.\, h(k(\lfloor s \rfloor))) \star \\ \lambda s.\, h(k(\lfloor s \rfloor)) \end{pmatrix})) \rfloor \end{cases} \\
& \hfill \text{(by strictness of } h \text{ and } k) \\
&= (\lambda e.\lambda s.\text{case } j(s) \text{ of } \left.\begin{cases} in_1(a) \to \lfloor j^{-1}(in_1(a)) \rfloor \\ in_2(f) \to \lfloor j^{-1}(in_2(\lambda t.f(\lambda u.(t\,*) \star e) \star e)) \rfloor \end{cases}\right\}) \circ c' \\
&= \gamma \circ c'
\end{aligned}
$$

By Lemma 18 and the minimal invariant property of (S, j),

$$i_{DS} \circ i_{DS}^{-1} \circ (\lambda s.\lfloor s \rfloor) = c'(\text{fix}(\lambda(h,k).(H(h,k), K(h,k)))) = \text{fix}(\gamma) = \lambda s.\lfloor s \rfloor$$

Thus, $i_{DS} : D \xrightarrow{\cong} S_\perp$ is indeed an isomorphism.

The fixed point equation $i_{DS} = H(i_{DS}, i_{DS}^{-1})$ immediately yields part (a),

$$
\begin{aligned}
& i_{DS}(i^{-1}(\lfloor in_1(a) \rfloor)) \\
&= H(i_{DS}, i_{DS}^{-1})(i^{-1}(\lfloor in_1(a) \rfloor)) \\
&= \lfloor j^{-1}(in_1(a)) \rfloor\,,
\end{aligned}
$$

part (b),

$$
\begin{aligned}
& i_{DS}(i^{-1}(\lfloor in_2(f) \rfloor)) \\
&= H(i_{DS}, i_{DS}^{-1})(i^{-1}(\lfloor in_2(f) \rfloor)) \\
&= \lfloor j^{-1}(in_2(\lambda t^{\mathbf{1} \to S_\perp}.\ i_{DS}(f(i_{DS}^{-1}(t\,*))))) \rfloor
\end{aligned}
$$

and part (c),

$$
\begin{aligned}
& i_{DS}(i^{-1}(\perp)) \\
&= H(i_{DS}, i_{DS}^{-1})(i^{-1}(\perp)) \\
&= \perp_{S_\perp}
\end{aligned}
$$

□

Lemma 19 in particular establishes Lemma 12.

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